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History of the Earth VI

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Volume VI: Science Through the Ages

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Foreword

It was the year 1996, and as I walked into my first University class it seemed as though everyone I spoke with had some type of plan and a career path designed since grade school. I was amazed as people told me in great detail how they mapped out their upcoming four years of courses and their future plans for graduate and professional schools. I nervously looked around the room at the 400 students ready for their first chemistry lecture and thought to myself 'What am I doing here?' It took me almost the entire year to figure out that it was okay that I didn't have a predestined path and that my interests were broad. As difficult as it may be to believe it was a textbook that made me understand the Earth Sciences were my calling. There was one geology book that I simply enjoyed reading and I eventually realized I was driving my friends crazy with interesting facts on glaciers, geomorphology and sedimentology. It was from that realization that I decided that not only would I enjoy a career in the Earth Sciences, but that I would also like to help others understand the world around them.

During my time as a PhD student I had my first opportunity to teach a class in the Earth Sciences, specifically a second year course in Geomorphology. Preparing for that first class made me the most nervous I have ever felt in my career. Trying to determine what aspects of the material was necessary to cover for the students to be successful moving forward with their studies, and how to incorporate current academic debates on geomorphic processes into the class in an engaging and interesting way, was a challenging task. My goal was to make the students as interested in the subject matter as I was through preparation and enthusiasm. I didn't expect everyone to have the same passion for geomorphology that I had, but I strived for each student to have at least one moment where their interest exceeded their expectations and they walked away with an appreciation of the complexity of processes shaping our Earth.

This book helped me reconnect with those memories by so thoroughly illustrating how fascinating the History of The Earth is. The classic photo of the Earth sent back from Voyager 1 at a point 6 billion miles from Earth sets the stage for just how big the universe is and the importance of being able to answer the questions of how our own planet formed. It helps me remember why I was drawn to the Earth Sciences. Reading through this book created by students from the award winning McMaster University Integrated Sciences Program made me think back to that first class where I tried to make sure everyone walked away with at least one moment where the material exceeded their expectations. Each chapter is rich with discussion ranging from philosophy through to physics and captures both the enthusiasm and the understanding of the authors. This is a wonderful contribution to the literature and I highly recommend it be read by anyone with an interest in the world around them.

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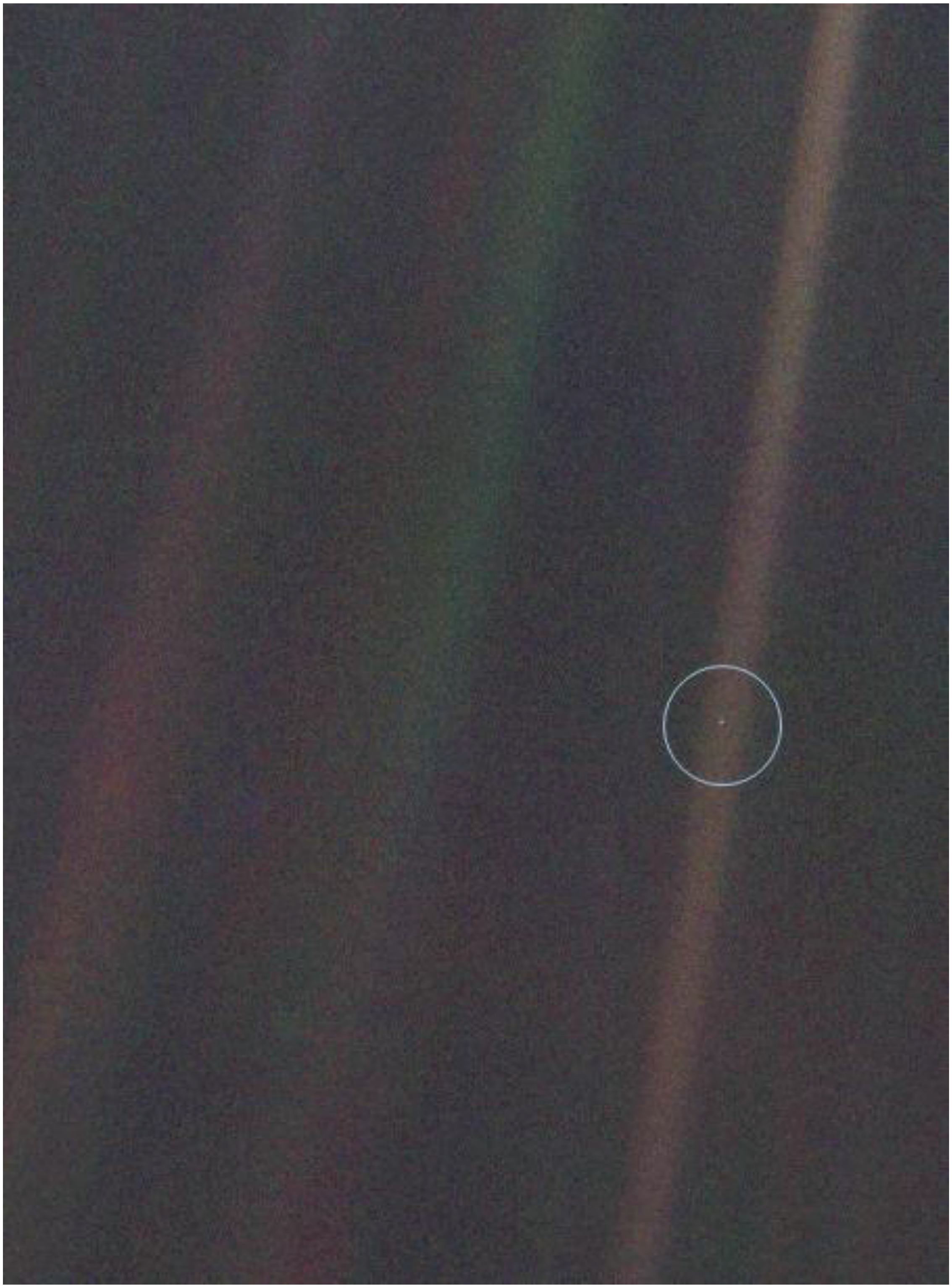

Figure 0.1 *'Pale Blue Dot' image of Earth, from Voyager 1 from six billion kilometers away (NASA 1990).*

Introduction

At times, Earth may seem nothing more than a simple drop within a sea of turbulence. The grandeur of the outside universe can often diminish the tragedies, glories, missteps, victories, and legacies that have shaped life on Earth. Yet, our planet has never failed to entertain and occupy humanity's greatest minds. Scientific frustration has come not from the realization of the small role that Earth plays within the vast universe, but by our limitations in providing suitable answers to perpetual questions surrounding our planet. Human curiosity is at the heart of scientific thought. It is a quality that dares scientists to shout and debate, for there can be no silence when the truths of this world have yet to be revealed.

Perhaps one the most impressive skills possessed by the human species is its ability to travel through time. The past lies like an open book all around us. We can look into the sky to observe stars, alien worlds, and the universe at large as they were thousands, millions, or even billions of years ago. Or, we can simply glance down at the dirt upon which we stand and and from which we originate. All that is necessary to flip back the pages of time is a shovel and scientific observation. To dig a centimeter into the earth is to read a few months into the past; to dig thirty kilometers is to read every page from start to finish. However, it is no easy task to sift through the endless vestiges of forgotten environments, lost oceans, and ancient lives. A few individuals have dedicated their lives to exposing, identifying, and interpreting the patterns and remains left buried in this planet.

From the study of the formation of the earth, to the geological phenomena exhibited on the surface and subsurface, to the wonders of the sea and the sky, and finally to life on earth, humans have made at least a dent in the mystery of this small rock we stand on. This book aims to tell the story of humanity's quest to understand Earth, showing how this story has evolved over time, and where it stands today. As Albert Einstein once remarked, "the most incomprehensible thing about the world is that it is at all comprehensible." This book is an ode to all those who have made the world at all comprehensible.

HISTORY

THE

Sapere aude Horace

The human mind may not have evolved enough to be able to **comprehend** deep time. It may only be able to measure it John McPhee

I know that I am mortal by nature, and ephemeral; but when I trace at my pleasure ***the windings*** to and fro ***of the heavenly bodies*** I no longer touch the earth with my feet: I stand in the presence of Zeus himself and take my fill of ambrosia. Ptolemy

The mind seemed to grow giddy by looking *so far into the* abyss of time *John Playfair*

Facts are stupid until brought into connection with some general law
Louis Agassiz

What we do not know today we shall know tomorrow ... very soon the last barriers between the living and the dead will crumble under the attack of patient work and powerful scientific thought Alexander Oparin

In the ***discovery*** of hidden things and the investigation of hidden causes, stronger reasons are obtained from ***sure experiments*** and demonstrated arguments than from probable conjectures and the opinions of philosophical speculators of the common sort William Gilbert

The greatest ***obstacle*** *to discovering the shape of the Earth, the continents, and the oceans was not ignorance but the* ***illusion of knowledge****. Daniel Boorstin*

Many people attribute to God's wisdom all they do not know of ***physical sciences****. Al-Biruni*

For small creatures such as we the ***vastness*** is bearable only through ***love***. Carl Sagan

What is a scientist after all? It is a curious man looking through a keyhole, the keyhole of nature, trying to know what's going on
Jacques Cousteau

ANY ONE MAY ***SEARCH*** FOR WHAT HE WISHES, AND MAY KNOW WHERE TO ***FIND*** IT PLINY THE ELDER

While everybody is uniformitarian in accepting as method that the present is the key to the past, it may no less be true, history the mentor, that the ***past is a key*** *to the present* D.C. Bowen

I am not accustomed to saying anything with ***certainty*** *after only one or two observations Andreas Vesalius*

I don't like to say bad things about ***paleontologists,*** *but they're really not very good scientists. They're more like* ***stamp collectors*** *Dr. Luis Alvarez*

The study of Nature is intercourse with the Highest Mind. You should **never trifle** *with Nature*
L.R. Agassiz

Spontaneous generation is occurrence of a **new organized beings** lacking parents and whose main elements were entirely extracted from the surrounding substances Louis Pasteur

For the present, however, we take the geographical locations for granted. Ptolemy

Finally we shall place the Sun himself at the center of the Universe Copernicus

The rise of an instinctive faith that there is an **Order of Nature** *which can be traced in every detailed occurrence* A.N. Whitehead

No fossil is buried with its birth certificate. That, and the scarcity of fossils, means that it is effectively impossible to link fossils into ***chains of cause and effect*** *in any valid way* Henry Gee

The sea, the great unifier, is man's only hope. Now, as never before, the old phrase has a literal meaning: **we are all in the same boat** *Jacques Cousteau*

OF

The glacier was ***God's great plough*** set at work ages ago to grind, furrow, and knead over, as it were, the surface of the earth Louis Agassiz

EARTH

Sometimes you have a really bad day and something falls out of the sky *Dr. Walter Alvarez*

One general law, leading to the advancement of all organic beings, namely, multiply, vary, ***let the strongest live*** and the weakest die. Charles Darwin

The magnetic force is animate, or **imitates a soul**; *in many respects it surpasses the human soul while it is united to an organic body* William Gilbert

With all grubs and all animals that break out from the grub state, *generation* is due primarily to the heat of the sun or to wind Aristotle

There are seas encircling the globe on every side and dividing it in two, ***so robbing us of half the world,*** since there is no region affording a passage from there to here. Pliny the Elder

There is ***geometry*** in the humming of the strings, there is ***music*** in the spacing of the spheres. Pythagoras

The tree grew large and strong, and the height thereof **reached unto heaven**, *and the sight thereof to the ends of all the Earth.* *Daniel 11:11*

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***Figure 1.1**: A view of the Eastern Hemisphere of Earth from space.*

Chapter One: Our Home in the Solar System – Understanding Earth's Properties

4.6 billion years ago a planet formed, the third one from a bright star; it was upon this planet where life would one day thrive. As the molten mass hurtled through space, it was sculpted into the round, rocky, water-covered globe that became our home in the Solar system. Humans are thrown headfirst into this immense universe with neither direction nor protection, left to find their way through a perilous and inscrutable existence alone. They must carve, from forces beyond their control or comprehension, food, shelter, warmth, family, friends, and even meaning, without instructions on how to do it. Every night, after their work is done, they lie on their furs and lose themselves in the thousands of gleaming motes of light that surround them, filling the pure black sky.

The heavens and their mechanics were, and continue to be, of great importance to the lives of those that lived beneath them. The stars and planets were, for much of human history, the purest expression of the character and order of the heavens. Throughout the ages humans have tried to categorize and define what they thought to be the realm of the gods, proposing and revising early models for our Solar system with both mathematical evidence and belief in the divine.

A person's beliefs of stars, and the order they represent, profoundly impact the way they perceive and process what happens around and to them. It is understandable that the night sky was such an important part of people's live all through history, and a subject of such intense study and speculation. Through studying the sky, people study their own relationship with nature, giving context to their lives. However, individual and cultural belief systems did not only apply to studies of the skies, but also to studies of the Earth. Civilizations throughout history have attempted to date the Earth, and early estimates in the West were based off of biblical interpretations. As time went on, these biblical interpretations were left by the wayside and replaced by evidence and empirical data.

Other enigmas about the Earth also had to be studied and solved. It is difficult to infer, for example, the shape and size of Earth when one can only see the small section of the planet in which one lives. These developments in knowledge have been spurred by political, social, and cultural pressures, as well as being driven by humans' innate curiosity about the natural world.

This chapter delves into the history of this innate curiosity humans possess. From the conception of the Solar system to the determination of many of its properties, humans have come a long way in uncovering the ground upon which they stand.

Formation of the Earth and the Solar System

Early Western philosophers believed that nature was a benevolent force, which would bring humanity ever greater joy. Aristotle (384-322 BCE), for example, believed that God is an entity of pure thought, happiness, and fulfilment (Russell, 2004). The material world, while imperfect, yearns to become more like God. All change in the material world is motivated by its evolution into God's likeness, day by day evolving into a greater and more perfect form. Although he believed that the evolution could never be complete, Aristotle saw nature as a growing benevolence (Russell, 2004) (**Figure 1.2**).

Figure 1.2: *Late 14th Century diagram showing Angels turning cranks to rotate the celestial spheres around the Earth. The image demonstrates the viewpoint of God's influence in a benevolent universe.*

This sense of benevolent nature serves as the cornerstone for many modern religions. Christianity, for example, is built upon the idea of a benevolent God, who cares so deeply about humanity that He would sacrifice His Son for its well-being (Whittingham, Gilby and Sampson, 1605). Such a view of a benevolent God is comforting, allowing those who believe it to rest assured that in the end nature would provide for them, fulfilling their needs and setting everything right, despite any adversity they may experience.

Agents of science, however, look for comfort in different ways. They reject the notion of a benevolent nature; rather than looking for harmony between nature and humans, they master and control nature to materially improve the human condition (Shell, 1980). To them, nature is a set of mechanistic, uncaring laws to be manipulated for human benefit. In their rejection of a benevolent nature, they destroy the sense of comfort and idle well-being that people draw from it, stripping many people of their comforting and protecting trust in nature (Shell, 1980).

Since the characteristics of nature are so deeply tied to humanity's sense of comfort and security, any question of science is also a question of relationships and belonging. If nature is continually changing, is there such thing as safety? If nature holds no respect for humans, is there such thing as justice? In considering matters of such import as the origin of the heavens and the essence of all that is, scientists have found themselves considering the question of humanity's relationship with nature (Shell, 1980). Their conclusions were influenced by sentiments of their time, and conversely had a great impact on the way humanity saw itself.

The Search Begins

Around the 15th century, academia was tiring of the Aristotelean approach – while his method of reasoning was applicable to virtually any question, it could not determine mechanisms in any detail (Grant, 1978; Hall, 1962). In search of certainty, philosophers and astronomers strived to apply a more mathematical approach to their studies (Hall, 1962).

Yet while the world wanted certainty, society also expected the outcome to substantiate what they were familiar with. Contrarily, as people tried to quantify physical relationships of the cosmos with more detailed observations and experiments, they found their new discoveries incompatible with central beliefs at the time, often resulting in more uncertainty.

Thus, a divide between philosophers and astronomers began to emerge. Philosophers kept their theoretical approach and did not learn to observe the skies, while astronomers became increasingly focussed on observations in an attempt to mathematically quantify their findings (Hall, 1981).

At the turn of the 16th century, Nicolaus Copernicus (1473-1543) was well-versed in both the theoretical and physical approach to astronomy, resulting in his revolutionary heliocentric model (Hall, 1962). Galileo

Galilei's celestial observations and Johannes Kepler's mathematical explanations of planetary orbits confirmed Copernicus' hypothesis (Encrenaz et al., 2004). This chain of events created a foothold within astronomy, which though controversial, supplied essential facts upon which future astronomers could base their investigations.

Vortex Theory

Building on Copernicus' idea of heliocentrism, René Descartes (1596-1650) developed one of the first theories of solar system formation (Hall, 1962). Descartes did not see the merit in experimental and observational work, and instead followed Aristotle's method of universal truths and reasoning. However, he was a skilled mathematician and pioneered the use of mathematical laws to prove natural phenomena. As well, he questioned Aristotle's and other previous knowledge, ascertaining that at the beginning of an investigation, only doubt was certain. This provided the basis for Descartes' main postulates – first, since doubt certainly exists and he performs the act of doubting, he must exist, as in his famous phrase, "I think therefore I am", and secondly, there must exist a greater being that puts these thoughts into his mind, namely God (Scott, 1950).

Descartes' philosophy forms the basis for his vortex theory of solar system formation. First published in *Principia philosophiae* (*Principles of Philosophy*) in 1644, he proposed that the universe is filled with an indivisible matter, 'aether' (Hall, 1981). God created this matter and set it in motion, to form planets out of whirling pools of matter (Descartes, 1998). Descartes believed that aether would fill any empty spaces if it were possible to create them, and therefore there could be no voids in the universe (Descartes, 1998). He also did not agree with the existence of any long-term forces such as gravity or magnetism, and so it was crucial for all matter to be touching (**Figure 1.3**) (Descartes, 1998). In this way, forces on one body could exert forces on the matter directly beside it, resulting in the synchronous motion of the solar system.

Descartes also asserted that much like boats bobbing in an ocean, planets moved locally with the matter around them, but were stationary overall (Scott, 1950). While it is not clear if he added this in response to religious pressure, it reflected societal preference at the time for a stationary Earth acted on by local forces over the implication that the Earth, their home, was moving in ways humans could not fathom.

Descartes' theory was satisfying and intelligible – many were convinced through his use of mathematical proofs and logic (Scott, 1950). Ultimately however, Isaac Newton (1643-1727) published the laws of motion in *Philosophiae Naturalis Principia Mathematica* (*Mathematical Principles of Natural Philosophy*), 1687, disproved the possibility of a vortex based model (Cohen, 1999). This was contended by several who had adopted Descartes' ideas, such as Daniel Bernoulli (1700-1782), an acclaimed scientist who continued to advocate for him into the following century (Scott, 1950).

Descartes was perhaps too consumed by his notion of the world to develop an empirical model of solar system formation. However, his model was the first to consider an evolution-based formation of the Earth and offered an immediately testable theory to perpetuate investigation (Encrenaz et al., 2004). His method of mathematical proofs would continue to underlie scientific discovery for centuries.

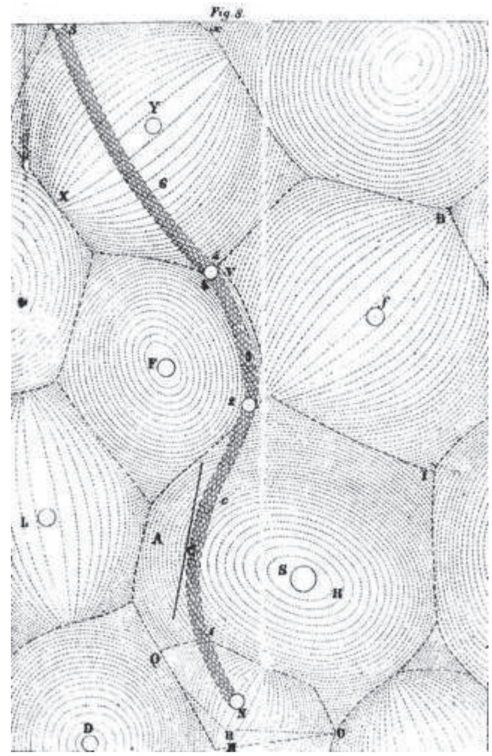


Figure 1.3: *Descartes' illustration of the Vortex model. Planetary bodies are surrounded by aether, resulting in no voids. The snaking path shows how an object would move, given the motion of aether.*

Tidal Theory

Completing most of his works a century after Descartes, Georges-Louis Leclerc, Comte de Buffon (1707-1788) demonstrated the long-lasting popularity of Descartes' mathematics and their role in scientific certainty (Steel, 1997). Buffon was hugely influential during his time period as a scientist, writer, politician, and businessman in France. Much of his popularity was due to his focus on the human perspective, such as his pre-Darwinian theories on the origin of species and his excellent writing style, as well as his use of mathematics to support his ideas (Fellows and Milliken, 1972).

Buffon was considered one of the four major literary figures in France, among Voltaire, Montesquieu, and Rousseau (Fellows and Milliken, 1972). This was an especially impressive achievement, considering his works were primarily scientific. Buffon had an excellent writing style and, according to philosopher Jean-Jacques Rousseau, was "the finest prose stylist of the century" (Fellows and Milliken, 1972).

In his writing, communicating to the reader was Buffon's top priority. He thought in terms of a single unifying ideal to explain the universe and strove for simplicity in his work (Fellows and Milliken, 1972). This manifested in his view of a welcome and optimistic world, wherein reality provided for and responded to man's needs. Buffon's reassuring perspective contributed to his immense popularity, because he could explain phenomena in ways that seemed both correct and relieved people's fears.

However, this introduced a dichotomy into Buffon's work. Newton was one of his personal heroes, and Buffon aspired after him to explain both the origin and mechanisms of phenomena (Solinas, 1979). Yet his concern with communicating to his reader meant that he often put style before scientific truth. When developing his planetary formation model, Buffon drew from imaginative, literary sources instead of scientific data and often determined details through his own interpretation (Fellows and Milliken, 1972).

Published in *Histoire Naturelle* (*Natural History*), Buffon's tidal theory postulates that a large comet collided with the Sun, resulting in the extrusion of large magma ribbons. This material from the Sun then aggregated into lumps of different composition, forming the planets (Steel, 1997).

Tidal theory represents Buffon's attempt to explain the origin of the solar system in terms of basic building blocks and Newtonian physics. At the time, comets were thought to be much larger and he cited Newton that comets occasionally collide with the Sun (Fellows and Milliken, 1972). His model was elegantly simple, in that the only materials required would be a comet and the Sun, and he thought the collision explained why planets rotated in the same direction and plane (Fellows and Milliken, 1972).

However, critics were swift to note that Buffon's understanding of motion aligned more with Descartes' idea of mechanics and less so with Newtonian physics. His tidal theory was dismissed soon afterwards. However, it was an attractive idea conceptually and in the coming centuries, many other scientists attempted to revise a collision-based model based on new discoveries (Encrenaz et al., 2004).

The Nebular Hypothesis

Like Buffon, Immanuel Kant (1724-1804), one of the most influential modern Western philosophers, wanted a reassuring sense of nature, but he was unwilling to inherit comfort without justification. On the contrary, he was deeply unsettled by the dichotomy between the comfort of a benevolent nature and the clear explanations and predictions offered by scientists (Shell, 1980). He had more trust in the mechanistic explanations for nature's phenomena, proposed by Newton and other early scientists, than in the more soothing but nebulous ones given by spiritual authorities. At the same time, however, he felt that the scientific understanding of nature as an indifferent system had done great damage to humanity's peace of mind. He worked to reconcile the utility and clarity of science with the reassurance of a benevolent nature, looking for ways in which they might work together as a coherent whole (Shell, 1980).

In 1755, Kant published a work entitled *Allgemeine Naturgeschichte und Theorie des Himmels* (*Universal Natural History and Theory of Heaven*), in which he proposes a model for cosmogony to accommodate both systems. In Universal Natural History, he describes a universe which follows Newtonian laws, which are in turn set in motion by God (Jastrow and Cameron, 1963). In fact, in the first paragraph of the first chapter, he expresses wonder at how "the infinite space swarms with worlds, whose number and excellency have a relation to the immensity of their Creator" (Kant, 1968).

Kant's unification of a beautiful Creator and mechanical laws is apparent in the details of his nebular hypothesis for the formation of the Earth and Solar system. His hypothesis begins with the assumption that space is filled almost uniformly with gas. Following Newton's law of universal gravitation, the scattered elements attract each other, and dense elements gather and accumulate upon them a mass of lighter ones. These larger, accumulated masses in turn accumulate into larger yet conglomerations. At certain points, where there is a large number of large masses, all of the surrounding elements will fall towards them, resulting in the formation of a massive body at the centre which will eventually become a star. Particles continue to fall towards it, and the "force of repulsion" that acts on them give them radial motion, pushing them into elliptical orbits in which they may continue falling towards the Sun forever. The particles limit each other's movement, naturally bringing each other into parallel orbits in the same direction, pulling the cloud into a plane where they obstruct each other as little as possible. Particles with close orbits are at rest with respect to each other, and so attract each other into large conglomerations (although much smaller than the central mass) which develop into planets. Thus the central mass becomes a star, and the particles that orbit it into planets, and the Solar system is formed. All star systems are produced in this way, and the same process on a larger scale produces galaxies (Kant, 1968).

Kant's hypothesis describes a universe of intense and beautiful, if uncaring, power. He proposed a universe in which worlds and star systems tend towards destruction (Kant, 1968). The orbits created through the mechanisms he described will not last forever; each will inevitably decay, and each world or star created will inevitably be destroyed (Kant, 1968). Nature is full of destruction, driven by enormously potent and entirely indifferent forces. The Earth and Sun could be destroyed, and humans would be powerless to save themselves; they are tiny and beautiful creatures, trapped on a mote of dust in a hurricane.

Even in this destruction, however, Kant found comfort. Just as worlds' orbits decay and their matter is torn apart and scattered, they produce material for the creation of new worlds elsewhere. Destruction is intimately linked to creation, such that there is no such thing as "loss to Nature" (Kant, 1968). The loss of one planet, in one location in space and time, allows for the creation of another, somewhere else (Shell, 1980). While humans live amidst indiscriminate destruction, they are also a part of infinite creation and endless beauty. That knowledge alone is precious comfort, as they weather the storm of nature.

A Different Nebular Hypothesis

Pierre-Simon Laplace (1749-1827), perhaps best known for his Laplace Transform, was an astronomer and mathematician who often pondered the properties of the knowable and unknowable (**Figure 1.4**). He was less concerned than Kant about the spiritual characteristics of the mechanistic laws and processes of nature, and of its benevolence or indifference, creation or destruction. Laplace was more interested in the concepts of omniscience and scientific determinism (Taylor, 2007). He wanted to know if everything in the universe could be knowable - in principle, and then by humans.

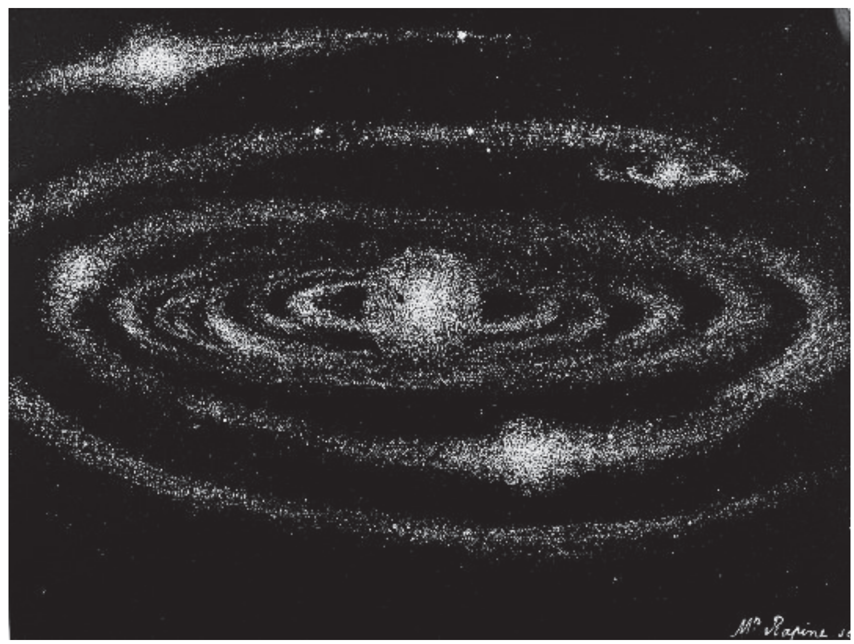


Figure 1.4: *A depiction of Laplace's Nebebular Hypothesis, motivated by his desire to understand the universe.*

In his work *Essai Philisophique sur les probabilités* (*Philosophical Essay on Probabilities*), he discusses scientific determinism and the limits of what is knowable (Taylor, 2007). He considered an ideal being as a vast intelligence which knows the positions of all the particles in the universe, and understands all the physical laws they follow (Laplace, 1902). This intelligence is known today as Laplace's demon. Laplace suggests that if such an intelligence, knowing all physical laws, could at one moment know the situation of all the particles in the universe, it could then analyze them and calculate all the events of the entire past and future, on all scales from the smallest atom to the largest galaxy; "nothing would be uncertain and the future just like the past would be present before its eyes" (Laplace, 1902).

Laplace's demon, while certainly possessing some deific qualities, is a very different creature than the benevolent gods of Aristotle or Christianity, or even Kant's balance of creation and destruction. Laplace's ideal being is an infinitely competent mathematician or physicist, capable of analyzing truths to produce more truths (Taylor, 2007).

According to Laplace, humanity has been advancing towards a state of omniscience throughout history. As centuries pass, the species constructs increasingly complete models of the universe. However, Laplace admits that the goal of omniscience is unattainable, to forever remain "infinitely removed" from humanity (Laplace, 1902).

In any case, since Laplace's ideal being is one of pure analysis, it is clear that Laplace held the analysis of facts and known relationships in very high regard. He was much fonder of deductive than inductive reasoning - that is, he preferred to use information to calculate certain conclusions than to use information to suggest a probable explanation (Jeans, 1923). It is with hesitation, therefore, that he proposed his explanation for the formation of the Earth and Solar system. It occupies just about 1,000 words in the last chapter of his work *Exposition du Système du Monde* (*The System of the World)*, in which he explained celestial mechanics using Newton's law of universal gravitation (Evans, 2015). Laplace puts forward his version of the nebular hypothesis "with the mistrust that anything which is a result of neither observation nor calculation should inspire", showing his lack of confidence in his hypothesis, since it is explicitly not the analysis and careful calculation inherent to his dreamt "vast intelligence", but rather the conjecturing of novel processes (Laplace, 1824).

Laplace's hypothesis was, however, useful to the development of cosmogony. Although his hypothesis is, like that of Kant, a nebular hypothesis, their mechanics differ considerably (Jastrow and Cameron, 1963). He conjectured that the Sun was once larger in size than it is today, and had an atmosphere which rotated around its axis with it. The atmosphere was limited by the surface at which the force of gravity was equal in magnitude to the centrifugal force from the rotation, and the two forces balanced each other out. The Sun cooled, and so its outer layers shrank and contracted, as is the case with all cooling stars. Therefore, its angular velocity must have increased to conserve angular momentum. The limiting surface of its atmosphere, rotating with it, must then have shrunk too. As the limiting surface shrank, rings of molecules found themselves outside it, and were consequently shed from the atmosphere. These rings would cool and undergo gravitational aggregation, forming the planets as the Sun shrank into what it is today (Laplace, 1824).

Laplace's discussion of cosmogony is much more technical and mathematically detailed and supported, than that of Kant. This difference is fitting to the difference in where they each find meaning and perfection; while Kant looked for benevolence in the mechanics of nature, Laplace strived towards an understanding of them as complete and thorough as possible. Perhaps unexpectedly, Laplace's hypothesis' higher level of mathematical and physical detail resulted in its refutation by recent observations, while Kant's less precise statements align better with astronomical observations (Ley, 1968).

On the Path to Resolution

Over the last four centuries, three main theories for the formation of the Solar System were developed and considered, each with their own merits and specific influences from within their time. Descartes was fueled by a need for a secure universe, resulting in the Vortex theory wherein aether cradles planets and transmits motion over short distances. Buffon valued consistency and simplicity, so that his Tidal theory requires only a pre-existing comet and Sun to account for the creation of the planets and their ordered motion. Kant pursued the melding of truth and beauty, resulting in his observation-based nebular hypothesis, where the frightening destruction of one universe would lead to the hopeful birth of another. Although he also created a nebular hypothesis, Laplace aimed most of all for a complete and precise truth, so that he lacked confidence in his hypothesis even with its impressive precision and mathematical detail. The evolution of science shows through each step of discovery, as society learned to acknowledge, face, and accept an uncaring universe, and even come to recognize it as their home.

The Protoplanetary disk

Modern explanations for the development of the Earth and the Solar system are direct developments of the nebular theory of Kant, Laplace and many others. Today, telescope observations show that stars form from molecular clouds, mainly composed of hydrogen (Williams and Cieza, 2011). Massive regions of molecular clouds collapse, due to gravity, towards their centre of mass. Initially, although the movements of particles in a molecular cloud are random, the cloud must still have some net angular momentum (Cardall and Daunt, 2015). As the cloud collapses, its angular momentum must be conserved, so since its radius is becoming smaller, the net radial velocity of particles in the direction of the net angular momentum must increase, as dictated by conservation of angular momentum (Knight, 2013):

$$L = I \times \omega = \frac{2}{5} m r^2 \omega$$

where *I* is the moment of inertia of the spherical cloud, ω is its angular momentum, *m* is its mass, and *r* is its radius.

Therefore, particles acquire a more uniform rotation, in the direction of the initial angular momentum, rotating more coherently as an initially spherical cloud. The cloud's rotation pulls it into a flat shape; there is more centrifugal force at the equator of a rotating spherical surface than at the poles, since particles at the equator are farther from the axis of rotation, and the force of gravity is the same everywhere on the surface. Hence, the difference between the magnitudes of the force of gravity and the centrifugal force on a given particle is larger at the poles than at the equator (Williams and Cieza, 2011). As the centre of the disk condenses, it gets hotter and hotter, eventually reaching temperatures high enough to start the nuclear fusion of hydrogen into helium, and thus a star is born (SUT, 2011).

Meanwhile in the disk, gravitational and electrostatic attraction causes the aggregation of dust and ice particles into clumps called planetesimals (Perryman, 2011). As these planetesimals accumulate more and more matter and mass, they attract each other, too, and collide and merge into protoplanets (Greenzweig and Lissauer, 1990). Finally, protoplanets collide to form today's planets.

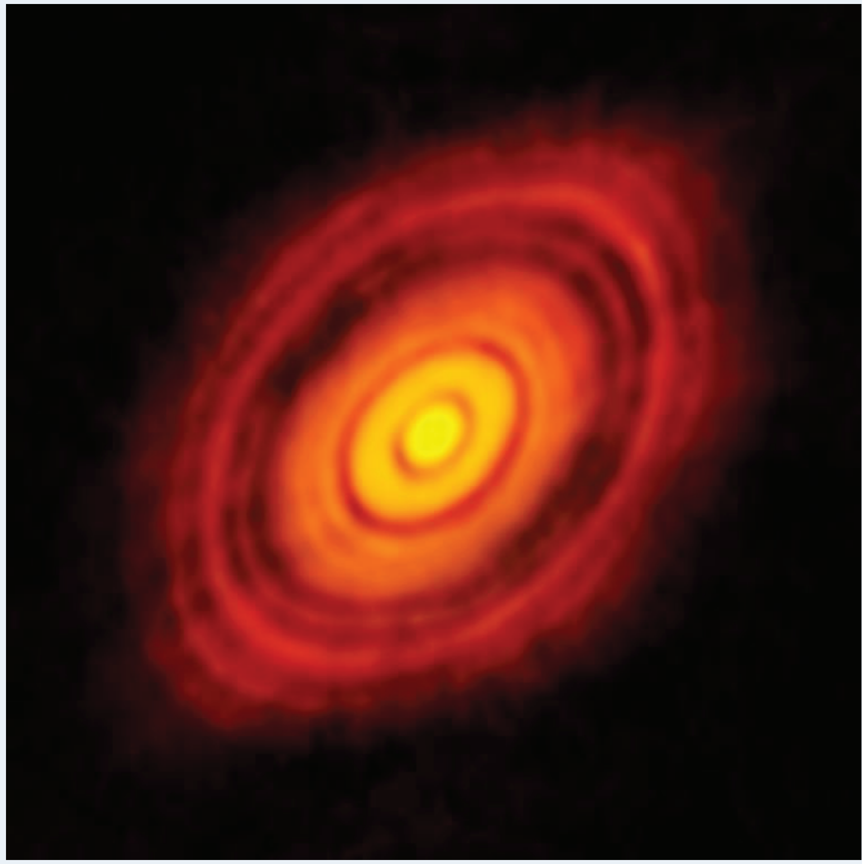


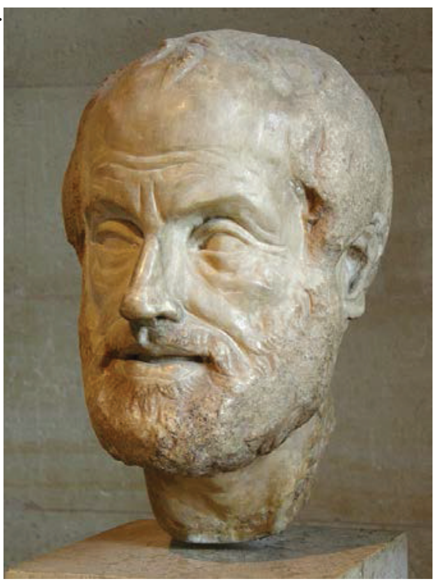
Figure 1.5: *ALMA image of protoplanetary disk of HL Tau, with gaps showing possible locations of planet-like bodies.*

Recent telescope observations offer intriguing insights into the nature of protoplanetary disks, and exciting possibilities for the future of the nebular hypothesis. A recent image (shown in **Figure 1.5**) taken by the Atacama Large Millimeter/submillimeter Array (ALMA) shows the protoplanetary disk around HL Tau, a 100-million-year-old Sun-like star (ALMA, 2014). The protoplanetary disk has annular gaps in it, which lack gas and dust. These gaps are likely results of planet-like objects in those orbits, which are accumulating material into dense chunks (i.e. planetesimals, protoplanets) which are too small to be seen (ALMA, 2014). As clearer and higher-resolution images of protoplanetary disks become available, it will hopefully be possible to directly observe the formation of planets, and conclusively verify one of the hypotheses of Solar system formation.

The Development of Solar System Models

The night sky has long been a subject of fascination for the human race. To many, it was a thing of beauty. To a few, it was a problem to be solved. Curious individuals looked to the skies for answers about the nature of the universe. The answers were there, but decoding them would take thousands of years.

Figure 1.5: The Greek philosopher Aristotle believed the motions of the heavens were constrained to uniform circles. This opinion was widely held for centuries.



From Plato to Hipparchus

Much of documented ancient astronomy came from the ancient Greeks, who studied the stars with a combination of mathematical and philosophical approaches (Leverington, 2013). Pythagoras (580-500 BCE) may have been the first of the Greeks to propose that the Earth was round and that planets moved in separate orbits around the Earth. He also noted that the morning star and evening star were in fact the same object, Venus, traveling across the sky. Following this vein, Plato (427-347 BCE) proposed that all heavenly bodies must be spherical and travel in circular orbits around a stationary Earth, as that was the perfect shape of the universe (Doig, 1950). Aristotle (**Figure 1.5**; 384-322 BCE) expanded upon Plato's idea, devising a model in which each planet, the Sun, the Moon, and the stars all inhabited their own spheres that revolved around a stationary Earth, the then-proclaimed centre of the universe (Heath, 1932).

As the subsequent sections will show, the ideas put forth by Plato and Aristotle would shape astronomy for over a thousand years. The concept of perfect, uniform circles in the heavens proved to be particularly long-lasting, and later astronomers would go to great lengths to accommodate it in their theories (Heath, 1932).

Nevertheless, it should be noted that not all models from this period were geocentric. Aristarchus of Samos (310-230 BCE) was a follower of Pythagoras who proposed that the planets orbit the Sun, and even placed them in the correct order. However, the idea was rejected at the time, and would not be revived for some 2000 years (Leverington, 2013).

In Greece, the concept of uniform circular motion persisted for some centuries. However, observations of the Earth, Moon, and planets did not support this principle (Hoskin 1997). Consequently, astronomers had to invent devices that allowed for variations in the speed and apparent size of celestial objects as seen from Earth. Two such devices, the epicycle and the eccentric orbit, were discussed by Apollonius of Perga (c. 265-190 BCE). The epicycle requires a planet to move in a small circle, the centre of which itself travels in a larger circle around the earth (Heath, 1932). In contrast, the eccentric model consists of motion in a single circle centred around a point some distance away from the Earth. Very little of Apollonius' mathematical work has survived the centuries, and his accomplishments have largely been determined through analysis of the works of Ptolemy of Alexandria (90-168 CE). Ptolemy asserts that Apollonius determined a method for converting eccentric and epicyclic models into one another, and was able to demonstrate their geometric equivalence (Ptolemy and Toomer, 1984). Apollonius' exploration of eccentres is particularly significant, as it represents a shift in astronomical thought away from Earth-centred revolutions (Neugebauer, 1975).

The writings of Hipparchus of Nicaea (c. 190-130 BCE) have also largely been lost to time. To determine the extent of his contributions to mathematical astronomy, historians look to his last surviving work, *Tōn Aratou kai Eudoxou Phainomenōn exēgēseōs biblia tria (Commentary on the Phaenomena of Eudoxus and Aratus*), and to the works of his successors. In *Commentary*, Hipparchus describes the rising and setting of the constellations, making reference to observations from his earlier works which have since been lost (Grasshoff, 1990).

Ptolemy also acknowledges Hipparchus in his *Almagest*, crediting the Nicaean for many of the observations upon which Ptolemy's own theories are based. After studying *Commentary* and *Almagest*, historians estimate that Hipparchus was the first person to systematically apply trigonometry to astronomical theory (Heath, 1965). Older sources also credit Hipparchus with combining epicycles and eccentricity in geocentric solar and lunar models (Heath, 1932), but some more recent historians dispute this claim (Neugebauer, 1983). Ptolemy, for his part, indicates that Hipparchus was unable to devise a complete working model of the motions of the planets (Pannekoek, 1947; Heath, 1965).

Ptolemy's Writings

Ptolemy's astronomical works contain excellent descriptions of ancient theories on the subject (Bernard, 2010). Written in the third century, his *Mathēmatikē Syntaxis* (known commonly by its Arabic name, *Almagest*) and *Planetary Hypotheses* were referenced by countless astronomers for well over a millennium (Hoskin, 1997).

Almagest is concerned mainly with mathematical descriptions of celestial motion. Ptolemy praises Hipparchus' accomplishments in the opening pages, but is quick to point out that even Hipparchus was unable to devise a planetary model like his own (Ptolemy and Toomer, 1984). The text is divided into 13 books, the first of which describes Ptolemy's theories regarding the sphericity of heavenly motions, his conclusion that the Earth itself is spherical, and his conclusion that the Earth must be at the centre of the universe. From his own observations, Ptolemy was aware that the motions of the planets did not follow the circles of uniform velocity that Aristotelian physics required. To correct this, he presents a geometric invention called the equant (Ptolemy and Toomer, 1984). Simply put, the equant model requires the main orbit of a planet to have its centre at a point equidistant from the Earth and a second point known as the equant.

When this eccentricity is combined with a planet's epicycle, the motion of the planet is circular around the centre point, and but has constant velocity when viewed from the equant. From Earth, however, it would appear to exhibit neither property (Evans 1983). In this way, Ptolemy attempts to avoid deviating from Aristotelian principles (**Figure 1.6**).

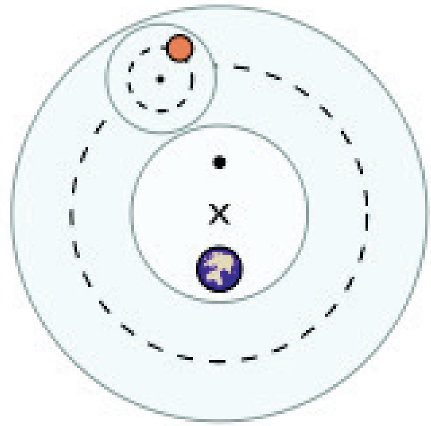


Figure 1.6: *Ptolemy's equant was a point opposite the Earth from which the velocity of a planet would appear constant. The device was despised by later astronomers.*

In *Planetary Hypotheses*, Ptolemy extends his geometric model into the physical world. He proposes a series of nested spheres that fill the universe, the first sphere being the orbit of the Moon and the last containing the stars. Between these boundaries he places the spheres of the planets, believing Mercury and Venus to lie before the Sun while Mars, Jupiter and Saturn lie beyond it (Goldstein, 1967).

Although Ptolemy's models are not entirely accurate, his work made important contributions to the development of mathematical astronomy and the field of spherical geometry. The historical significance of his writings is undeniable, and his theories were frequently referenced by astronomers for the next millennium (Hoskin 1997).

Islamic Astronomy: Improving on Ptolemy

The death of the prophet Mohammed in 632 CE was followed by the rapid spread of Islam across the Middle East and North Africa. This swift expansion brought Muslim scholars into contact with their Christian counterparts in the Byzantine Empire, from whom they began to purchase Greek manuscripts. The Muslim appetite for such texts proved voracious; by the early 800s CE the Caliph al-Ma'mun (786-833 CE) had established a "House of Wisdom," where scholars translated Greek works into Arabic and Syriac (Lyons, 2009).

There followed several centuries of criticism and improvement of Ptolemy's models by Muslim astronomers (Hoskin, 1997). Many of the issues with the Ptolemaic planetary theory were presented by Ibn al-Haytham (965- c.1040 CE) in *Shukuk ala Batlamyus* (*Doubts about Ptolemy*). Al-Haytham disapproved of the equant and Ptolemy's assumption that his geometrically sound model applied to the physical world (Hogendijk and Sabra, 2003). Later, Nasir al-Din al-Tusi (1201-1274 CE) summarized several hundred years of objections to Ptolemy's work in *al-Tadhkira fi cilm al-hay'a* (*Memoir on Astronomy*), a fairly comprehensive text on Islamic astronomy of the time. These objections were generally focused on two topics: the necessity of non-uniform motion, and the necessity of incomplete rotations to reconcile Ptolemy's model with observational data (Tusi and Ragep, 1993).

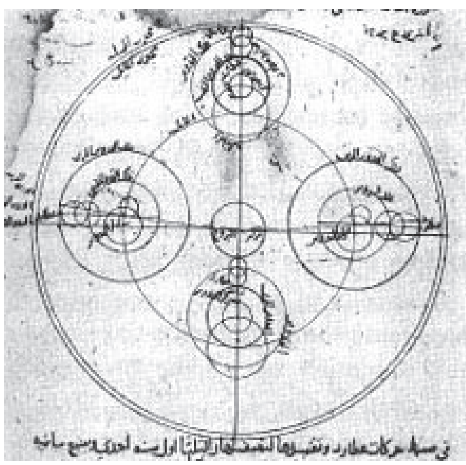


Figure 1.7: *Ibn al-Shatir's model of the motion of Mercury. The planet's movements are complicated and required many epicycles to describe.*

Dissatisfaction with the Ptolemaic model led al-Tusi to formulate a new device to explain orbit eccentricity entirely through uniform circular motion. This construction, sometimes referred to as a "Tusi couple" places a planet on the edge of a circle that rolls along the inside of a larger circle, which itself travels in a circular orbit around the Earth (Kennedy, 1966). The couple permits an object to oscillate laterally as it orbits, allowing al-Tusi to explain observed orbital eccentricities with purely circular motions (Kennedy, 1966).

Further modifications to Ptolemaic astronomy were made by Ibn al-Shatir (1307-1375 CE). While many of his contemporaries objected to Ptolemy on purely philosophical grounds, al-Shatir declares at least one of his misgivings to be based on observational inconsistency.

In his *Nihāyat al-suʾl fī taṣḥīḥ al-uṣūl* (*The final quest concerning the rectification of principles*), al-Shatir observes that the Ptolemaic lunar model would require the Moon to periodically double its apparent diameter (Saliba, 1987). To eliminate the problem, al-Shatir placed the Moon in an orbit with two epicycles. Secondary epicycles were a favourite tool of this astronomer, and also appeared in his geocentric models of planetary motion (**Figure 1.7**; Kennedy and Roberts, 1959).

Some historians have noted that the lunar model proposed by al-Shatir is nearly identical to that put forward by Nicolaus Copernicus (1473-1543) over a century later (Roberts, 1957). Furthermore, it has been suggested that Copernicus' model of the Solar system is merely a heliocentric version of either al-Shatir's models or a system put forward by al- Tusi's observatory (Kennedy and Roberts, 1959; Hoskin, 1997). The first theory is difficult to support, as al-Shatir's work is not known to have been translated into Western languages until fairly recently (Roberts, 1957). However, a Greek translation of some of al-Tusi's work travelled to Italy after the fall of Constantinople. It is possible that Copernicus came into contact with it while studying there (Hoskin, 1997).

Copernicus' Heliocentric Model

Many ancient Greek astronomical texts were lost during the decline of the Roman Empire, and only began to circulate in Europe again in the 11th or 12th century. Early Christians reverted to the Bible as a source of knowledge, using only biblical texts to deduce the structure of the universe (Leverington, 2013). However, during the Renaissance period of the 16th century ancient Greek texts were rediscovered, and Ptolemy's theories were once again widely studied in universities (Hoskin, 1997). Nonetheless, conflicts in the Ptolemaic models quickly became apparent. Like the Arab scholars before them, Renaissance astronomers found that for the moon to orbit in the proclaimed motion, its size would have to vary greatly, a requirement that was easily disproved through observation (Hoskin, 1997).

Nicolaus Copernicus, a Polish-born physician, economist, and painter, was one such critic of Ptolemy. In a manuscript entitled *Commentariolus* (*Little Commentary*), he expressed his disapproval of the existing order (Hoskin, 1997). He then set out to develop the first outline for his heliocentric theory, in which the stationary Earth was no longer the centre of the universe, but rather orbited the Sun in a plane along with the other planets. Copernicus' complete theory was first published in his book *De Revolutionibus Orbium Caelestium* (*On the Revolutions of the Heavenly Spheres*), in which he also developed a sequence for the planets based on their increasing periods (**Figure 1.8**; Hoskin, 1997).

Despite his earlier criticism of the old Greek models, many of the positions that Copernicus held did in fact align with Ptolemy. He noted that the universe was spherical, as this was the most spacious form, and in a later chapter showed that the motions of the planets must be either uniform, circular, or comprised of epicycles (Macpherson, 1933).

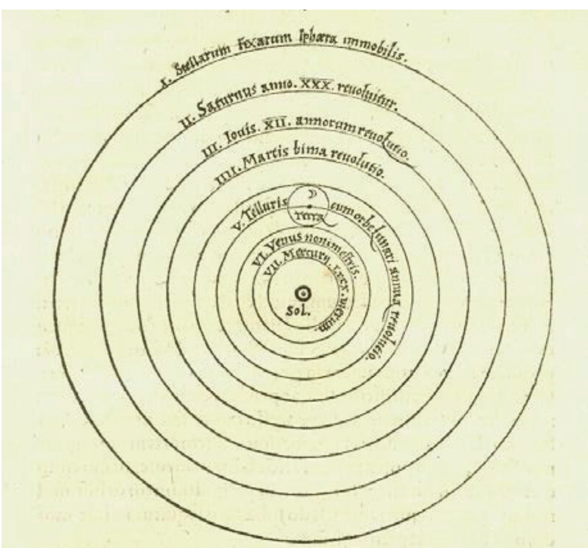


Figure 1.8: A simplified diagram of Copernicus' heliocentric system, showing the order of the planets as he determined them.

In *De Revolutionibus*, Copernicus acknowledges that his idea had been proposed before by Aristarchus (Dorschner and Loffler, 1975). Although Copernicus' model was not superior to Ptolemy's in terms of the evidence he provided, the publishing of *De Revolutionibus Orbium Caelestium* marked the start of a scientific revolution. It was an event that catalyzed the separation of astronomy from theology in an era that was eager for new ideas (Mizwa, 1943).

Tycho Brahe's Hybrid System

Another influential academic leader of the Renaissance was the eccentric astronomer Tycho Brahe (1546-1601 CE). Brahe was foremost a practical astronomer, believing that an understanding of the position and motion of planets could only be achieved through precise, systematic observations (Macpherson, 1933). Like many before him, Brahe rejected the Ptolemaic theory, but he did not wholly accept the heliocentric model proposed by Copernicus (Macpherson, 1933). Instead, he created his own hybrid model, stating that the Moon and Sun moved in circular orbits around the Earth, but all other planets orbited the Sun. In this way he avoided certain religious difficulties which arose from having a moving Earth in the heliocentric model. Brahe's hybrid system was ultimately rejected by his contemporaries due to overwhelming evidence supporting the heliocentric model, but his observational skills and attention to detail are still admired today (Leverington, 2013).

Galileo's Observations

Throughout the Renaissance, scientific thought and progress underwent rapid development due to new economic booms of trade and commerce. Galileo Galilei (1564-1642) was a brilliant experimental scientist of the time who attracted the minds of many during his tenure at the University of Padua (Macpherson, 1933). It was during this time that he began to specialize in astronomy, becoming a follower of the Copernican system but looking at it through the lens of velocity and acceleration of the planets (Drake, 2011). Galileo believed the Tychonic system to be dynamically incorrect, as a Sun that had enough force to move all the other planets would undoubtedly have an effect on Earth (Drake, 2011).

The invention of the telescope around this time provided scientists with new methods of examining the universe. Galileo heard about the invention while on a trip in Venice, and by 1609 had made an instrument that could magnify objects three times compared to a naked-eye observer. Telescopes of eight and thirty times magnification rapidly followed, allowing for greater accuracy compared to traditional sighting methods. Using the telescope, Galileo discovered mountains and craters on the Moon, which contradicted the idea of perfect sphericity in the heavens (Drake, 2011). These discoveries were published in his book *Sidereus Nuncius (The Starry Messenger)*, but were rejected by natural philosophers who argued that the telescope was fraudulent and could not be trusted (Machamer, 1998). Later, Galileo used his telescope to observe the moons of Jupiter and the phases of Venus. He thus disproved the Ptolemaic idea that everything in the universe revolved around the Earth, and provided more support for the Copernican model (Drake, 2011).

Kepler's Laws of Planetary Motion

Johannes Kepler (1571-1630) was born in Wurtemburg and attended the University of Tubingen, eventually becoming a lecturer on mathematics and astronomy at the school of Graz. At this time he also published his first book, *Mysterium Cosmographicum*, which solidified his reputation as an important figure in astronomy at the time (Doig, 1950). As described in a letter he wrote to a patron, Kepler saw the heavenly bodies as akin to clockwork, describing planetary motion like the gears and levers of a clock (Boner, 2013). Soon after his publication, Kepler gave up his teaching position and travelled to Prague to work with Brahe.

In his Astronomia Nova (New Astronomy), Kepler expanded the natural philosophy of Copernicus with mathematical reasoning and realistic orbits, thus making the Copernican system mor plausible (Field, 1988). The book also contains Kepler's first law, which dealt away with the previously undisputed idea that all orbits were circular by presenting bifocal elliptical orbits, with the Sun at one of the foci (Field, 1988). He also posited his second law in this book concerning the speed of planets orbiting the sun. Kepler stated that planetary bodies travel in a way that a line joining the planet to the Sun will sweep out equal areas in equal intervals of time (Field, 1988). In this way, Kepler established that a planet will move fastest when it is closest to the Sun, and will move slowest when it is at its furthest distance from the Sun (F**igure 1.9**; Doig, 1950). Kepler's wrote his third law almost a decade later. He found that the cube of the distances of the planets from the Sun are proportional to the squares of their periods of revolution, usually measured in years. This discovery allowed for accurate calculations of the distances between planets in the Solar system. Driven by minds such as Kepler, the Renaissance saw a monumental shift in the study of astronomy, away from theology and philosopy and into the realm of true science.

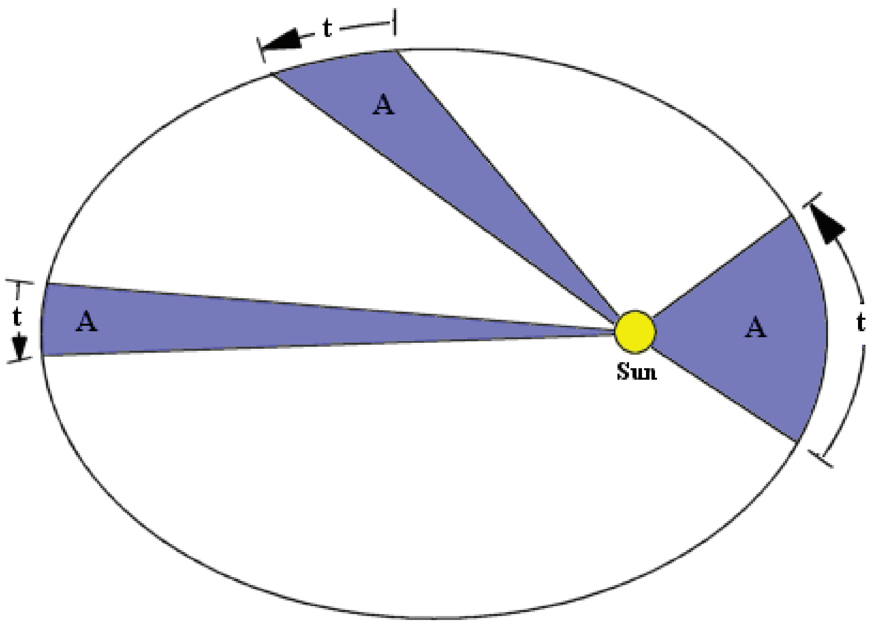


Figure 1.9: *Kepler's second law states that a planet's speed is greatest when it is closest to the sun. In this figure, the length of time "t" stays constant even though the planet travels over longer sections of the orbit's circumference.*

The *Voyager* Space Missions

By the late 1970s, human understanding of the motions of the Solar system had advanced to the point where precise predictions of planetary positions were possible. This allowed astronomers to take advantage of a temporary alignment of the outer planets and maximize the efficiency of the *Voyager* probe missions. Both *Voyager 1* and *Voyager 2* used the gravitational pull of Jupiter to slingshot themselves toward Saturn, and upon reaching Saturn *Voyager 2* used the same method to propel itself toward Uranus (Kohlhase and Penzo, 1977). Since their launch in 1977, the two spacecraft have been providing valuable information about the outer regions of the Solar system.

Getting a Boost from Jupiter

A satellite's flyby is determined by three parameters: the periapsis distance of the close encounter, the excess velocity of the satellite's approach hyperbola, and the approach angle. Altering these parameters allows astrophysicists to determine the best possible scenarios for a gravity assisted gravity assisted slingshot before a craft is launched (Brouke, 1988). The passing satellite gains a tiny fraction of the planet's kinetic energy. This exchange produces a negligible change in the momentum of the planet, but translates to a significant boost for a small spacecraft. In general, for a satellite to have greater momentum after the exchange, its approach angle must be smaller than its exit angle (Dykla, Cacioppo and Gangopadhyaya, 2004).

Craft Design

Each *Voyager* craft is equipped with a wide array of sensors, including high definition cameras, radio receivers, spectrometers, and photometric instruments (**Figure 1.10**). These have been used to conduct visual surveys, temperature probing, and surveys of atmospheres and ionospheres, among other things (Kohlhase and Penzo, 1977. The power supplies of the *Voyager* were uniquely suited to their long-range mission. Each probe is fuelled by decaying radioactive fuel sources, as solar panels are not viable in the outer reaches of the solar system (Kohlhase and Penzo, 1977).

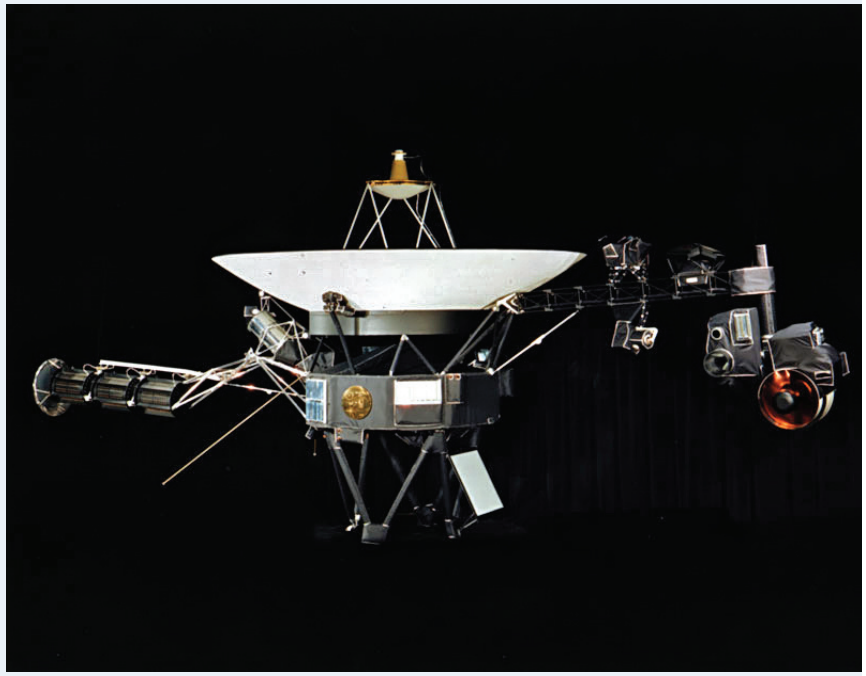


Figure 1.10: *The Voyager 1 probe weighs almost 900 kg and contains an impressive array of equipment.*

Both *Voyager* craft send information home over the Deep Wave Network. This network utilizes an array of enormous parabolic antennae, the largest of which has a 70m diameter. The considerable area of these giant receivers allows them detect extremely weak radio signals, even from the depths of interstellar space (Imbriale, 2003).

Achievements and Future Goals

The achievements of the *Voyager* missions have been formidable. *Voyager 2* was the first human craft to have an encounter with Uranus in 1986, and it took the first colour pictures of Neptune in 1988 (NASA, 2015). In 2012, *Voyager 1* exited the Solar system; an exciting success that *Voyager 2* is soon expected to repeat. Both probes are still actively transmitting data, and over the next decade astronomers hope to receive information on interstellar matter in regions beyond the reach of the Sun's solar wind (NASA, 2015).

The *Voyager* Missions represent achievements beyond anything that early astronomers could have imagined. As the probes explore new regions of the universe, they carry the spirit of scientific curiosity with them.

Evolving Theories of the Shape of the Earth

The shape of the earth has been a popular debate throughout history. It was only in the last couple of centuries that the general shape of the Earth was decided upon. To reach this consensus many theories, journeys and debates were had. The three most famous theories are flat Earth, spherical Earth and ellipsoid Earth. General acceptance of the spherical Earth came about in the first century CE, even though the theory was postulated 600 years earlier by Greek civilizations (Garwood, 2007). The flat Earth theory resurfaced now and again in the Middle Ages, most commonly on religious grounds. Since the 17th century, it is safe to say that the Earth is not flat or spherical, but an oblate spheroid. Hence, the figure of the Earth is a sophisticated concept with a long history of evolution.

Figure 1.12: *The Flammarion engraving is a wood engraving that first appeared in Camille Flammarion's L'Atmosphere: Météroroloqie Popularie in 1888. This image portrays a man crawling through the firmament at the edge of the sky, where the heaven meets the Earth.*

Flat Earth Theory

The theory of Earth's shape can be traced back to some of the most ancient and prehistoric civilisations in world history. The earliest theory of flat Earth originates from the Sumerians and Babylonians (4500-500 BCE). These people inhabited Mesopotamia, the site of modern day Iraq and developed the model of a tripartite universe. A tripartite universe was composed of three distinct levels, specifically, a flat Earth sandwiched between the sky and the underworld (Chapman, 2002). The Babylonians believed the Earth to be a flat circular disc, with the Earth's interior being hollow, to provide space for the underworld. The landform was floating on an ocean and surrounded with a dome-like sky. The ancient Egyptians had a similar three-layered model, however they believed the Earth to be a flat square, with the sky resting on four pillars or four mountains escalating from the four corners of the Earth (Chapman, 2002). The ancient Israelites also had similar beliefs about the formation of the Earth. These three civilizations bordered each other, and so it follows their beliefs regarding cosmology and the form of the Earth resembled each other. In fact, the Old Testament receives most of its stories about cosmology and creation from Mesopotamian mythology and as a result the Bible is often accused of supporting a flat Earth. The Bible portrays the Earth as a similar three-tiered system containing the firmament, a flat disc-like Earth and the underworld. Moreover, the firmament is a biblical term referring to the vault of heaven and the sky as a solid substance, which overlies the flat Earth below resting on pillars which were most likely mountain ranges (**Figure 1.12**). The underworld lies beneath the Earth and is called Sheol, the place of the dead (Jacobs, 1975).

Comparably, other ancient civilizations held different views relating to the shape of the Earth. The ancient Chinese thought the Earth was a seamless square surrounded by a round sky and an ocean (Needham, 1959). On the contrary, ancient India believed the Earth to be a flat circular disk with one great mountain steaming from the centre of the world; the ocean then encircled this landform. They believed this since the sun would disappear at night beyond the mountain; therefore they thought the sun would travel around the mountain once a day, traveling behind the mountain at night, and in front in the morning (Garwood, 2007). The ancient Norse people had a view analogous to that of ancient India, however they believed there was a world tree in the centre of the Earth instead of a great mountain. This world tree was named Yggdrasil and was believed to connect the centre of the Earth to heaven above (Philpot, 2004). The theory of flat

Earth was also supported in Ancient Greece. Homer (c. 760-710 BCE) one of the earliest Greek poets believed the Earth to be a flat disc-like plane which was then surrounded by an ocean called Oceanus (Homer, 1990).

The theory of flat earth was also common with pre-Socratic Greek philosophers. In the early 6th century BCE, Thales of Miletus (625-547 BCE) the earliest Greek philosopher, founded the Milesian school of thought where he along with two other philosophers from Miletus, Anaximander (611-545 BCE) and Anaximenes (585-525 BCE), worked to introduce new ideas on how the world is organized. The three philosophers were material monists due to the fact they believed that the world's objects were composed of the same material. Thales argued that the Earth was a circular disk floating on the ocean, similar to that of a piece of driftwood. Thales' student Anaximander debated that the Earth was a cylindrical column floating in the centre of the universe, with a height one third of its diameter. He claimed that the uppermost layer of this cylinder was the inhabited world, which was then surrounded by a circular ocean (Garwood, 2007). This theory came to fruition by talking to travelers; one who traveled north would see several stars disappear beyond the southern horizons and new stars appear from behind their bath in the northern horizon. Anaximander assumed to experience this phenomenon the Earth must be curved in a north-south direction (Asimov, 1980). Anaximander was the first person to suggest any shape for the Earth's surface other than flat. On the other hand, Anaximenes, a student of Anaximander, thought the Earth to be a flat disc, surrounded by air instead of water. He maintained that air covered the universe and the Earth was formed through the compression of air (Garwood, 2007).

Spherical Earth Theory

In the late 6th century BCE, the flat Earth philosophy that had once dominated the world was coming to an end, since a majority of societies considered the theories of the past to be insufficient. One reason was that ships that were heading out to sea did not grow smaller and smaller until they disappeared into a very small point, which would be expected if the Earth's surface was flat. Instead, ships heading out to sea disappeared rather quickly when they were still at a reasonably large size with the hull of the ship disappearing first, which would be expected if the Earth's surface was round. No matter which direction ships headed the ships disappeared in the same way, meaning that the Earth not only was curved in a north-south direction, like Anaximander previously stated, but in all directions equally. Therefore the Earth must be a sphere because it is the only surface that curves equally in all directions (Asimov, 1980). The history of scientific geodesy begins with the idea of a spherical Earth (**Figure 1.13**). The Mesopotamians, Egyptians, and the earliest Greeks saw the Earth as being flat. Throughout history, the topic of a spherical earth was brought up several times. The Greeks were the first to change the way the Earth was perceived by commenting that the Earth's figure was actually round.

Figure 1.13: *A medieval representation of the spherical world with compartments representing the Earth, air, and water.*

The earliest of Greek philosophers had very little proof or explanation as to why they believed the planet was round. Some Historians have found it particularly difficult to determine the first Greek philosopher to identify the Earth as a sphere, however they believe the concept should be attributed to Pythagoras (575-493 BCE) (Novotný, 1998). Pythagoras' idea of spherical Earth was founded on mystic reasons as opposed to scientific ones. The Pythagoreans were known for their mystical interest with a simple and harmonious world. For example, Pythagoras described the universe using the term cosmos, suggesting that the universe was an orderly system with simple relationships between integers. At the time, there were thought to be ten planetary bodies, and the number ten was assumed to be a perfect number (Novotný, 1998). Hence, the Pythagoreans supposed that, in order for the world to be constructed as perfectly as possible, the 10 planets must be of perfect form, a sphere.

The idea of a spherical Earth was revisited by Plato (427-347 BCE) and his best student, Aristotle (384 -322 BCE). Plato believed that the Earth was spherical, but he offered little mathematical evidence and proof. At the time, most people accepted that the Earth was spherical even though there was still no cogent proof. Aristotle sought to prove the spherical model and proposed several pieces of evidence explaining a spherical Earth by expanding on theories from Anaximander. In Aristotle's, *On the Heavens*, he explains that the Earth is round because as an individual travels from the north to the south the position of the stars and constellations differ (Hoare, 2005). For example, travellers noted that in Egypt and Cyprus there were stars and constellations seen in the sky at only those positions, and not in the northerly regions. These stars were not seen in the northerly regions of the Earth. In addition, Aristotle offered another explanation to a spherical Earth relating to the law of universal gravity. He stated that, all heavy bodies have an affinity to fall towards the center of the world, where the parts of the Earth compete for the lowest place, so that the parts are pressed together into a spherical ball (Novotný, 1998). Moreover, Aristotle pointed out that the Earth is spherical because the celestial horizon differs manifestly as one proceeds north or south. Also, the round shadow of the Earth on the moon during a lunar eclipse supports his theory (Fischer, 1975). In Aristotle's writings he explained that the shadow created is always curved, and since it is the interposition of the Earth that makes the eclipse, the curve must come from the Earth's surface, which is therefore spherical. If the Earth was not spherical then the shadow would look different from eclipse to eclipse. If the Earth was flat, then the shadow would have a flat side when the eclipse occurred at sunrise or sunset.

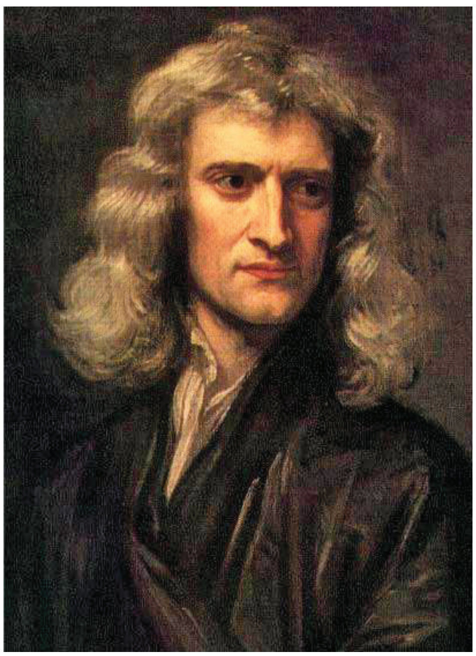


***Figure 1.14**: A portrait of Isaac Newton*

Eratosthenes (276-195 BCE), a Greek mathematician, astronomer, geographer, and poet, also believed that the Earth was a sphere. He used this theory and shadows to measure the size of the Earth, in the process he determined that the Earth had an arc distance from Alexandria to Syene of approximately 7.5 degrees (Fischer, 1975). The theory of the round Earth was spread as far east as India by Alexander the Great (356-323 BCE). In the 2nd century CE, Ptolemy (90-168 CE) created one of the most popular maps in the Middle Ages that portrayed the Earth as being round. By the 8th century CE, there were very few people who still believed that the Earth was flat. The last people who held on to the theory of a flat Earth were the Christian Syrians and most people in China (Hoare, 2005). However, in the 17th century, European Christian mercenaries brought the round Earth theory to China, the last place on Earth to believe the Earth was flat.

Contrary to common belief, Christopher Columbus (1451-1506) did not sail from Spain in 1492 and crossed the Atlantic Ocean to India in order to disprove the theory of a flat Earth. In truth, Columbus as well as other sailors already knew that the Earth was spherical (Fischer, 1975). It is important to note that there are still some societies and movements that continue to hold onto the theory of a flat Earth, due to mainly religious reasons. In the end, the ancient Greeks and the ingenuity of Renaissance Europe is responsible for the well-known spherical model of the Earth, which remained uncontested until the Enlightenment (Fischer, 1975).

Elliptical Earth Theory

As time passed, scientists and explorers began to realize that the Earth was not a perfect sphere. The considerations about harmony and simplicity, which played an important role in forming the ancient notions of the Earth's shape were no longer helpful in determining the Earth's shape in the 17th century. Jean Picard (1620-1682), a French astronomer, performed meridian arc measurements in 1669 and 1670. He measured the arc from a point near Paris to Amiens, and astronomically determined the latitude difference at the end points (Hoare, 2005). In 1683 and 1716, Jacques Cassini (1677-1756), a French astronomer, continued Picard's arc northward to Dunkerque, and southward to the Spanish border. When the measurements were completed, the arc was divided into two parts, one northward to Paris, and one southward to Spain. The calculations were sufficiently accurate and could be used to not only calculate the size of the Earth but also the shape of the meridian. When Cassini and his team calculated the length of a 1^{o} meridional arc independently from both chains, they found that the length in the northern part of the chain was shorter than the southern part (Hoare, 2005). This contradicted the conception of a spherical Earth and suggested that an ellipsoid would be the better and more accurate shape of the Earth. Additionally, Cassini found that the length of the arc at the 1^{o} latitude mark decreased northward. He calculated that the northern part of the chain was 111,017 meters, while the southern part was 111,284 meters (Fischer, 1975). An explanation for this asymmetry was explained by the polar flattening of the Earth. However, the real reason for the decrease in length northward was due to the fact that the radius of curvature northward is less than that southwards (Robinson, 2011). Therefore, the Earth ellipsoid is actually elongated in the polar regions, creating an egg-shaped figure.

The egg-shaped Earth, however, did not agree with the recent discoveries and theories in physics made by Isaac Newton (1643-1727) and Christiaan Huygens (1629-1695) (**Figure 1.14**). Newton's publication of Principia in 1687 theorized that the centrifugal and gravitational forces caused by the Earth's rotation would cause the Earth to be flatter in the polar regions near the equator, similar to the shape of a grapefruit (Novotný, 1998). Newton believed this because if the Earth rotated around its polar axis, then the equatorial axis would not only experience a gravitational force, but also a centrifugal force. In order to satisfy the universal inverse square law, the equatorial axis must be longer than the polar axis. Therefore, Newton's theory of gravitation predicted that the Earth was an oblate spheroid with a flattening of 1:230 (Novotný, 1998). This situation resulted in a large debate between the French and English scientists during the Enlightenment.

Newton's conclusions were mostly derived theoretically, however there were two observations that helped support his theory. First, Jean Richer (1630-1696) supported Newton's theory by proving that a pendulum had a shorter swing time by approximately 188 seconds per day in Cayenne compared to that in Paris (Fischer, 1975). This means that between the two latitudes the oscillation

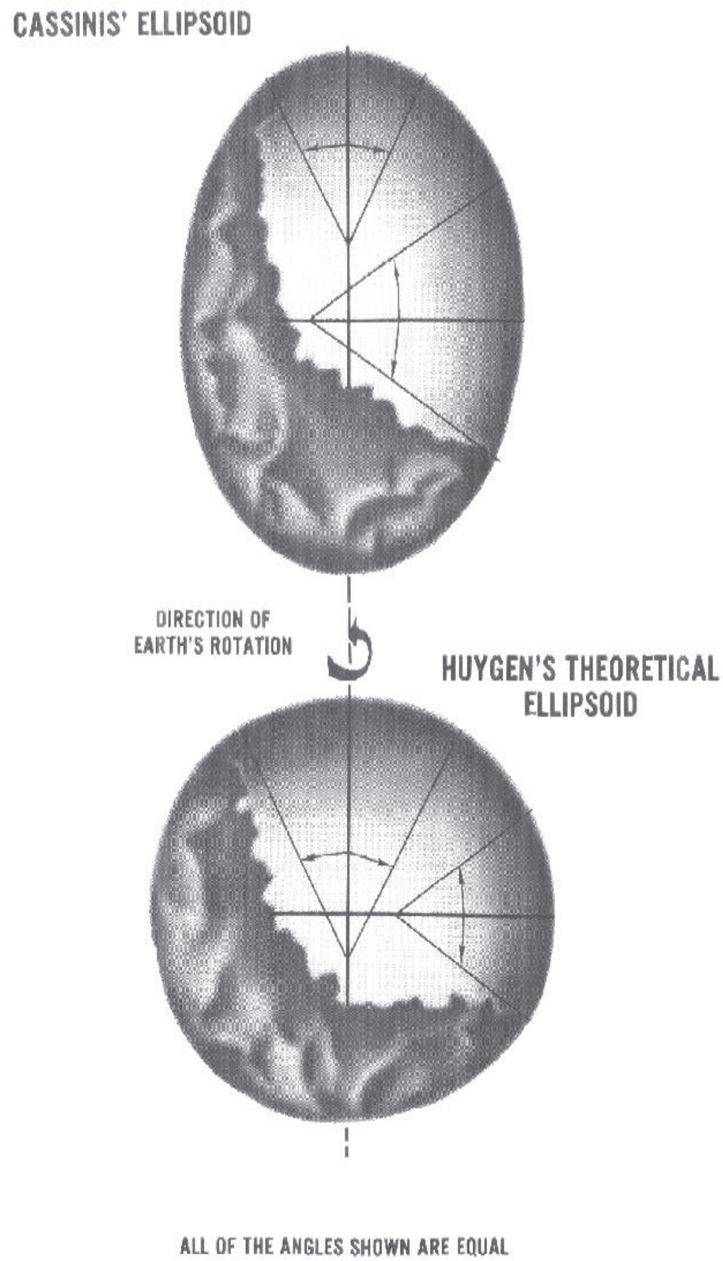


Figure 1.15: *This image shows the prolate (top) and oblate (bottom) ellipsoids. These shapes were debated between the French and British.*

period changed. Secondly, the rotation and flattening of Jupiter which was discovered by Giovanni Domenico Cassini (1625-1712), had a similar form and shape to the Earth (Fischer, 1975). The flattening of Jupiter was easily recognised through a telescope because of the large size of the planet.

The debate between the French and British on whether the earth was a prolate or oblate ellipsoid continued until Pierre Bouguer (1698-1758) and Charles Marie de la Condamine (1701-1774) set off to Peru and Lapland to measure the length of the meridional degree close to the equator (**Figure 1.15**). If the 1° meridional arc in Peru was longer than that in Lapland, then the French would be correct (Fischer, 1975). As it turns out, the measurements of these expeditions confirmed that the meridional degree in Peru was shorter than that in Lapland, proving that Newton was right (Novotný, 1998). Therefore, the Earth is an oblate spheroid, and this figure is still accepted today. This discovery was an important contribution in understanding the properties of the Earth. Furthermore, this discovery helped in expanding the field of geodesy and provided insight to many useful applications such as mapping and navigation.

Visualizing the Earth through Map Projections

Throughout time, visualizing the Earth has been a fundamental part of human history; to aid society in this endeavour the art and science of cartography was invented. Cartography is known as the study and practice of map making. A map is classified as a graphic representation of all or part of the Earth surface (Mailing, 1993). The oldest representation of a world map known to mankind is a Babylonian world map from 600 BCE (**Figure 1.16**). This map is an engraved clay tablet, small enough to fit into the palm of the hand and represents an interpretation of flat Earth theory (Garwood, 2007). In fact, maps have been used for centuries since they are essential tools to help societies outline and navigate the world. In the beginning, maps began as two-dimensional drawings, however they also came to adopt three-dimensional shapes such as globes. A particular critical challenge facing cartographers when the Earth's shape was decided upon was how to display a curved surface onto a flat sheet of paper and as a result map projections were invented (Campbell, 1984).

Figure 1.16: *This is the oldest known world map created by the Babylonians in the 6th century. This broken clay tablet shows the mythological and geographical world known to the ancient Babylonians.*

Map projections are a method of transferring features of the world particularly the graticule, the network of parallels and meridians of the globe grid, onto a flat surface. Map projections can be categorized by either the property they preserve or the surface they are projected upon (Mailing, 1993). When map projections are grouped by their preserved property they fall into one of the four following classes: conformal, equidistant, azimuthal, and equivalent (Snyder, 1987). A conformal projection preserves shapes and local angles, while an equidistant projection sustains scale along certain lines or from specific points. An azimuthal projection conserves direction, whereas an equivalent projection maintains an area's relative size. Azimuthal and equidistant characteristics are commonly referred to as local properties because they are only accurate to and from the centre of the map projection. However, conformal and equivalent properties can apply to the entire map projection and are therefore commonly referred to as global properties (Campbell, 1984). Map projections can also be classified by which developable surfaces onto which they are projected, the three main types include cylindrical, planar and conic. A developable surface is defined as a surface that can be unrolled into a plane without stretching or expanding the original figure (Mailing, 1993).

There are a variety of map projections that have been developed over the years. Three well-known world map projections include the Mercator, Robinson and Peters. Gerardus Mercator invented the Mercator projection in 1569 (**Figure 1.17**). It is a cylindrical projection where both lines of latitude and longitude appear as straight lines. This projection portrays the shape of the continents correctly but greatly distorts the area and distance of continents, specifically in regions of higher latitudes. It is also very useful in navigation due to the fact that it gives accurate compass bearings between two points. Due to this many early sailors used the Mercator projection and it remains the standard for many world nautical charts today (Campbell, 1984). The Robinson projection was developed in 1963 by Professor Arthur E. Robinson in an effort to create a visually appealing view of the entire world. Unlike other map projections Robinson decided that he would try to minimize all types of distortion throughout his projection, instead of trying to eliminate a single distortion type (Fowler, 1999). The Robinson projection is an oval in shape with curved lines of longitude that do not converge to a single point and lines of latitude that are straight and parallel. This results in the North and South poles appearing as lines instead of single points, therefore distortion close to the poles is severe, whereas near the equator it is not. This projection is still used today and was originally designed for the map and atlas production company of Rand McNally (Campbell, 1984). Dr. Arno Peters, a German journalist and historian created the Peters projection in 1973. He wanted to develop a map in which the sizes of the countries were accurately represented, however in doing this he highly distorted the shapes of the continents. When he first invented this projection it was used by the United Nation Development Programme as well as the National Council of Churches, but it is not used in modern cartography (Snyder, 1987).

It is important to remember that when trying to project a spherical object such as the Earth onto a flat surface there will be some type of distortion. No matter how one tries to flatten the Earth its will never be correctly displayed in terms of relative distances, shapes, areas and directions (Snyder, 1987). In general, a cartographer is responsible for choosing a map projection that can preserve the aspects of Earth relationships that are most important given the purpose of their map; while minimizing the distortions that are unavoidable. Most modern cartographers create map projections digitally through a variety of software, which make it easier to keep track of this distortion (Fowler, 1999).

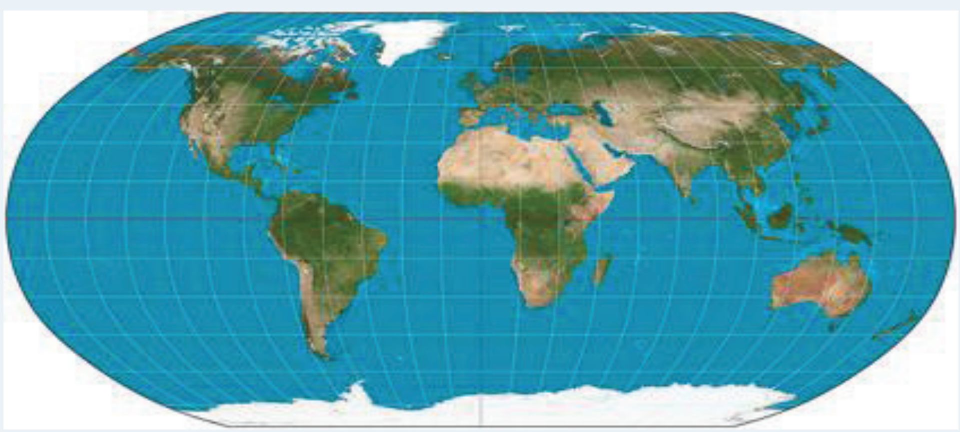


Figure 1.17: *This image depict the Robinson Map Projection, where the meridians gently curve therefore stretching the poles into long lines rather than points.*

Size of the Earth

Human curiosity has always led to questions about the planet we live on. While some people were most interested in the shape of Earth, others began to question how large it was. Experiments and ideas on the size of the Earth took place independently in regions across the globe. This section will present discoveries and techniques throughout time and across cultures. These concepts of size and relative positions of places were fundamental in creating the first representations of Earth in maps (**Figure 1.19)**. In turn, these maps had great impacts on explorers of the times and were adjusted and refined over the centuries to guide navigation and exploration of the world. While some of the calculations led to incorrect assumptions about our planet, they governed the future processes used in comprehending size and presenting such information.

Figure 1.18: *Early representation of the Earth by Macrobius Ambrosius Theodosius based on Pliny's description. The red strip is the Torrid Zone, the yellow regions represent ice, and the blue areas are the habitable temperate zones. There was no conceivable way to cross the yellow or red zones (Taylor, 1943).*

Ancient Greeks

In ancient Greece, scientists were well-rounded, studying the natural world, philosophy, and the heavens. Even thousands of years ago, humans had an appreciation for the grand scale of the Earth. They were aware that the mountains, which seemed so tall and unconquerable, were still merely rough patches on the globe and that Earth itself was a prick in the universe.

The observation of sphericity laid the essential groundwork for all future work in determining the size of the Earth. During this period of time, new theories of the world were being developed and combined with known geography; one important figure in this work was mathematician and geographer Eudoxus of Cnidus (408-355BCE). Based on Eudoxus' work, Aristotle (384-322BCE) estimated that the Earth was 400,000 stadia in circumference. (Diller, 1949). For his computation, Aristotle compared shadow lengths relative to the objects producing them at the same time of day at different latitudes (Taylor, 1943). Archimedes (287-212BCE) believed that the Earth had to be much larger than this, and estimated 3 million stadia instead (Diller, 1949; Dutka, 1933). One of the main obscuring factors in all of these calculations was a lack of fixed standard units of length. The Greek stadia was a highly variable measurement; across cities, several standards were in place simultaneously. The stadia was a unit based on the Roman mile. A Roman mile was a distance of 1,488 meters, and either 7.5, 8.5, or 9.0 stadia would fit inside it, making estimates in kilometers of these calculations highly variable (Diller, 1949).

Many ancient philosophers argued that the equator would be too hot and the poles too cold to cross, and regardless of the Earth's size, humans were confined to one island. Pliny the Elder (c.23-79CE) believed that Europe, Asia and the parts of Africa known at the time were well navigated and formed an island. Pliny's known world was in the Northern temperate zone with another smaller, unknown island also in this zone. Two additional smaller, unknown islands were in the southern temperate zone. He believed that it was too hot in the middle to communicate or pass between the two temperate zones (Taylor, 1943). The Torrid Zone (**Figure 1.18**) at the equator forbid crossing to the south and he wrote, "there are seas encircling the globe on every side and dividing it in two, so robbing us of half the world, since there is no region affording a passage from there to here." He believed people lived in the south but that every place on Earth was isolated (Goldie, 2010).

Eratosthenes: Astronomical Tools

In Egypt in the 3rd century BCE, humans continued the quest to determine the size of the Earth. The head of the library in Alexandria, Eratosthenes of Cyrênê (276-195BCE), was interested in a broad range of fields, including philosophy, poetry, grammar, musical theory, history, mathematics, astronomy, and geography. Despite such diverse interests, cartography was one of his greatest passions (Möller, 2003). He studied Pytheas' travels form the latter half of the 4th century BCE, which may have inspired him to construct a map of the habitable world (Dutka, 1993). To do this, however, he needed to find an accurate measurement of the size of the Earth. He was one of the first people to calculate a realistic circumference of Earth. To do this, he required the angular distance between two locations on the same longitude and their terrestrial distance apart (Calle, 2009).

For Eratosthenes' land measurement, rather than measure distance by travel time, he used surveys of the area completed by the Egyptian Government of the Ptolemies (Diller, 1949). He chose the distance from Syene (now Aswan) to Alexandria because it was so well surveyed, in addition to being very long, straight, and running almost meridionally (Fischer, 1975).

To obtain the most accurate angular measurement between the cities, Eratosthenes used the best astronomical equipment that he could (Fischer, 1975). A gnomon was the standard astronomical instrument; it consisted of a vertical rod or pole mounted onto a graduated plate for keeping track of the sun's shadow as a means for telling time. He decided to use an improved version of the gnomon for his measurements: the skaphe (Dutka, 1993). The skaphe's rod was mounted in a hemispherical bowl. This allowed the angular measurement of the shadow to be taken, rather than a length measurement that a conventional gnomon gave. In 230BCE, Eratosthenes completed his measurement of the circumference of the Earth, calculating that it was 250,000 stadia (Dutka, 1993).

Eratosthenes' number was accepted as the best possible measurement. Even Hipparchus, who had previously criticised Eratosthenes' geography work could not refute the measurement. Pliny considered it to be a bold measurement that must be accepted (Diller, 1949). Today, Eratosthenes' measurement is considered to be the most accurate of his time.

Ptolemy: A Guide to Cartography

Klaudios Ptolemaios (100-c.170CE), known as Ptolemy, was an Alexandrine geographer. Most world maps in antiquity were very schematic. Many were circular with a ring of ocean surrounding the *oikuménē* (the known world). Ptolemy was the first person to represent Earth with projections that showed curvature and kept relative distances and sizes realistic. He did not use schematic representations and turned instead to travel records and astronomy. His guide to geography, *Geographia,* dominated for 1,500 years and strongly influenced cartographers of the Middle Ages (Taylor, 1943).

Geographia described the topography of Europe, Africa, and Asia in far greater detail than any other work. Ptolemy identified and labeled thousands of towns, boundaries, and features. He described how astronomy and other forms of data-gathering were used for determining the geography he listed. A majority of *Geographia* was dedicated to explaining the process of creating maps. Ptolemy not only presented an understanding of the size and locations of places on the Earth, he also provided teaching resources to spread this knowledge and ability (Berggren & Jones, 2000).

Ptolemy began the concept of writing latitude and longitude on all features so that others could reproduce his works at different scales. His principal latitude parallels were defined by greatest length of daylight. They are unevenly spaced by half hours in some locations, and full hours in others. Ptolemy deduced that plants and animals' native ranges, as well as the appearance of humans, was correlated to climate and could be used for extrapolating the latitude based on similar conditions present equidistant from the equator. His meridians were also based on time, each one differing by one third of an equinoctial hour.

Figure 1.19: *Four prominent figures in the origins of mapmaking and perception of the size of the Earth. From left to right, Eratosthenes, Ptolemy, al-Bīrūnī, and Mercator.*

He divided the world by time, but he still used degrees for measuring arcs. This unit first came from the Babylonians who divided the day and the zodiac into 360 sections. While degrees were used for circles already, Ptolemy was the first to use degrees for specifying positions on the Earth. He used 500 stadia to equal one degree at the equator (Berggren & Jones, 2000).

Figure 1.20: *A 15th century recreation of Ptolemy's map of the world. The faces blowing along the edge represent the 12 winds. Latitude and longitude lines are shown, and the Indian Ocean is land-enclosed by a peninsula connecting Asia and Africa (Berggren & Jones, 2000).*

Ptolemy had two main directional systems. The first was based on where the sun sets and rises, using a due east rise and a due west set on autumnal equinox. The other was a system of twelve winds given by the conventional names for winds from these directions (Berggren & Jones, 2000).

Marinus of Tyre's (c.70-c.130CE) map and writings formed the base from which Ptolemy began. It is only from this work by Ptolemy that historians have even heard of Marinus. Other than this connection, the prehistory of his work and maps is complex to trace. When he made improvements on previous men's work he wrote about why he made such alterations, but when anything followed from predecessors, he rarely mentioned the source. Ptolemy's maps also contain names of places that have since been lost and are unknown in present times. It is hard to know what he originally wrote because as it was copied over years, people in different places made their own small adjustments (Berggren & Jones, 2000). *Geographia* was not translated from Greek to Latin until 1407. All the coordinates Ptolemy wrote about were lost to the Western world before this time. Medieval mapmaking was thrown on its head – they had been creating maps where countries' sizes were based on their importance not mathematical calculations. Even though Ptolemy's size estimate was off, his methods changed the nature of mapmaking across Europe (British Library Board, 2015).

In fact, his estimate was 18% too small. The maps covered as far south as Sri Lanka, which itself was misrepresented as a gigantic island. Europe, a place with the most research and available data, is quite recognizable on this map, with a distorted Atlantic coast (**Figure 1.20**). Perhaps most interestingly, the Indian Ocean is a land-enclosed sea because Ptolemy's Asian and African continents combine around it to the South (Berggren & Jones, 2000).

Al-Bīrūnī: Locating Mecca

Abū al-Rayhān Muhammad ibn Ahmad al-Bīrūnī (973-c.1048CE) was a self-made man from modest means living in central Asia, part of the eastern Islamic world. He excelled in school from a young age and believed that science revealed God's relationship to mankind. He also said, "many people attribute to God's wisdom all they do not know of physical sciences." Looking into al-Bīrūnī's works provides perspective on developments in science in parts of the world that are often overlooked (Scheppler, 2006).

During his life there were more than six princes in power and thus much of his work took place under political turmoil and violence. Maḥmūd took control in 998CE and al-Bīrūnī became a companion, likely living in fear, to this warrior. Al-Bīrūnī wrote down an index of all his written works, yet of the 146 titles he penned, only 10 have been published (Saliba, 2015).

He spent a great deal of time defending his mathematical and scientific progress from the confrontations of religious scholars. One of the best examples is how he presented his estimates for the size of the Earth. By learning the radius of the Earth he could determine the curvature of the sphere, and with such knowledge he would be able to point in the direction of Mecca from new locations. Finding Mecca is not a trivial problem. The direction between two places on a flat map is not necessarily the shortest distance on the globe when one takes into account the curvature (Al-Khalili, 2015). This calculation involved complicated spherical trigonometry.

He managed to tie his own scientific objectivity into the daily lives and religion of those around him (Saliba, 2015).

Al-Bīrūnī was responsible for very early use and development of the trigonometry used in modern times. In 900CE many of the ancient Greek works, including mathematical volumes, were first translated into Arabic, opening doors for many Islamic scholars (Al-Khalili, 2015). In one book, *Chords,* al-Bīrūnī wrote trigonometric identities with up to twenty proofs for each one. All six modern trigonometric functions were used, but relative to gnomons. He used shadow functions for all of his trigonometry as this was of practical use. With these gnomonics, he was also able to determine the cardinal points when the North Star was not present (Brummelen, 2009).

Al-Bīrūnī's estimate for the size of the Earth was the most accurate of the Middle Ages at just 322 km off of the current measurment. His estimate that the radius was 6339.6 km was within one percent of the actual value. Al-Bīrūnī treated Earth as a perfect sphere, something that is not precisely true. If current figures used this assumption, the modern number would match his calculation (Scheppler, 2006).

He first used a technique inherited from the Greeks to measure the angle of inclination of the sun above two different places. While this produced results that were just four percent off of the real value, al-Bīrūnī was not satisfied as the distance between points was only determined through counting footsteps across the desert. He turned to his own new method. He used angles made between two points on land with the peak of a mountain to determine the height of the mountain with trigonometry. Then after climbing to the peak, he would measure the dip angle below the horizontal to a flat are on the horizon, typically the sea. Using an astrolabe, essentially a giant protractor, al-Bīrūnī only needed to measure three angles and one distance to calculate the size of the entire Earth (Al-Khalili, 2015).

Mercator: Navigating the Globe

The 16th century was a time of great exploration, trade, discovery, and expansion (Abbattista, 2011). Gerard Mercator (1512-1594) grew up in this bustling time. Mercator was initially interested in studying philosophy and the Bible. Financial pressures from Europe's crop failures and famine led him instead to turn to geography and cartography to make a living. He was introduced to the principles of geography by the monk Franciscus Monachus and inspired by many prominent figures in his field (Crane, 2002).

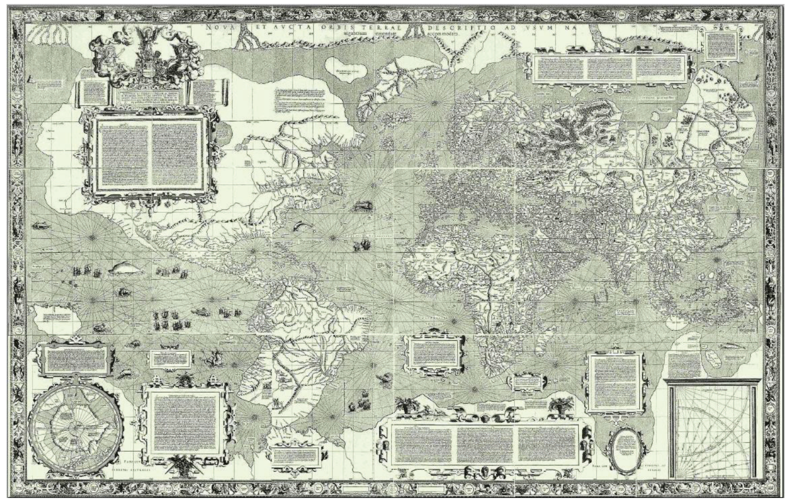


Figure 1.21: *Mercator's 1569 map of the world. The map utilized his new projection system, in which lines of constant bearing could be drawn from one location on Earth to another. Places that were not well-studied were concealed with strategically-placed boxes of text (Crane, 2002).*

Ptolemy's *Geographia* had arrived in Florence approximately 100 years before Mercator, and although it was 1,200 years old, it was still the gold standard template for modern mapmakers. Times were changing, however, and maps were no longer merely required for describing the appearance of the world; they were becoming more and more tied to trade, exploration, diplomacy, and the economy (Crane, 2002). Navigation was an especially big concern; sailors would often end up far away from where they wanted to be, costing time, money, and sometimes even lives (Monmonier, 2004).

In 1535, Mercator began working with Gemma Frisius and Gaspar Van Der Heyden to create an exquisite globe requested by Emperor Charles V. He was tasked to show newly discovered locations, refined coastlines, and hundreds of labelled features (Crane, 2002). Globes were very difficult and expensive to produce, as they had to be carefully engraved on metal balls or printed onto wood or paper. The globe for Charles V was to be printed onto gores, flat pieces of copper that would bend to fit together on a sphere. In the development of this globe, Mercator created and perfected a convention for calligraphic writing in order to accurately communicate the huge number of place names that must fit onto a single map or globe. He used capital letters for regions, roman for place names, and cursive for star names and geographical descriptions. He published this convention into a manual in order to aid future mapmakers (Crane, 2002).

Mercator was then commissioned to create a map of the world for Antoine Perronet, a statesman and politician. There were problems in the existing view of the world that he was determined to address. Ever since Ptolemy, Asia's southern coastline was severely distorted, containing a peninsula that connected to Africa. This feature had recently been moved westward to accommodate for the new discovery of Malacca. Mercator attempted to correct this coastline in addition to drawing on Marco Polo's travels, which added detail to Antarctica (Crane, 2002).

In 1541, Mercator was the first to add rhumb lines to a globe in order to aid navigators in their travels. Rhumb lines are lines of constant bearing that are used to guide sailors on their paths across oceans (Crane, 2002). Much later, he tackled the problem of putting these rhumb lines onto a flat map. In 1569, he created a new projection in which he straightened the longitude lines so that the network of latitude and longitude lines was a rectangular grid (**Figure 1.21**). This required spacing out the parallels, but resulted in a map that was easy to read and follow (Crane, 2002). The presence of rhumb lines are characteristic of this projection, and they helped countless navigators find their way at sea (Monmonier, 2004).

Throughout history, the workings of the natural world have perplexed and fascinated humans. We have always been curious about the world we inhabit and, as such, determining the size of the Earth has been a cornerstone in our understanding of the world. This measurement has been crucial to our development of maps, which have driven exploration and discovery. Mapmaking has become one of the most influential manifestations of this knowledge, as it is a way of communicating scientific information in a way that the general public can understand and use. Maps are a concise way to display our evolving views of the Earth.

Earth's Inner Core

While pondering about the size of our planet has been relevant to scientists as long as humans have been on Earth, it was much later that people turned to consider the sizes of features under the surface. This is mainly due to the technologies required for investigating the interior of the planet.

Studying the Core

Information on the Earth's core comes mainly from seismic data, meteorite analysis, lab experiments that use factors like temperature and pressure to model the conditions, and advanced computer simulations. Seismic waves are the shock waves caused by earthquakes. While they originate at the surface and not at great depths, their propagation velocity and frequency change as they go through the Earth and encounter different pressures, temperatures, and rock types (National Geographic, 2015).

Most waves do not penetrate the very center of the core, and thus it is challenging to obtain data about this region. Lab experiments have immense difficulty recreating the extreme conditions found in the core. In the lab, diamond anvil cells are the method used to model potential conditions. A diamond anvil cell involves a sample squeezed between diamonds to simulate the high pressure while intense x-rays simulate high temperature. This can be used to examine the solubility of materials in the core, as well as the stability of various structures believed to be present. One example of recent research in the lab produced conditions of 407 GPa and 5960 K to look into the phase relations of iron-silicon alloys in the core (Tateno, Kuwayama, Hirose and Ohishi, 2015).

It was only in 1936 that the inner core was first discovered through recognition of a boundary where compressional wave speed was discontinuous (Ishii & Dziewonski, 2002). Soon afterwards the theory of a solid inner core was established. Despite temperatures of 5,200°C, well above iron's melting point, the inner core is solid due to the extreme pressure exerted by the entire planet and its atmosphere. The matter is too dense for the atoms to move apart and flow in a liquid state. These unique properties led some geophysicists to call this region a plasma behaving like a solid (National Geographic, 2015).

Although the inner core makes up less than one percent of Earth's total volume, it has affected evolution of the planet and processes on the surface today. For example, the core is responsible for stabilizing the magnetic field (Ishii & Dziewonski, 2002). The inner core begins 5,100 km beneath the surface and has a radius of 1,200 km (National Geographic, 2015).

Like the ever-changing surface of the Earth, processes at these depths also alter the composition of the interior. While inner core solidification began one billion years ago, Earth is still cooling and this results in an extra 0.5 millimeters added to the inner core annually (Morelle, 2015). The edge of the inner core expands as the previously liquid outer core solidifies. The growth is happening in lumps, not equally across the edge. Growth is more common around subduction zones. While this action of surface plates slipping into the mantle takes place thousands of kilometers away from the inner core, the sinking plates are still capable of drawing heat from core and causing solidification. Growth is least common around superplumes. These form hot spot volcanoes on the surface above huge masses of superheated mantle. Beneath such plumes, the excess heat leads to more liquid conditions in the outer core. Despite this growth, the outer core will never fully solidify, as the Sun will burn out in 5 billion years and the solidification process would take a further 86 billion years (National Geographic, 2015).

Innermost Inner Core

One recent advance is the delineation of an innermost inner core (**Figure 1.22**). This delineation relies on the concept of anisotropy. If something is anisotropic there is directional dependence, or a difference in physical or mechanical properties along different axes. This applies to seismic waves as they travel at different speeds along different planes of the same material. This happens when features, whose size is on the order of magnitude of a seismic wavelength, are predominantly aligned in a given direction. These could be crystal structures, cracks, layers, or pores that repeat throughout the material (Margheriti et al., 1997). It was determined in 1986 that the inner core is anisotropic. Compressional waves travelling in an east-west direction are slower than waves travelling in a north-south direction. Propagation along the spin axis is faster than the equatorial plane (Harvard Seismology Group, 2015).

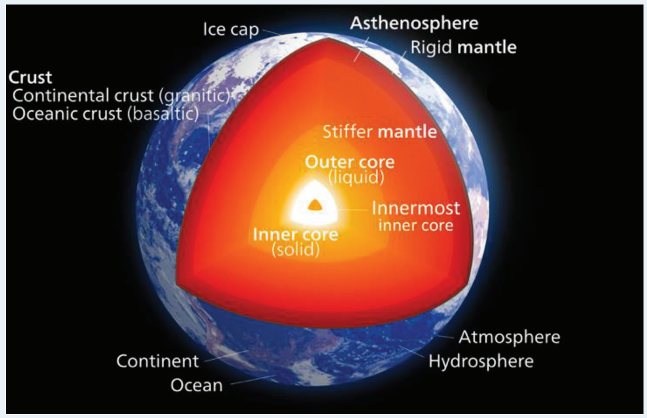
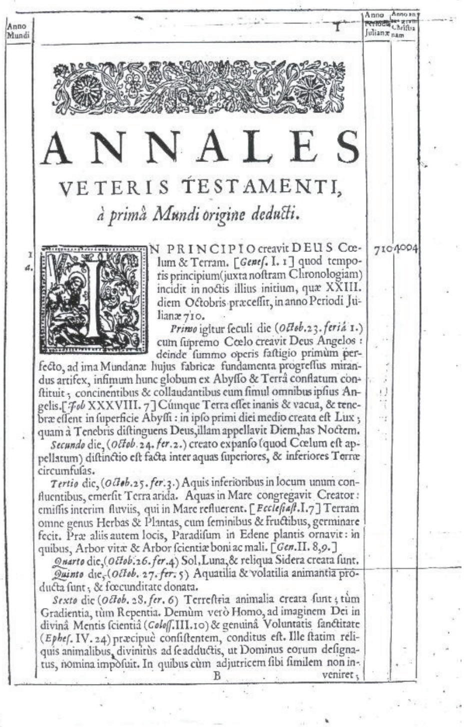


Figure 1.22: *Schematic representation of the interior of the Earth. The inner core begins 5,100 km beneath the surface of the Earth at a boundary between liquid and solid matter. The inner core has a radius of 1,200 km, 300 km of which is the innermost inner core, determined by unique anisotropy (Harvard Seismology Group, 2015).*

The innermost inner core has a radius of 300 km, and was first described in 2002. It was identified based on a unique transverse isotropy compared to the rest of the inner core. In this region, time travel anomalies showed that the waves propagate the fastest at 45 degrees from the rotation axis. This anisotropy is also stronger than elsewhere and could tell us many things about the early history of the core's formation (Harvard Seismology Group, 2015). More recent research suggests even more striking differences, with up to ten second delays in waves travelling the same distance through the core. These new models propose that the fast axis in the innermost inner core is near the equatorial plane, almost perpendicular to the alignment of the outer inner core (Wang, Song & Xia, 2015). It indicates distinct episodes of core development during two different environments. The innermost one may have formed as soon as the Earth differentiated. When the radius reached 300 km it may have substantially changed the convection flow patterns in the liquid outer core, thus altering subsequent inner core formation (Ishii & Dziewonski, 2002). Definitions of the sizes and boundaries within the Earth are not fixed and with new discoveries, regions are defined and refined continuously.

Age of the Earth

For thousands of years, mankind has been plagued with the desire to understand the nature of the Earth in order to answer a most challenging question: what is the age of the Earth? This is a question that has been attached to much controversy over mainly the last few centuries, but leading back even thousands of years. Early attempts to answer this question were done in the 17th with much speculation and theorizing, and little evidence. Coming into the 18th century, empirical methods became strongly valued and evidence was gathered to try and come up with an age that was not given purely by biblical literature. In the 19th century, Lord Kelvin (1824-1907) dominated the scene with his seemingly irrefutable calculations involving the thermodynamics of the Sun and the Earth, but his calculations left deep–age geologists and biologists unsatisfied. It was not until the 20th century and the discovery of radioactive elements that the Earth was determined to be billions of years old.


Anno Mundi | Anno Periodi Julianæ

ANNALES
VETERIS TESTAMENTI,
à primâ Mundi origine deducti.

1 | 4. IN PRINCIPIO creavit DEUS Cœlum & Terram. [*Geneſ.* I. 1] quod temporis principium (juxta noſtram Chronologiam) incidit in noctis illius initium, quæ XXIII. diem Octobris præceſſit, in anno Periodi Julianæ 710. | 710 4004

Primo igitur ſeculi die (*Octob.* 23. *feriâ* 1.) cum ſupremo Cœlo creavit Deus Angelos: deinde ſummo operis faſtigio primùm perfecto, ad ima Mundanæ hujus fabricæ fundamenta progreſſus mirandus artifex, infimum hunc globum ex Abyſſo & Terrâ conflatum conſtituit; concinentibus & collaudantibus eum ſimul omnibus ipſius Angelis. [*Job* XXXVIII. 7] Cúmque Terra eſſet inanis & vacua, & tenebræ eſſent in ſuperficie Abyſſi: in ipſo primi diei medio creata eſt Lux; quam à Tenebris diſtinguens Deus, illam appellavit Diem, has Noctem.

Secundo die, (*Octob.* 24. *fer.* 2.) creato expanſo (quod Cœlum eſt appellatum) diſtinctio eſt facta inter aquas ſuperiores, & inferiores Terræ circumfuſas.

Tertio die, (*Octob.* 25. *fer.* 3.) Aquis inferioribus in locum unum confluentibus, emerſit Terra arida. Aquas in Mare congregavit Creator: emiſſis interim fluviis, qui in Mare refluerent. [*Eccleſiaſt.* I. 7] Terram omne genus Herbas & Plantas, cum ſeminibus & fructibus, germinare fecit. Præ aliis autem locis, Paradiſum in Edene plantis ornavit: in quibus, Arbor vitæ & Arbor ſcientiæ boni ac mali. [*Gen.* II. 8, 9.]

Quarto die, (*Octob.* 26. *fer.* 4) Sol, Luna, & reliqua Sidera creata ſunt.

Quinto die, (*Octob.* 27. *fer.* 5) Aquatilia & volatilia animantia producta ſunt; & fœcunditate donata.

Sexto die (*Octob.* 28. *fer.* 6) Terreſtria animalia creata ſunt; tùm Gradientia, tùm Repentia. Demùm verò Homo, ad imaginem Dei in divinâ Mentis ſcientiâ (*Coloſſ.* III. 10) & genuinâ Voluntatis ſanctitate (*Epheſ.* IV. 24) præcipuè conſiſtentem, conditus eſt. Ille ſtatim reliquis animalibus, divinitùs ad ſe adductis, ut Dominus eorum deſignatus, nomina impoſuit. In quibus cùm adjutricem ſibi ſimilem non inveniret;

B

***Figure 1.23**: The first page of the Annales Veteris Testamenti (Annals of the World) published by Archbishop Ussher. This chronology states that the Earth was created a few thousand years ago by God.*

Early Attempts

The first person to estimate the age of the Earth is not known, but the earliest attempts at interpreting the natural processes can be found in the ancient world (Dalrymple, 1991). Several of the earlier attempts made did not differentiate the age of the Earth from the age of mankind. For example, the Chaldeans held the belief that the Earth arose from chaos over two million years ago; whereas, the Indian Brahmins believed that Earth and time were eternal (Dalrymple, 1991; Holmes, 1937). On the other hand, Lucretius (99 BC-55 BC) believed the formation of the Earth was a fairly recent occurrence, and therefore the birth of the Earth was dated to when the poets first sang of famous deeds (Holmes, 1937). Quite contrarily, many civilizations had ideas of an eternal universe that was cyclically recreated. The great Greek philosopher Aristotle believed time to be endless and cyclic (Vaccari, 2001). The Maya believed the most recent date of re-creation to be 3114 BCE, while the Han Chinese believe the universe to be recreated every 23,639,040 years (Badash, 1989).

Other civilizations limited the age of the Earth by establishing a defined date. According to Persian sage Zoroaster (c. 600-680 BCE), the Earth is roughly 12,000 years old. The Babylonian astrologers determined that humankind had appeared roughly half a million years ago. By interpreting Hebrew chronology tables, Archbishop Ussher defined the birthdate of the Earth as 4004 BCE (**Figure 1.23**). This date prevailed in Western world as the biblical date of the year of creation (Dalrymple, 1991; Holmes, 1937).

The establishment of these beliefs led to a pause in the development of scientific method and geological research, for "so long as natural events were regarded as capricious happenings depended on the chance will of irresponsible gods, no scientific progress was possible" (Holmes, 1937). Though there was some progress made in other parts of the world, there were no significant advancements made in Europe until the late Renaissance. This was due to the intolerance of the opposition to the Bible by the Catholic Church in effort to protect the Christian belief (Holmes, 1937).

Despite the large number of exaggerated ideas proposed, the 18th century marked a period where there was a rapidly growing number of philosophers rejecting theological beliefs, and accepting notions that explained the formation of the Earth as a result of slow and continual processes. The coming of the 18th century brought with it an empirical state of mind, with evidence in nature valued over authoritative texts and pure speculation. (Vaccari, 2001) Geologists now agreed that the Earth had a history which spanned millions of years in length. Along with this, there were a growing population starting to support the Theory of Uniformitarianism, which stated that all geological processes resulted from external forces that occurred in equivalent intensity in the past as they do presently. Despite these efforts, the opposition of the biblical date by those supporting Uniformitarianism was regarded as a threat to religious beliefs; hence geological principles were established with strong opposition (Dalrymple, 1991; Holmes, 1937).

The separation of scientific and theological ideas was a slow and tedious process. Though all estimates before 1950 were incorrect, these estimates were significant in understanding the process by which the age of the Earth was determined and comprehending how the perspective on geology evolved to what it is today; the result of slow and continuous processes.

De Maillet's Approach

Benoît de Maillet (1656-1738), a French diplomat was one of the first to oppose the biblical date as a result of his observations and scientific theories. De Maillet proposed that the Earth was once completely covered by water, and that sea levels had been continuously decreasing following the formation of the Earth. Using these assumptions, he was able to measure the rate at which the sea levels had been decreasing (he calculated ~3 inches per century) and estimated that the Earth could not be less than two billion years old. Though this date is incorrect, he did however believe that all life originated from the sea, an idea that is still held to be true. (Dalrymple, 1991; Chambers and Mitton, 2013)

Figure 1.24: Charles Lyell, a British lawyer and geologist published the Principles of Geology which summarized the concepts of Uniformitarianism originally proposed by James Hutton.

De Maillet became the first to understand and study the history of the Earth through the precise measurements of natural processes. Living in an age where the society was heavily influenced by the power of the church, De Maillet understood the repercussions of opposing traditional Christian beliefs. As a result, De Maillet did not publish his work, and instead his work remained as a handwritten manuscript until ten years after his death. (Dalrymple, 1991)

Lyell and the Rise of Geology

Resistance to age estimations much longer than biblical values was brought down largely due to work done by geologist Charles Lyell (1797-1875) (**Figure 1.24**). Lyell absolutely abhorred the concept of creationism, believing that the complex stratigraphies in the Earth's crust could not be accounted for a single event (Bryson, 2003; Burchfield, 1998). Thus, Lyell took it upon himself to make this so and collect evidence for the age of the Earth. During a visit to Italy, he saw that the base of the columns of a temple in Pozzuoli were covered with mollusc markings (Oldroy, 1996). This suggested that sometime within the last 2,000 years, the temple had been underwater. Lyell took this to mean that the land had sunk and then risen again; these changes had to have been gradual enough such that the temple would not fall down (Oldroy, 1996).

Collecting further evidence, Lyell travelled next to Mt. Etna, a volcano in Sicily. He approximated the age of the volcano by measuring the height and rate of growth, giving a value of several hundreds of thousands of years old (Oldroy, 1996). Furthermore, Lyell discovered fossils under the mountain whose physiology told him they were young (in geological terms). However, knowing these fossils had to be older than the mountain above them, they also had to be several hundreds of thousands of years old (Oldroy, 1996). This indicates a game–changing fact: hundreds of thousands of years, in geological terms, is a short period of time.

In 1830, Lyell put forth the idea that rocks and geological formations were constantly changing through erosion and deposition at a constant rate; in 1838, he stated that strata could be dated by studying the order in which they were deposited as well as the minerals, fragments, and fossils contained within (Badash, 1989; Thompson, 1988) (**Figure 1.25**). As Lyell saw at Mt. Etna, even young fossils were very old, suggesting that geologic periods had lasted hundreds of million years (Badash, 1989; Oldroy, 1996). This led to the formation of the idea that processes occurring today have always occurred at the same rate, and can thus account for processes in the past; this process was dubbed Uniformitarianism (Oldroy, 1996). Uniformitarianism was a huge blow to the notion of catastrophism, the idea that Earth was shaped by a single catastrophic event like the Deluge (Badash, 1989). Uniformitarianism guided the next era of geological thinking in terms of the Earth's age, giving Lyell the satisfaction that geology had finally become established as a science (Oldroy, 1996).

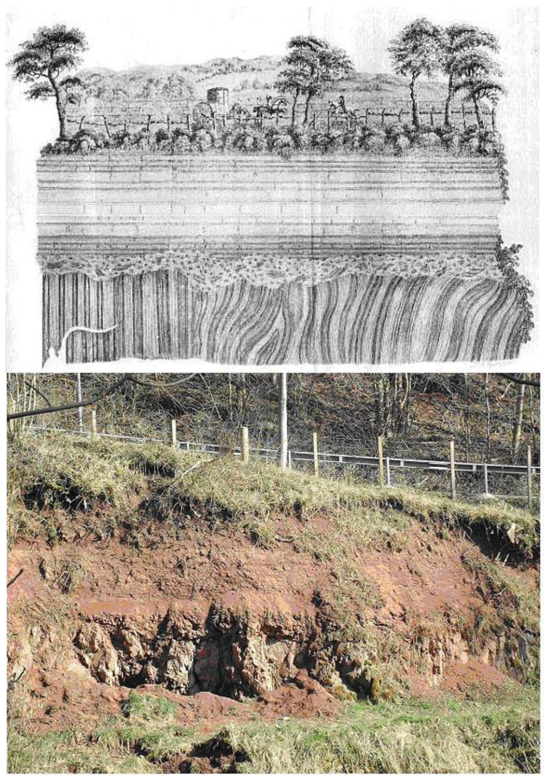


***Figure 1.25**: The drawing on top shows Uniformitarianism explaining how each geological structure has been laid over at a fixed rate; the bottom picture shows how this looks like in life.*

John Joly and the Saline Earth

While Lyell measured the growth rate of mountains, an Irishman named John Joly (1857-1933) delved into the oceans to take a different approach in determining the age of the Earth. Joly's (1857-1933) method was rather simple: he measured the salinity of the oceans to get an estimate for the Earth's age (Moore, 1956). Joly was not the first to try this – in the 18th century, an English polymath, Edmond Halley (1656-1742) stated that the sodium concentrations in closed lakes should be measured every 100 years (Wyse Jackson, 2001). Based upon the increase in sodium volume, Halley said the age of the lake would be able to be determined (Wyse Jackson, 2001). Another scientist before Joly by the name of Mellard Reade (1832-1909) examined the rates of accumulation of sulphates, carbonates, and chlorides in the ocean, and stated that it took 25 Ma, 500,000 years, and 200 Ma for each substance, respectively, to build up in the oceans (Wyse Jackson, 2001).

However, these two methods raised some problems. Halley's longitudinal method was not feasible for the obvious reason that most people do not live longer than 100 years. For reasons unstated, Joly was displeased with Reade's methods, saying they would not have produced reliable results (Wyse Jackson, 2001). And so, Joly took it upon himself to measure the rate of accumulation of sodium in the oceans. He did this using several assumptions: one, all salt in the oceans came from mineral deposits that had eroded and dissolved; two, that sodium concentrations in the ocean could only increase, and not decline; and three, under the principles of Uniformitarianism, that mineral deposits had to be eroding at a constant rate and that river discharge was constant over time (Badash, 1989; Wyse Jackson, 2001). Following these assumptions, Joly took the volume of sodium in the oceans and divided it by the rate of sodium input to give an estimate of the Earth's age as 80-100 Ma (Moore, 1956; Wyse Jackson, 2001).

Lord Kelvin's Estimates

One of the key players in physical determination of the Earth's age was the Irish physicist and engineer, William Thompson (1824-1907), more famously known as Lord Kelvin (**Figure 1.26**). Kelvin had no interest in the petty observations geologists and biologists were making of strata and fossils; he used the exact science of physics to come up with an estimate for the age of the Earth. Like most physicists, Kelvin believed that the Earth began as molten, whose surface had cooled and solidified, while the core remained hot (Badash, 1989). Thus, Kelvin published two papers applying the Laws of Thermodynamics to calculate the age of the Sun and the Earth (Burchfield, 1998). The calculations in these papers were meticulously done and difficult to argue with. Assuming gravitational contraction responsible for formation of the Earth initially generated most of the heat, and the only current sources of heat to be from the Sun and tidal friction, Kelvin calculated the rate of cooling of the Earth (Badash, 1989). His calculations, in both papers, brought about an estimated age of around 100 Ma, with the upper estimate being 400 Ma (Badash, 1989). Throughout the rest of his life, Kelvin refined his calculations and came to a final estimate of 24 Ma (Bryson, 2003).

This new estimate put forth by Kelvin was devastating for followers of Uniformitarianism. The processes which governed their theory happened over a very long timescale, much more than 100 Ma, and Kelvin came to be a disliked figure in the area of geology. However, his calculations appeared to be very accurate and indisputable; and so, for a good while, estimations for the age of the Earth remained in the range of 100 Ma.

The Era of the Atom

By the end of the 19th century, most geologists had come to the conclusion that the age of the Earth was approximately in the range of 100 Ma or less, even independently of the calculations done by the geologically disliked Lord Kelvin (Badash, 1989). John Joly's calculations of the salinity of the Earth gave an age of approximately 80-100 Ma; G.H. Darwin gave an estimate of 57 Ma from calculations relating the separation of the Moon from the Earth; Hermann von Helmholtz estimated 22 Ma from his calculations of the Sun's shrinking rate (Moore, 1956; York and Farquhar, 1972). However, a new discovery was about to change all this.

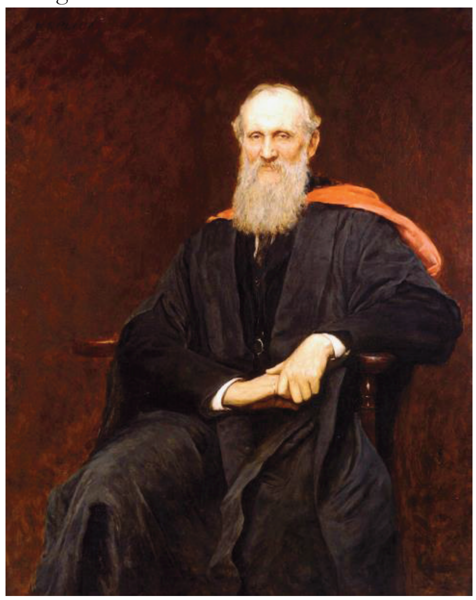


Figure 1.26: *Lord Kelvin, or William Thompson, was an Irish physicist and engineer who formulated the first and second laws of thermodynamics and also made significant contributions to electricity.*

In 1896, physicist Henri Becquerel (1852-1908) discovered radioactivity (**Figure 1.27**), the phenomena in which some elements emit large amounts of energy in the form of high–energy waves and particles (York and Farquhar, 1972). This process was shown in 1902 by Ernest Rutherford (1871-1937) and Frederick Soddy (1877-1956) to be the spontaneous transmutation of an atom of one type of element to another type of element. In 1903, Rutherford demonstrated that the rays emitted during the radioactive process carried large amounts of energy (Badash, 1989). To add to this new fascination, Pierre Curie (1859-1906) and his assistant Albert Laborde showed that radium generates enough heat to melt more than its weight in ice (Badash, 1989). This was the tipping point in the determination of the Earth's age. Kelvin's calculations relied on the assumption that the only sources of heat on Earth were the Sun, gravitational contraction, and tidal friction (Badash, 1989). The discovery of radioactivity added another source of terrestrial heat, and after a quick survey of the materials on Earth, it was found that radioactive substances were indeed ubiquitous enough to significantly change the calculated rate of cooling of the Earth (Badash, 1989).

Rutherford also noticed something interesting in radioactive substances: it always took a characteristic time for half of one radioactive substance to decay – this was named the half-life of a radioactive substance (Bryson, 2003). This observation led to an entirely new method for determining the age of the earth: radiometric dating. By knowing the rate at which a radioactive substance decays and how much a material contains said radioactive substance, the age of that material can be determined (Bryson, 2003). Rutherford dated pitchblende, an ore of uranium, in this way to be 700 Ma old (Bryson, 2003). Much of this pioneering work on radiometric dating was done with his colleague radiochemist Bertram Boltwood (1870-1927) (Dalrymple, 2001). After more experimentation and examination of naturally occurring uranium metals, Boltwood noticed that they always contained lead and uranium; furthermore, he noticed that the geologically older samples contained more lead and helium than the younger samples (Dalrymple, 2001). Thinking to Rutherford's idea of the half-life, Boltwood decided that lead and helium were decay products of uranium (Dalrymple, 2001). This led to the development of the U-He and U-Pb series. These series became very effect methods of dating the age of geological samples, and thus the age of the Earth. During a lecture at Yale University, Rutherford presented two samples dated with the U-He method that had ages of 497 Ma and 500 Ma (Dalrymple, 2001). Even more astonishing was geologist Arthur Holmes' (1890-1965) usage of the U-Pb in 1911 series to date a 1640 Ma sample (Wyse Jackson, 2001).

Of course, as is often the case, many scientists were still displeased with this breakthrough in determining the age of the Earth. Joly, of the ocean salinity method, tried very hard to dispute Rutherford and Boltwood's new method, clinging on to his estimate of 80-100 Ma (Wyse Jackson, 2001). Kelvin, known for his self–assurance, held true to his final claim of 20 Ma until his dying day (Bryson, 2003). However, the evidence for a much older Earth was mounting. As indisputable as the early calculations may have seemed, Rutherford and Boltwood had just discovered a method of dating the Earth that was far more indisputable and became the cornerstone of modern geological dating.

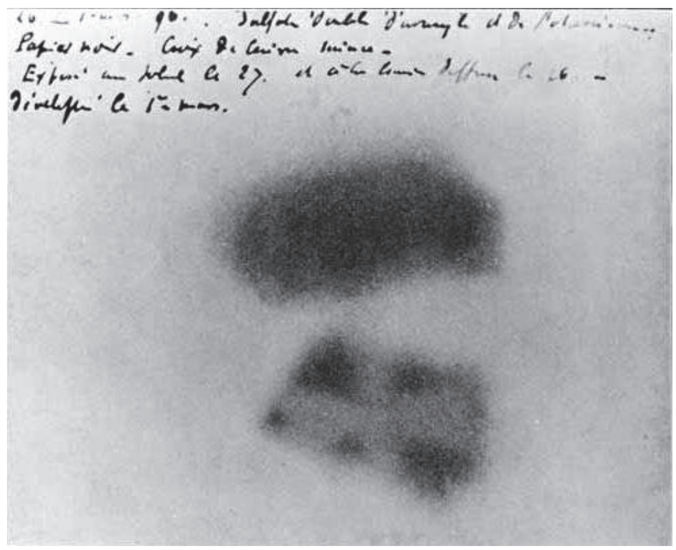


Figure 1.27: *Becquerel's photographic plate fogged by uranium radiation exposure.*

Radiometric Dating of Meteorites

After over 200 years of studying and understanding the chronological history of the Earth, modern science has determined that the most accurate dating techniques do not solely depend on the use of terrestrial rocks. Due to the dynamic nature of the planet, it is possible, though not necessarily likely, that the Earth's earliest rocks have been long destroyed through recycling, weathering, and erosion (Dalrymple, 1991). The oldest rocks currently known are dated to be approximately 3.5-3.96 Ga old (Dalrymple, 1991). This confirms that the Earth is older than 3.96 Ga; however, the exact date requires further work to be done on non-terrestrial rocks, such as meteorites.

Holmes–Houtermans Model

In 1946, Arthur Holmes (1890-1965) and F.G. Houtermans (1905-1966) proposed the Holmes-Houtermans model, which described that the isotopic composition of lead in the Earth evolved from primordial lead through the replacement of uranium and thorium with radiogenic Pb-206, Pb-207 and Pb-208. The

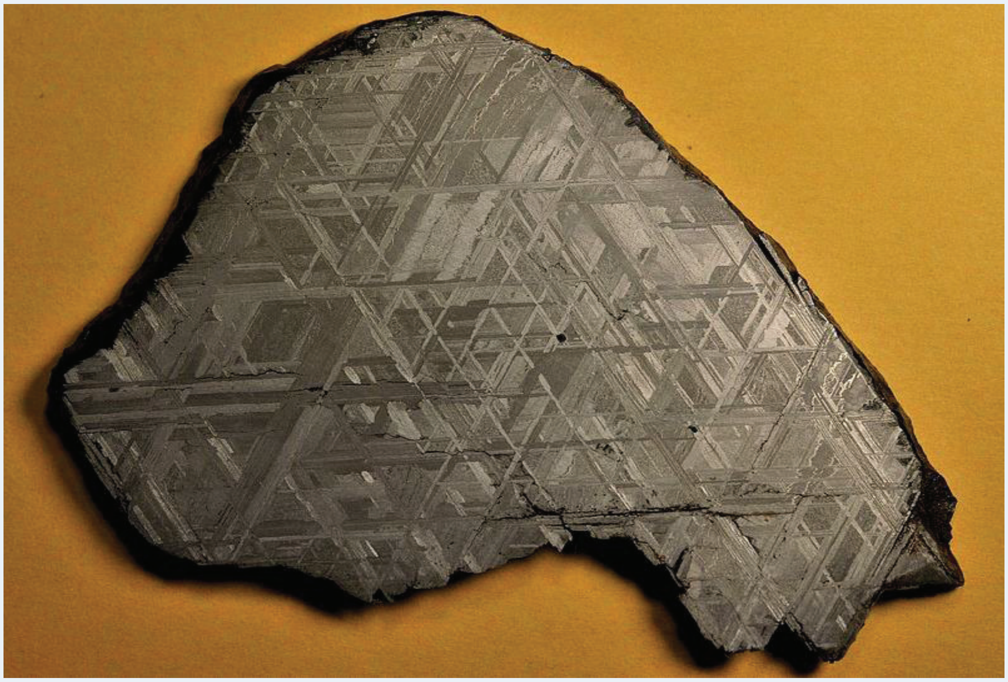


***Figure 1.28**: An image of a slice of the Muonionalusta meteorite, which is one of the oldest meteorites known, dating 4.5 billion years old.*

model describes that iron-meteorites and the Earth may have been formed from a common primordial cloud and would therefore have common isotopic compositions of lead. However, unlike the Earth's crust where uranium and thorium is replaced by radiogenic lead isotopes, lead ores in iron-meteorites have little to no uranium and thorium concentrations and therefore the isotopic compositions of iron are thought to have remained intact. Hence, the composition of the Earth from when it was first formed is hypothesized to be the same as the composition of iron-meteorites today (Eicher, 1968) (**Figure 1.28**).

In 1956, Clair Cameron Patterson (1922-1995), an American geochemist was the first to use the Holmes–Houtermans model to calculate the currently accepted age of the Earth, 4.55 ± 0.7 Ga (Eicher, 1968). This date has been further refined to 4.543 Ga with an error range of one percent (Dalrymple, 1991; Eicher, 1968). This is currently the most accurate calculation of the age of the planet, as it is consistent with the radiometric dates of majority of ancient rocks found on both the Earth and Moon (Dalrymple, 1991).

Errors in Radiometric Dating

Due to the fact that the oldest known rocks do not depict the currently accepted age of the planet, there is still much to be learned about the chronological history of the Earth. Hence, there is a probability that the currently accepted date of formation may someday be proven wrong if new evidence emerges (Dalrymple, 1991). At the moment, when used properly, radiometric dating is considered an accurate and reliable technique (Dalrymple, 1991). However, there is a two percent error margin associated with the decay constants used in radiometric dating (Eicher, 1968). Aside from these systematic errors, the use of radiometric dating relies on the assumption that the rock or mineral existed in a completely closed system. Thus, there will always remain an error associated with the extent to which the mineral or rock remained in a closed system. Likewise, recent evidence suggests that lead content in ocean sediment, which is currently accepted as the most accurate, may not be the optimal sample for the mean representation of the Earth's crust lead ratio content (Eicher, 1968). Thus, the answer to the question "what is the age of the Earth?" will continue to be a topic further explored in the future.

Despite the errors associated with the current techniques of dating and the information that is still lacking, the study of geology has progressed significantly over the past 200 years. Understanding the natural processes of the Earth and Solar system to explain the chronological history of the formation of the Earth is one of the most distinguished achievements of modern science.

The Impacts of Christianity on Astronomical Thought

It was considered, for many years, that religion and science were so ideologically different that consolidating the two was considered impossible (Stark, 1963). Ancient religious ideals dictated that a higher power governed human truth and reason, whereas scientific ideals contradicted that higher power, placing reason as the only direct means to truth and knowledge (Stark, 1963). Religion, however, did not always contribute to the detriment of science. Particularly in modern science, religion has often been a catalyst to the emergence of scientific thought (Bainbridge, 2004). The relationship between religion and science since antiquity has been extremely dynamic, and its study has led to differing perspectives on the nature of their relationship.

Religion and Science in Ancient Greece

Ancient Greeks were not foreigners to cosmology or astronomy. Several educated Greek thinkers including pre-Socratics such as Homer (c. 900-c. 710 BCE) and Hesiod (750-650 BCE) and ancient scientific philosophers such as Aristotle (384-322 BCE) and Claudius Ptolemy (100-170 CE) made observations about the Earth, its properties, and its role in the cosmos. The ancient polytheistic religion of ancient Greece and its associated mythology was also seen in such texts, albeit more heavily featured in earlier works, especially those of Hesiod, Homer and other archaic Greek texts (Carnagie et al., 2007). Ancient Greek scientific thought was advanced for the era and provided a foundation on which Medieval and Renaissance scientists such as Nicolaus Copernicus (1473-1543), Galileo Galilei (1564-1642) and Isaac Newton (1643-1727) expanded upon, if not corrected (Fieser, 2008; Violatti, 2013).

Pre-Socratic Greek Thought

Homer was known for his epic poems, one being *Iliad* (c. 760-c. 710 BCE), the story of the ten-year-long war fought on the plains outside of Troy, located in modern Turkey (Leeming, n.d.). While *Iliad* is often referred to for its literary, historical and cultural greatness, the astronomy described within it provides an excellent glimpse of Greek observations about their surroundings in Homeric times. One example of Homer's impressive observation of the cosmos is documented in the 18th book of the *Iliad*, in which the crafting of Achilles' shield is described in great detail (Dicks, 1970). Homer beautifully details the central part of the shield as decorated with the Earth, heavens, sun, moon, and several star clusters such as Pleiades, Hyades, Orion and Ursa Major (Hannah, 1994; Homer, 762 BCE). The inclusion of these astronomical structures is one of the first Greek documentations of circumpolar stars (Dicks, 1970). Homer's acknowledgement of the stars being stationary or in transit correlates with the subsequent sections of *Iliad*, wherein agriculture and harvest is discussed. For example, the lower transit of Ursa Major signifies the time of summer harvest, while the upper transit signifies the time of winter harvest and Homer gives this constellation the second name "Wagon", alluding to the farmer's job of ploughing and sowing a field (Hannah, 1994). The significance of this passage is an indication that the ancient Greeks associated observations on locations of stars with the passage of time, an important precursor to theories on the structure of the universe (Hannah, 1994).

While *Iliad* has its scientific aspects, it is not void of classical Greek mythology. Specifically, Hephaestus, the Greek god of fire and metalworking, is credited as the constructor of Achilles' shield (Atsma, 2015). He builds this shield at the request of Achilles' mother, Thetis, herself a nymph (Atsma, 2015). Even the great river ocean that surrounds the cosmos described is Oceanus, a synonym for the native Greek god of the river itself (Dicks, 1970; Atsma, 2015). While these are just a few examples, *Iliad* is laden with references to Greek theology, culture, and mythology, the poem itself being a true example of archaic Greek text intertwining observational science and mythology.

Hesiod, another great Greek poet, also shows evidence of observational astronomy. His works describe the driving force of Greek astronomical discoveries: the practical need for a calendar (Dicks, 1970). Hesiod's poem *Works and Days* (700 BCE) displays a more systematic approach to the cosmos by relating the transits of stars to agriculture and farming (Evans, 1998). The agricultural calendar devised in the poem is represented by the central character in Hesiod's poem, the farmer (Evans, 1998). Hesiod uses the constellation Pleiades as a significant star cluster with which to tell time. When Pleiades rose (in May on the Gregorian calendar), the summer harvest would begin, and when Pleiades set in the west before dawn, it would initiate the fall harvest (Evans, 1998). The poem ends with a farmer's almanac, which uses observational astronomy to guide farmers as to the time of year (Taub, 1999).

While Hesiod's work seems very scientific and applicable, it also utilizes concepts from traditional Greek mythology. Even his references to Pleiades, the major star cluster used to tell time, are frequently associated with the seven daughters of the Greek sky god, Atlas (Evans, 1998). Even when Hesiod describes various astronomical phenomena, such as equinoxes and solstices, he claims that they are the doing of Zeus, and does not suggest a scientific reason (McMahon, 2007; Evans, 1998).

Clearly, Greek science of early antiquity was deeply connected to ancient Greek religion and its associated mythology. As shown in Hesiod's *Works and Days* and Homer's *Iliad*, observable astronomical phenomena were frequently useful in their applications, but the sources of the phenomena were frequently attributed to religious mythology.

Ancient Greek Thought

Thus, most Greek pre-Socratics delved into astronomy as a means of utility. It was only later that pre-Socratics, such as Anaxagoras (500-428 BCE), began to use astronomy to explain the cosmos, such as Anaxagoras' accurate explanation of eclipse occurrence (Patzia, n.d.). However, while pre-Socratics did begin the development of astronomy, it was their successors, the ancient philosophers, who developed Greek astronomy as it is remembered today.

Aristotle's thoughts were extremely influential on early Greek philosophy. He was known throughout Athens for his deductive reasoning, observational logic, and rationality, believing that the ability to identify nature and its purpose was of the utmost importance (Carnagie et al., 2007). It is in the astronomical works of Aristotle, particularly *De Caelo* (On the Heavens) (350 BCE), that the diversion from previously typical Platonic astronomy can be seen. Further, Aristotle's naturalistic view on the cosmos, considered more than religious and mythological explanations for his observations (Bowen and Wildberg, 2009). Thus *De Caelo* contains a number of Aristotelian arguments based on observation, nature, numerical principles, and much less mythology (Bowen and Wildberg, 2009). It must be noted, however, that Aristotle's natural view did not guarantee accuracy. For example, Aristotle believed that the Earth was naturally attracted to the centre of the universe and other celestial bodies would be attracted to it (Aristotle, 2012). *De Caelo* does provide extensive reasoning for such theories, using natural observations, such as lunar eclipses, as evidence (Aristotle, 2012).

The Aristotelian model was well-preserved by the Church. Medieval scholars such as Tommaso d'Aquino (1225-1274) re-interpreted several of Aristotle's theories and was supported by Christian authorities (Fowler, 1995). Disagreements between the new doctrine and Aristotle's works were noted by d'Aquino but left ambiguous in his revisions to works such as *De Caelo* (Elders, 2009).

The Greco-Roman scientist Claudius Ptolemy was essential to the development of astronomical models of the Solar system. The *Tetrabiblos* (Four Books), written in the second century, contains evidence of Ptolemy's acknowledgement of Catholicism and its importance to astronomy. The *Tetrabiblos* was considered accurate in Ptolemy's time as astrology, discussed extensively in the text, was considered a valid discipline (Thayer, 2012). The third book discusses Catholic astrology, and was translated and accepted into the Christian doctrine by Albertus Magnus and Tommaso d'Aquino (Arthur, 2015). The *Tetrabiblos* was subsequently used as the theologically-accepted textbook of Ptolemaic astrology in schools and even in medical colleges during the Medieval era, leading into the early European Renaissance (Arthur, 2015).

Ptolemy's other great text written in the second century, the *Almagest*, was more influential; it was his first description of epicycles and equinoxes, a major addition to astronomical theory. Ptolemy adopted a geocentric model of the Solar system, with the Earth at the centre (Fitzpatrick, 2013). His model worked from an Earth observer's frame of reference (Fitzpatrick, 2013). While many modern scientists condemn Ptolemy for using a quasi-Aristotelian planetary model, claiming his presentation of epicycles to simply be crude support for his geocentric model, others believe his work was revolutionary and necessary to the progression of astronomy and the understanding of the cosmos (Fitzpatrick, 2013). In fact, Ptolemy's *Almagest* was crucial to subsequent Medieval Christian theology, due to its similarity to Aristotelian astronomy, remaining as one of the primary texts of reference for the Church until controversy arose with Nicolaus Copernicus' opposing heliocentric model (Taliaferro and Marty, 2010).

The Copernican Revolution

In the 11th century, Europe, particularly western Europe, achieved a state of political and economic stability. The population exploded; urban city centers developed, and with them, urban schools appeared, teaching wider curriculums than monastic schools (Lindberg, 2010). Education became theoretically accessible to students from all classes of society by the 16th century, with the development of a great number of large and influential universities (Langford, 1992). The famous Polish scholar, Nicolaus Copernicus, attended one such university, the Academy of Krakow (Sobel, 2012; Gassendi and Thill, 2002).

It was there that Copernicus discovered his love for astronomy, Krakow being internationally acknowledged as the centre for astronomical education in Europe (Sobel, 2012; Knoll, 1975). He was a gifted student, learning both mathematics and astronomy, and reading and analyzing, in particular, Epitoma in Almagestum Ptolemaei (Epitome of Ptolemy's Almagest), an abridged translation of Ptolemy's Almagest, edited and translated by Georg von Peurbach (1423-1461) and Regiomontanus (1436-1476) (Sider, 2007; Contopoulos, 1974; Swerdlow and Neugebauer, 2012). Copernicus continued his studies in Italy: canon law at the University of Bologna, and medicine at the University of Padua, becoming a lawyer by profession, but retaining his passion for astronomy (Contopoulos, 1974). However, in 1503, Copernicus returned to Poland, to become a canon of the Cathedral of Frombork, where he would remain for the rest of his life (Contopoulos, 1974).

Copernicus rejected the geocentric motion of the planets given by the Ptolemaic model, because it violated the accepted notion that the motions of the planets must be circular and uniform (Sobel, 2012). Ptolemy's model could only account for his observations by assigning the planets a second axis of rotation, off-centre from the true axis (Sobel, 2012). Copernicus hypothesized that planets traveled in a circular orbit around the Sun, and the Earth in particular spun on its own axis (Sobel, 2012). He published his ideas in a manuscript he called *Commentariolus* (Little Commentary) sometime before 1514 (Koyré, 1973; Contopoulos, 1974). However, recognizing that he needed to support and elaborate his hypothesis with data, Copernicus collected observations from 1512 to 1529, and worked on his landmark oeuvre: *De Revolutionibus Orbium Coelestium* (On the Revolutions of the Heavenly Spheres) (Swerdlow and Neugebauer, 2012).

The work was published with a preface written by Andreas Osiander, a Lutheran theologian and a friend of Copernicus, who feared the consequences of publishing such a potentially heretical work (Koyré, 1973). His preface advises the reader that the work simply presents a convenient way in which to calculate the motions of the planets, rather than a claim on the nature of the world system (Koyré, 1973). In Copernicus' own letter of dedication to Pope Paul III in *De Revolutionibus*, he explains his delay and hesitation in publishing his thesis for fear of being attacked for his novel theory (Koyré, 1973). Nevertheless, Copernicus proudly defends his position, and suggests that those ignorant in matters of astronomy (implying religious figures) should refrain from criticisms of his work (Koyré, 1973). Nicolaus Copernicus died the same year that his thesis was published (Koyré, 1973). Legend states that he received his first printed copy of *De Revolutionibus* on his deathbed (Omodeo, 2014).

The Galileo Affair

Shortly after Copernicus' death, Galileo Galilei was born near Pisa (Drake, 1999). Galileo's education began at the age of twelve in the monastery of Vallombrosa, learning Latin, Greek, and logic (Langford, 1992). He studied at the University of Pisa, but did not complete his degree (Langford, 1992). Despite this setback, he obtained the post of professor of mathematics at the University of Pisa in 1589 (Langford, 1992).

It was there that Galileo began questioning the knowledge of his predecessors, frustrations he expressed in his lectures (Langford, 1992). He wanted to use logic and observations to determine the mechanisms of the world, and not depend on philosophical faith (Langford, 1992). This attitude was extended to religious faith when Galileo used his improved telescope, based on the instrument invented by Hans Lippershey (1570-1619), to observe various aspects of the sky in greater detail than had ever been seen before (King, 1955). Having observed the phases of Venus and sunspots, as well as the tides on Earth, Galileo adopted Copernicanism, since the physics of a geokinetic Earth and heliocentric Solar system pleased him logically (Finocchiaro, 2008).

A Copernican perspective, however, directly opposed the geostatic and geocentric opinions of the Roman Catholic Church, which was based on scripture and Ptolemy's model (Finocchiaro, 2008). However, Galileo held the view that the Bible should not be taken literally, and that though the Holy Scripture was never wrong – to say otherwise would be total blasphemy – its interpreters could easily take literally that which should be taken allegorically (Finocchiaro, 2008). As such, he thought that passages dictating that the Earth stood still and was the center of the universe were simply allegories, should not be used to determine mechanisms of natural phenomena, and that therefore scripture could not be used to refute Copernicanism (Mayer, 2015; Frankenberry, 2008).

Galileo expressed these views in a letter to his former pupil, Benedetto Castelli, in 1613 (Mayer, 2015). Dominican friar Niccolò Lorini used the contents of the letter as evidence against Galileo in a formal complaint to Cardinal Paolo Sfondrati, a member of the Roman Inquisition (Finocchiaro, 2008). This complaint, coupled with Tommaso Caccini's (1574-1648) 1615 deposition to the Inquistion against Galileo's Copernican views, led the Inquisition to launch an investigation into whether Galileo was a heretic (Mayer, 2015). Galileo, at this time, visited Rome, to attempt to neutralize Caccini and other members of the clergy that opposed him (Mayer, 2015). A committee was assembled, which announced in February of 1616 that heliocentrism and the geokinetic thesis were philosophically absurd and formally heretical, and Copernicus' famous *On the Revolutions* was subsequently banned until release of a corrected version by the Church (Finocchiaro, 2008). Galileo was subsequently warned by Paul V, the Pope, to abandon his Copernican views (Finocchiaro, 2008).

Figure 1.29: *Galileo's trial by the Roman Inquisition, depicted in a 19th-century painting by Joseph-Nicholas-Robert-Fleury.*

Having acquiesced to the Pope's order, Galileo returned to his study of astronomy. In 1632, he published the consolidation of all of his astronomical knowledge: *Dialogo sopra i due massimi sistemi del mondo* (Dialogue Concerning the Two Chief World Systems) (Finocchiaro, 2008). The book was met with great enthusiasm, but also extreme criticism, both scientific and religious, in Rome (Finocchiaro, 2008). The Pope, now Gregory

XV, immediately banned the sale of the book and appointed a commission to investigate *Dialogue* for heresy. The case was forwarded to the Inquisition (**Figure 1.29**) and Galileo was ordered to Rome to stand trial for heresy (Finocchiaro, 2008).

In spring of 1633, Galileo was convicted of "vehement suspicion of heresy", and as part of his sentence, was forced to renounce his Copernican views. Sentenced to imprisonment, which was commuted to house arrest, Galileo Galilei lived the rest of his life in Villa Medici in Tuscany, under the watchful eye of the Church (Finocchiaro, 2008). He died in Arcetri, near Florence, in 1642, and was buried in the church of Santa Croce in Florence (Shea and Artigas, 2004).

Figure 1.30: *A portrait of Martin Luther in 1548, aged 65 by Lucas Cranach the Elder.*

The Reformation

Despite the all-encompassing reach of the Catholic Church and the power of the Roman Inquisition, Europe in the 16th century saw an earth-shattering change in religious opinion. Changes made to Protestantism by Martin Luther (1483-1546) (**Figure 1.30**) constituted perhaps the greatest controversy of the time. By the time of the Renaissance, the Roman Catholic Church had become corrupt, and Luther called their doctrines into question (Sharp, 2005). Luther's movement was also indirectly involved with the rapid progression of the Scientific Revolution at the time (Sharp, 2005). In retrospect, Protestant beliefs during the Scientific Revolution in the 1500s had more influence on the promotion of science than the Catholic Church (Mason, 1953). In this era of enlightenment, civilians began to value humanitarianism and individual thought over the word of the Church. This, coupled with Luther's similar ideas in Protestantism, frustrated the Roman Inquisition (Mason, 1953). While the reformation did not directly promote scientific thought, it introduced the concept of defying the Catholic Church, which had been hitherto unheard of. This idea allowed scientists and society to think freely, advancing much of modern science.

The Newtonian Revolution

The rapid progression of scientific thought during the enlightenment paved the way for more advanced and influential scientific discovery in the next century, including Sir Isaac Newton's theory of gravity. The enlightenment period, in fact, ended with Newton's revolutionary publication of *Philosophiae Naturalis Principia Mathematica* (Mathematical Principles of Natural Philosophy) in 1687 (Draper, 1874). In particular, the third book, De Mundi Systemate (On the System of the World) described the laws of gravitation and explained the motion of celestial bodies based on these laws (Smith, 2008). Newton managed to consolidate the observations and theories of his predecessors, Copernicus, Galileo, Kepler, and a host of others, into one theory of gravitation that would explain all the observational evidence of the movements of the planets. Much like Kepler before him, Newton was a devout, if unorthodox, Christian, and believed similarly that the simplicity of the laws of the university could only be evidence of God, an intelligent designer (Cohen and Smith, 2002). Such an influential work, if published in previous years, was bound to have attracted the attention of religious authorities. However, due to the political conflict during the Reformation, no religious group had the power nor the time to concern itself with Newton's mathematical demonstrations (Draper, 1874).

Religion: A Double-Edged Sword

Throughout history, religion has been both an opposing and an encouraging force for scientific development, particularly in astronomy. In ancient Greece, astronomical observations were frequently explained by religious mythology. A similar attitude was adopted by the Catholic Church, culminating in their complete rejection of Copernicanism in the 17th century. Despite the historic all-permeating influence of the Church, however, scientific thought persisted to bring humanity to its golden age of knowledge today.

Christian Astronomy

The first chapter of this book has provided ample evidence for characteristics and structure of the Earth and the Solar system. While such evidence is abundantly documented in books, articles, papers, and other sources of experimentation and results, other theories exist on how the Earth came to be. These theories vary greatly between belief systems, as well as within. In this section, Christian theories, beliefs, and thoughts involving religion will be discussed.

Young- and Old-Earth Creationism

Between Christian astronomers, two main beliefs about the creation of the Earth prevail: young-Earth creationism and old-Earth creationism.

Young-Earth creationism states that Earth was created, in its entirety, over the duration of 10,000 or less years, following the Genesis (Wiles and Richardson, 2004; Bartlet, 1997). The old-Earth theory was adopted by the 19th century, when the Church accepted that the Earth was not a young body and that it was reasonable to believe it was created a long time ago (Scott, 2001). Creationists who believed in this theory would think that the Earth's age corresponded to scientific evidence of the time (Scott, 2001).

Modern Research in Creationism

Henry Morris (1918-2006) was the influential founder and president of the Institute of Creation Research in the United States approximately 20 years ago (Scott, 2013). Morris was a young-Earth creationist and civil engineer who rejected evolutionary theory and often sought to express this with his students, peers, and others (Numbers, 1993). By 1970, Morris had switched his career from civil engineering to religion and developed the Institute for Creation Research (ICR) (Institute of Creation Reseach, n.d.). The institute seeks to continue scientific research, within the beliefs of Young-Earth creationists and Christian apologetics, reasoned defenses for the Christian faith (Institute of Creation Research, n.d.). Objectively, the institute is impressive in that it remains relevant with its research and expansion. In 2010, the ICR went to federal court and fought against the Texas Higher Education Coordinating board to establish a Master's program from a Biblical scientific standpoint, which was rejected by the Texan education system (Wilonsky, 2010). More recently, the ICR proposed to expand towards northwest Dallas, adding a 3D planetarium, lecture hall, and exhibit space in the hopes of further educating observers of its beliefs (Wilonsky, 2015). The ICR has been very active since its establishment in 1970; however, it is not the only creationist-based institute out there.

Hugh Ross is a Canadian old-Earth creationist who created the Reasons to Believe institute with his wife, Kathy in 1986 (Ross, 2011). Ross became completely convicted in his beliefs when he completed his PhD in astronomy at the California Institute of Technology (Ross, 2011). Currently, the institute has over 200 staff members and over 40 global chapters (Reasons to Believe, n.d.), a significant growth since its inauguration in 1986. The institute seeks to spread Christianity by showing that new and emerging scientific research continuously supports that which is said in the Bible and the existence of a God (Reasons to Believe, n.d.). Similar to the ICR, Reasons to Believe has been very active in its associated communities as well, including lecture talks, seminars, information sessions, and other forms of educating the public of its views (Reasons to Believe, n.d.) Ross, himself is active in the Christian community, relating Christian apologetics with astronomy, (Ross, 1994). Given young-Earth and old-Earth creationism, it is evident that differences in belief concerning scientific thought exist within Christianity. Despite opposing evidence, however, Christian beliefs on traditionally scientific topics continue to persist, through the maintenance of organisations such as the Institute for Creation Research and Reasons to Believe. Regardless of modern increased acceptance of science and the advent of a secular society, many still believe in a religious perspective on scientific topics.

Figure 2.1: *View from the summit of the Eyjafjallajökul glacier in Iceland, at an elevation of approximately 1,666 m.a.s.l. The glacier overlies a volcano that erupted in 2010, disrupting air travel across Europe. Due to the country being situated on top of two plates, it is normal for some seismic activity to be recorded, though truly dangerous earthquakes rarely occur.*

Chapter 2: Geological Phenomena on the Earth's Surface

As the most grand aspects of the Earth came to be understood, humans shifted gears and turned their sights inwards to seek out answers to the phenomena that occurred all around them. There was still so much to understand about the processes of everyday life, and for good reason. Humanity sought to answer such questions as: why does a volcano spew fragments of flaming rock up into the sky? Or why does the ground grumble and shake? Explanations for these events were first attributed to hidden entities. However, over time, our understandings developed as people continued to observe and study the Earth. Past ideas and explanations found laughable today were simply part of the scientific process, and paved the way for the development of current theories.

An integral element of the scientific process is proof, followed swiftly by disproof. With no challenge, a theory may remain correct for all of time when it rightly should not. Disproof is essential to progress. In studying the geological phenomena on the Earth's surface, many scientists felt their spirits soar as their work was accepted, and subsequently fell from the sky as another theory explained the event more correctly. Without the rivalries and competition between the ancient philosophers and scientists of the past, there would be no development in understanding the many processes that shape and characterise the Earth.

The Earth is a dynamic system, and as a result, its surface is constantly changing. The majority of these changes occur at very slow rates and over long periods of time. For instance, it takes many generations to build great mountains or cover continents in ice. Hence, time has been a great limitation to our understandings of geological phenomena. No one person could understand these phenomena in their lifetime without having access to information from those before them; in this way, science can be likened not to a solo performance of one instrument, but a resounding symphony of complementing pieces. Observations over the course of many lifetimes must have been recorded to allow humans to develop current understandings. This chapter will discuss the wonders of the natural world and how scientists have studied and observed these phenomena. From the constantly shifting tectonic plates to the atmosphere that offers protection from harmful solar radiation, this chapter will cover only a few of the geological phenomena found on Earth. At length, powerful earthquakes, massive glaciers, and explosive volcanoes, will be discussed. This chapter will illustrate how beautiful the Earth truly is and why it so important to study such features.

Development of the Continental Drift Theory

The Theory of Continental Drift was first proposed by Alfred Lothar Wegener (1880-1930), a German meteorologist, in 1912 (**Figure 2.2**) (Kious and Tilling, 1994). This theory explains that the continents are in motion and over long periods of time adjoin to create supercontinents that eventually break apart in a perpetual cycle of motion. The idea was a successful model for explaining observations such as the jigsaw fit of the contour of the continents, how mountains formed, and why marine fossils can be found on land. It was a pivotal moment in the understanding of the Earth and the process by which it evolves. But was a step in the right direction that for half a century was overshadowed by the dominant theories of the past. It was not until the late 1960s when strong evidence for Continental Drift Theory sparked the development of Plate Tectonic Theory that geologists were won over and Wegener's idea popularly accepted (Oreskes and LeGrand, 2003).

Figure 2.2: *A photograph of Alfred Wegener the proponent of continental drift theory.*

Precursors to the Continental Drift Theory

Humans have for a long time pondered the question 'how did the Earth come to take the form we see it to be today?'. For a long time divine creation, such as the Lord creating the world in six days as written in the holy bible, was the accepted answer to this question (The Bible, Exodus, 20:11). Pre-cursing ideas to Continental Drift Theory however, can be found as early as 1596. At this time world exploration and cartography was taking off and Dutch map maker Abraham Ortelius (1527-1598) suggested that North America was 'torn apart' from Europe and Africa by earthquakes and floods after considering the shape of the coasts of three continents (Kious and Tilling, 1994). This was an important step as it implied a non-permanence to the features of the Earth. But the journey from here to Wegener's Continental Drift Theory was wrought with twists and turns.

It was not until the late 18th and 19th century when serious academic inquiry into the formation of major land features took place and the development of theories picked up. It was at this time when geologists concerned themselves with the origin of the mountains rather than continents (Oreskes, 1999). In 1795, Scottish philosopher James Hutton (1726–1797) proposed uniformitarianism, the first scientific theory of geology which states: Earth is self-renewing and is constantly breaking down by erosion, with new land built up by volcanic action and the heat of the earth's interior (LeGrand, 1988). Following this idea Charles Lyell (1797-1875), in 1830 further developed the idea of uniformitarianism by stating present process had always been around in their current rate to produce an endless succession of cycles (Marvin, 1973; LeGrand, 1988). This theory explained present day erosion sufficiently. It acknowledged that small scale featured changes, introducing a degree of dynamicity, while macroscopic features remained the same (such as that of the position of continents).

The 19th century was ripe with new geological ideas, and shortly after uniformitarianism was proposed the theories of permanentism and contractionism were developed. Both theories were based upon the principle that a cooling Earth will contract (Oreskes and LeGrand, 2003). Contractionism was a theory popularized by Austrian geologist Edward Suess (1831-1914), and as a result became popular in Europe. He accomplished this by using the simply analogy of Earth as a drying apple to convey the core concept of the theory. As the apple dries (shrinks) it wrinkles. This is analogous to the Earth cooling. A cooling material will contract as it cools, and so as the Earth cools it contracts and deforms: producing mountains (Oreskes and LeGrand, 2003).The theory also suggests continents and ocean basins would occasionally switch places as continued cooling causes the continents to become unstable. This allowed the theory to answer the longstanding questions of why ancient ocean fossils are found on continents, and why there are interleaving of marine and terrestrial sediment deposits (Oreskes and LeGrand, 2003).

Permanentism on the other hand, was a theory pioneered by James Dwight Dana (1813-1895). Permanentism took a different spin on the cooling of the Earth. Dana suggested that continents formed early in Earth's history when low temperature minerals such as feldspar and quartz had solidified. After continued cooling and contraction the high-temperature minerals solidified to form the ocean basins on the Earth. The theory then states that the Earth continued cooling, causing more contraction and thus stress on the continental-ocean margins which form mountains and deep sea trenches (Oreskes and LeGrand, 2003). As such, continents and oceans were not interchangeable in Dana's theory, contrasting contraction theory. This implied that the continents and ocean would be comprised of different material (Oreskes, 1999), a correct prediction of the theory.

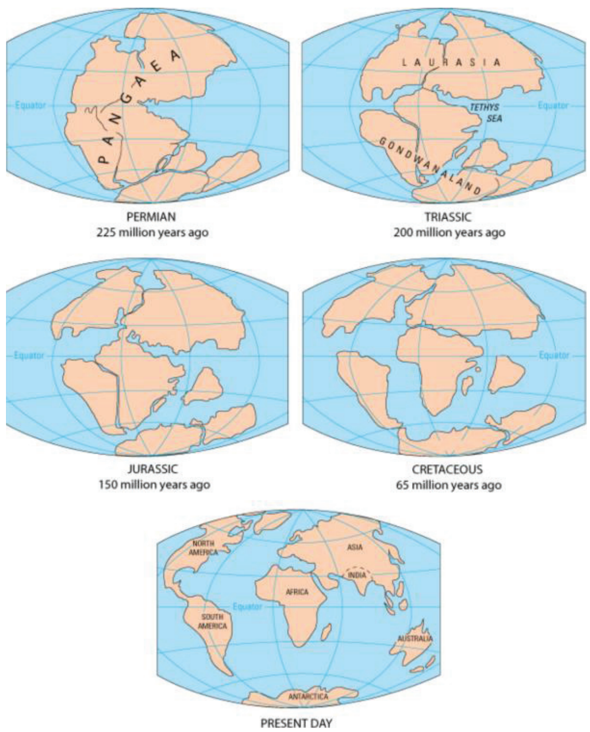


Figure 2.3: *An illustration of the movement of the continents. Beginning with their unification in the supercontinent through to present day arrangement.*

Both permanentism and contractionism provided some valid evidence and explanation of different geologic features. However, the theory of contractionism came under fire in the early 20th century from multiple lines of evidence (Oreskes and LeGrand, 2003). First, the theory states that mountains are comparable to wrinkles on an apple, which were once spread out fat across the surface like a fresh apple. However, field mapping of the Alps showed that the presently folded layers of rock that constitute the alps would extend for hundreds of miles if unfolded. This meant that if contraction theory is true then an almost unreasonable amount of contraction would have occurred to produce the Alps.

Secondly, while surveying India, discrepancies were found in measured distances between two surveying stations. Problems associated with the gravity of the Himalayas interfering with their plumb bobs, a tool used in surveying and construction to determine what is vertical were present. Mathmatician John Pratt (1807-1871) calculated the effect the Himalayas should have on their plumb bobs to compensate for the discrepancy. What he found was that the Himalayas weighed less than they should (Oreskes and LeGrand, 2003). This ultimately lead to the concept of isostasy, the idea that the added mass of mountains above ground level was accompanied by a deficit of mass underneath (Oreskes and LeGrand, 2003). This was reinforced by Osmond Fisher (1817-1914), who in the 1870's attempted to mathematically look at the concept of contraction and found that thermal contraction was not capable of causing observable differences in the elevation of the globe (Oreskes, 1999).

The Continental Drift Theory

The Theory of Continental Drift proposed by Alfred Wegener, states that the Earth's continents were once united, making up a single landmass, a super continent referred to as Pangea (Kious and Tilling, 1994; LeGrand, 1988). Wegener believed that the landmass Pangea broke up into the smaller landmasses Laurasia and Gondwana, which then further broke up into the continents that are present today (**Figure 2.3**) (Kious and Tilling, 1994). He believed that the continents had spread apart over time, drifting through the ocean floor, arriving at their current locations (LeGrand, 1988). Wegener's drift theory was a fairly controversial theory as it opposed two major geological ideas at the time, permanentism and contractionism. Scientists in support of permanentism, believed that the location and configuration of continents and ocean basins were unchanged. While scientists in support of contractionism, known as contractionists, believed that the contraction of Earth's dry land became ocean floor over time (LeGrand, 1988).

Wegener began developing his theory in 1910 while examining a world map and observing the fit of modern continents together. He identified that modern continents could fit together like a puzzle, thus referred to this pattern as the jigsaw fit (LeGrand, 1988). Wegener based his theory especially on the fit of South America and Africa, further developing his ideas by referring to geological structures and fossils across these continents (Kious and Tilling, 1994). He noticed that the plant and animal fossils on coastlines of South America and Africa were identical, suggesting that these continents were once connected (**Figure 2.4**) (Kious and Tilling, 1994). Wegener then began to further examine fossils on continents around the world. Through his research he found fossils of tropical plants within coal deposits discovered on Antarctica (Kious and Tilling, 1994). This further supported his idea of Continental Drift, suggesting that the frozen land mass (currently Antarctica) was once situated in a temperate environment, similar to regions closer to the equator (also referred to as paleoclimatology) (LeGrand, 1988). Wegener further backed his idea through geodetic evidence, examining patterns in the size and shape of the earth (LeGrand, 1988). To explain how these continents had once shifted, breaking apart from a larger united supercontinent, Wegener suggested that the Earth was composed of concentric shells of increasing density from the crust to the core of the Earth (LeGrand, 1988). This suggestion was made as he identified discontinuities between properties of shells, their composition, and changes in pressure and temperature to which these shells were exposed (LeGrand, 1988).

Although Wegener had proposed a great deal of evidence supporting his theory, it was not easily accepted throughout history, ultimately being rejected during his lifetime (LeGrand, 1988). Wegener provided minimal

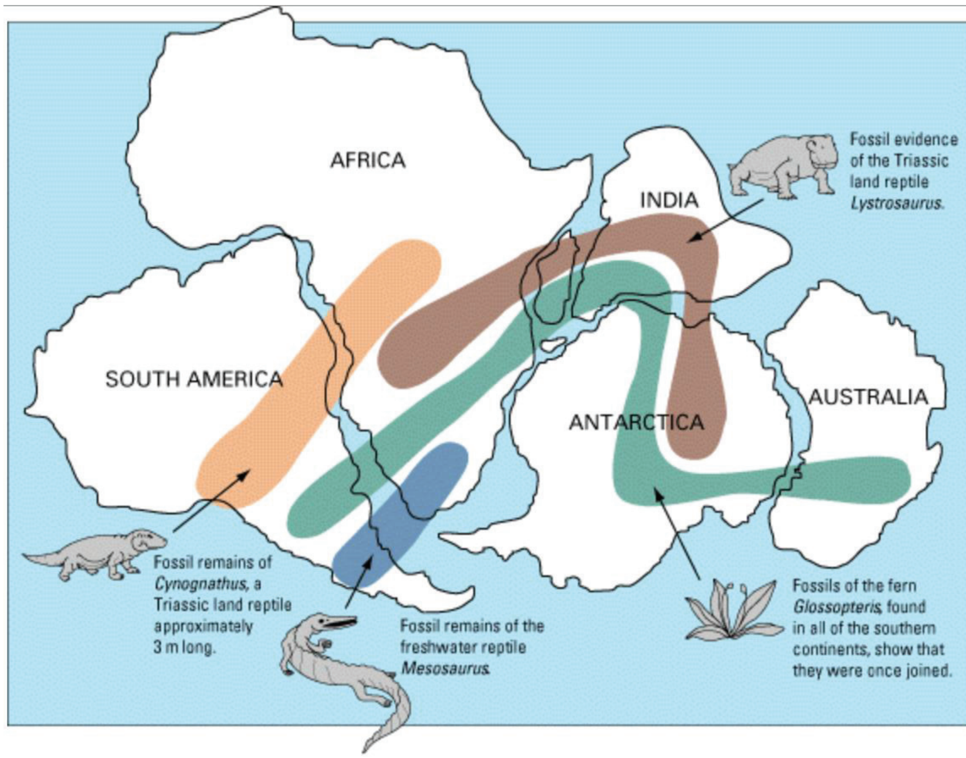


Figure 2.4: *A diagram showing ranges in which similar fossils are found, spanning 5 different land masses. The fossil evidence suggests continents were unified as depicted in the diagram.*

information supporting why and how the continents had moved, reluctant to describe a mechanism by which continents moved through the ocean floor (LeGrand, 1988; Oreskes and LeGrand, 2003). Additionally, he did not discuss how exactly islands and island chains had formed through time, and failed to explain which forces were strong enough to move such large land masses across the seafloor (Kious and Tilling, 1994). Harold Jeffreys (1891-1989), a geophysicist at the time, argued that it was physically impossible for masses of land as large as present day continents to plow through the ocean floor as Wegener had suggested (Kious and Tilling, 1994). The forces he presented were simply too weak to have had any affect on the movement of continents. Furthermore the jigsaw fit was not as great a fit as Wegener had claimed, as it would require some bending for the continents to fit well together. Some would go as far to say that "Wegener violated the scientific method by putting his theory first, without a proper explanation" (Oreskes and LeGrand, 2003). The faults in his scientific methodology therefore lead to a faulty conclusion (Oreskes and LeGrand, 2003).

Wegener's evidence was not as convincing as he had hoped, but it was not the only reason the Continental Drift Theory was rejected at the time (Oreskes and LeGrand, 2003). The theory was an antithesis of all theories and ideas currently accepted in that time period. Rollin Thomas Chamberlin (1881-1948), an opponent to Wegener's theory stated "if we are to believe in Wegener's hypothesis we must forget everything which has been learned in the last 70 years and start all over again" (LeGrand, 1988). Thus this was not an idea scientists could readily accept. Because Wegener could not provide the method by which continents moved, scientists concluded the continents did not move (Oreskes and LeGrand, 2003). From the 1920's to the 1960's scientists therefore proceeded with the Premanentist and Contractionist views (Oreskes and LeGrand, 2003).

Development of the Continental Drift Theory

Although the Continental Drift Theory was initially rejected, the discovery of paleomagnetism (changes in the Earth's magnetic field) in the 1950's provided new evidence supporting Wegener's theory (LeGrand, 1988). Paleomagnetism indicated that the Earth's magnetic field had changed over time, and continues to do so, suggesting that the position of continents were once different from what it is today. However, it was not until the 1950's and 1960's when new light was shed on the Continental Drift Theory, completing the once rejected theory (Kious and Tilling, 1994).

In 1954, Harry Hess (1906-1969) developed the idea of seafloor spreading based on ocean floor mapping conducted by the U.S. Navy (**Figure 2.5**) (Kious and Tilling, 1994). Although scientists were originally fairly certain that the Earth's oceans were at least 4 billion years old, the accumulation of sediment and rock layers of the ocean floor suggested otherwise. Oceanographic surveys of the seafloor found mid-ocean ridges (great mountain ranges on the ocean). Hess determined that Earth's crust was expanding along these mid-ocean ridges, and descending at ocean trenches (Kious and Tilling, 1994). His idea not only explained the little sediment accumulation present on the ocean floor, but provided the mechanism by which continents moved which Wegener's theory had lacked (Kious and Tilling, 1994). Hess' hypothesis was greatly accepted by geoscientists at the time, and was confirmed through modern geological techniques such as seismic data (Silverstein, Silverstein and Nunn, 1998). Between 1967 and 1968, geoscientists further developed the Theory of Continental Drift suggesting that the Earth's outer layer is composed of solid plates which float through the semi-solid liquid mantle below them (Silverstein, Silverstein and Nunn, 1998).

Figure 2.5: *A photograph of Harry Hess wearing his naval captain's uniform. Hess proposed the idea of seafloor spreading.*

Detecting Plate Tectonic Movement

Developed through the 1950's to the 1970's, plate tectonics is a modernized concept formulated from the basis of Wegener's Continental Drift Theory, upon which advancements have been made. This concept suggests that "the Earth is a body in constant motion and change" (Frisch, Meschede and Blakey, 2011). The Earth's outer layer, the lithosphere, is formed by seven large and several smaller fragmented plates. These plates float on the asthenosphere, a semi-solid layer of the mantle, allowing for constant motion of the plates (**Figure 2.6**) (McElhinny, 1973).

Now almost universally accepted, plate tectonics has gained acceptance amongst scientists since its development in the 1970's (Frisch, Meschede and Blakey, 2011). Some geoscientists would even say the importance of plate tectonics to geoscience is comparable to that of Charles Darwin's Theory of Evolution to the biological sciences (Frisch, Meschede and Blakey, 2011). Through various techniques such as a global positioning system (GPS), palaeomagnetism, and seismic tomography, geologists have been, and continue to study the movement of plates through time.

Global Positioning System

Popularized in the 1970's space-based geodesy is one of the most commonly used methods for tracking plate movements today. It measures changes in the position of two points on the Earth's surface to study motion of the earth's plates (Gupta, 2011).

These points are positioned on a set of plate boundaries matched with the same formation on both boundaries (**Figure 2.7**). The San Andreas Fault and the Atlantic Ridge are some examples of these plate boundaries (Kious and Tilling, 1994). The GPS is composed of 21 satellites which orbit the Earth. Signals are transmitted from GPS stations on Earth to a minimum of 3 satellites for an accurate triangulation of position (Dewey et al., 1973; Frisch, Meschede and Blakey, 2011).

Additionally, this system allows for the repeated measurement of distances between two specific points to determine plate movement through changes in distance (Dewey et al., 1973). The exact rate at which continents are movingat the present time can thus be determined by comparing the longitude, latitude, and elevation of two different points over time (Frisch, Meschede and Blakey, 2011). Currently, the fastest rate of plate movement in the world is along the East Pacific Rise, whixh is spreading apart at 15cm each year. Data from thousands of GPS stations are used by geoscientists around the world to study the motion of plates (Gupta, 2011).

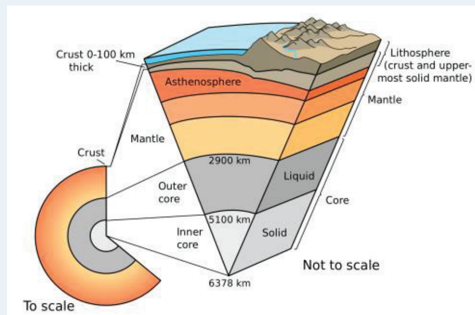


Figure 2.6: *An illustration depicting the various concentric layers composing the Earth.*

Paleomagnetism

Paleomagnetism is the study of the Earth's past magnetic field. From 1968 to 1983 core samples were taken from 624 seafloor sites from the Glomar Challenger, a ship which sailed the world's oceans (Silverstein, Silverstein and Nunn, 1998). Since then, paleomagnetic sampling (using motorized coring drills) procedures have been an important method in the study and understanding of plate movement, dating, and correlation (Gupta, 2011). Geoscientists study the magnetic field orientation within magnetic anomalies of ferromagnetic minerals (iron-titanium oxides), in order to calculate the rate of seafloor spreading at mid-oceanic ridges over time (this confirmed Hess' Seafloor Spreading hypothesis), and thus the rate at which continents were and are continuing to move (Frisch, Meschede and Blakey, 2011; Gupta, 2011). Magnetic minerals present in the lava flows forming at the mid ocean ridge orient themselves parallel with the direction of Earth's magnetic field and are fixed at the time of solidification (below a temperature of 580˚C or the Curie temperature).

Using instruments such as the magnetometer, which measures the strenghth and direction of magnetization in various rock types, the magnetization of mineral samples from various time periods are recorded. (Gupta, 2011). Through these studies geoscientists have confirmed the motion of plates of the lithosphere over time (McElhinny, 1973). Paleomagnetism has also allowed for the creation of geomagnetic polarity time wich record periods of normal and reversed polarity on the Earth (Gupta, 2011).

Seismic tomography

Seismic tomography, a tool developed in the 1980s, has allowed geoscientists to decipher the shroud of mysteries which have surrounded the inner workings and details of Plate Tectonic Theory since it's conception 45 years ago (Tanimoto and Lay, 2000). Seismic tomography is an umbrella term describing a variety of different methods of studying transmitted seismic waves in order to estimate the spatial variation of properties inside the Earth (Gupta, 2011).

Different materials have different densities and as the speed of waves is dependent on the density of the material through which

they travel the medium through which they travelled can be determined from their velocity (Gupta, 2011).

Two common waves employed in seismic tomography are P and S waves. These are both body waves, as opposed to a surface wave, where P is a longitudinal wave and S is a shear wave. Longitudinal simply means the oscillations of particles are parallel to the direction of the wave front, whereas shear means the oscillations of particles are perpendicular to the direction of the wave front (Gupta, 2011). After observing the arrival time of the P and S waves at multiple seismic stations, computations are performed to analyze the raw data provided by seismic tomography to produce the corresponding visualizations of the Earth's interior (T. M. Mahadeva, 1994). Visualizations of the Earth's interior and structure of plates provide important information relating to flow direction of rocks in the mantle and other variables helpful in determining the fine details of how plate tectonics function (Beghein et al., 2014).

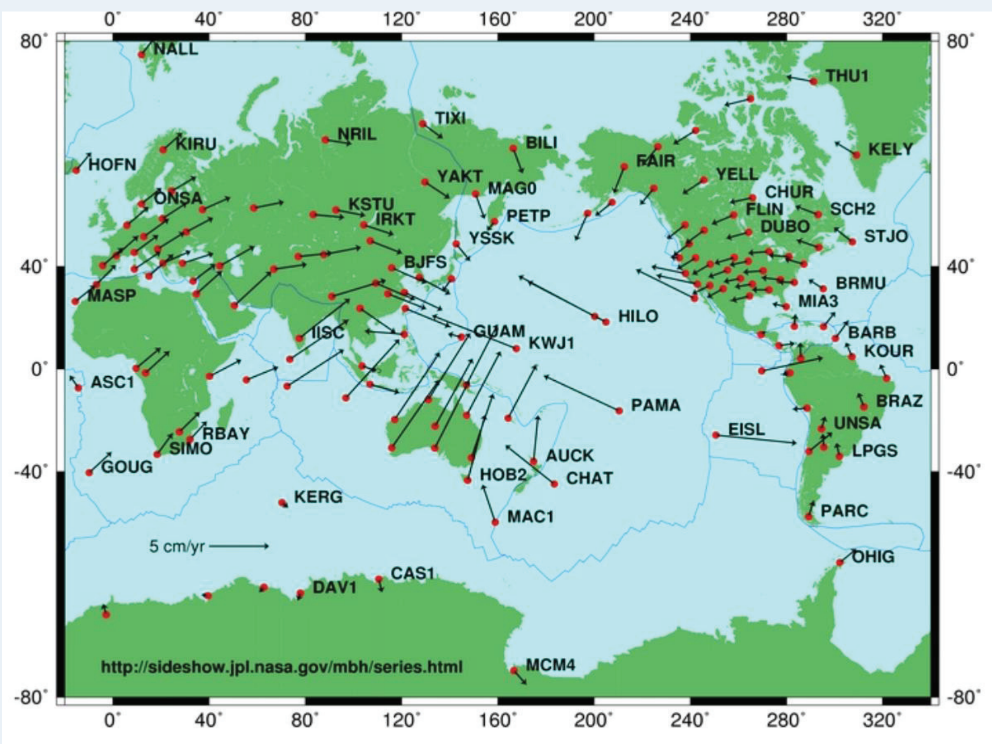


Figure 2.7: *A map of the world overlaid with plate boundaries and plate movement vectors. The size of the plate movement vector arrows depicts the relative magnitude of motion of a point on the Earth's surface relative to other points.*

Seismology and Earthquake Responses

Why Study Earthquakes?

Earthquakes are a natural phenomenon that plague our world. They can be disastrous, resulting in destruction and death. Earthquakes can also result in physical changes to the Earth's surface. They demonstrate that the Earth is constantly changing, that the Earth is dynamic. Furthermore, the destruction and physical changes caused by Earthquakes have been the motivation for humans to understand and explain them. For centuries, humans have studied and explained Earthquakes with the hope of eventually finding ways to prevent and detect them.

Before globalization, information was much less mobile. Hence, the earliest explanations of earthquakes come from individuals living in seismically active regions as it is impossible for someone to explain something that they do not know exists. Throughout this section, you will come across several contributors to the field of seismology. You will notice that the majority of these individuals lived in seismically active regions, such as the Mediterranean, Japan, New Zealand, and California. Simply put, the history of seismology has been greatly influenced by geography.

Figure 2.8: *Japanese painting showing Kashima immobilizing the earthshaker Namazu.*

Earthquake Mythology

In 464 BCE, a powerful earthquake (with an estimated Richter magnitude of 7.2) struck Sparta, Greece, killing about 20,000 Spartans and changing the course of Greek history (Gates and Ritchie, 2007). At the time of this event, the ground would have trembled violently, buildings would have collapsed, debris would have blown through the streets, and people would have been screaming, running, and singing Poseidon's paean. The last of those things may have come as a surprise to you. However, scientifically based explanations for earthquakes are quite modern. The Ancient Greeks believed that Poseidon was the god of earthquakes. They attributed the earthquake that struck Sparta in 464 BCE to Poseidon (Burkert, 1985).

The Maori are the indigenous people of New Zealand. They have been experiencing earthquakes for centuries before European settlement took place, and like the Ancient Greeks, they turned to the gods to explain the shaking of the land. According to the Maori, earthquakes are caused by Ruaumoko, the god of earthquakes and volcanoes. Ruaumoko is the youngest son of Ranginui, the sky, and his wife Papatuanuku, the Earth. He was sent to Rarohenga, the underworld when his brothers turned their mother over while he was still at her breast. In Rarohenga, Ruaumoko was given fire for warmth and comfort. However, he became angry with the upper world, using *aki Komau* (fire under the surface of the Earth) to cause the Earth to shake in attempt to destroy the Maori people (Grapes, 2000).

Japan has a long history of earthquakes as the country overlays the collision zone of four plates: the Eurasian Plate, the North American Plate, the Philippine Plate, and the Pacific Plate. In Japan, mythical explanations for earthquakes prevailed up until 1860 (Bressan, 2012a). The Japanese people believed that earthquakes were caused by Namazu, a giant catfish who is controlled by the god Kahima (**Figure 2.8**). Kahima immobilizes the fish using a heavy capstone. However, when Kahima is not paying attention or is tired, Namazu can wiggle his tail. This causes the land to shake. Furthermore, Namazu was believed to be associated with earthquakes from the late 18th century to the late 19th century. In the late 19th century, it was believed that Namazu caused earthquakes to punish the Japanese people for being greedy. At this time, an earthquake became a sign that the people must redistribute their wealth and Namazu was called *yonaoshi daimyojin*, meaning "god of world rectification" (Bressan, 2012b).

Pleasing the Divinity

Up until the 6th century BCE, explanations of natural phenomenon involved untouchable, divine beings. Earthquakes connected the supernatural and natural worlds, often acting as a way for the gods to communicate with people. For instance, people believed that the gods would shake the Earth to punish them for past wrongdoings. Others believed that the gods would shake the Earth to deliver good or bad omens (Pollard and Reid, 2007; Hine, 2009).

Those who believed that earthquakes were punishment turned to rituals that would please the gods in order to prevent these events. In both the Incan and Greek cultures, the gods needed to be appeased through sacrifice. Further, blood offerings to Poseidon were frequent in Ancient Greece. For instance, Homer wrote of an extravagant sacrifice carried out by King Nestor and his people in his publication *The Odyssey*. Eighty one black bulls were sacrificed and "…the people tasted the innards…" and "…burned the thighbones for the gods." There is also evidence that the Ancient Romans carried out expiatory sacrifices like the Greeks.

In addition to animal sacrifices, human sacrifices were carried out, typically during times of high seismic activity when the people were desperate for relief. The most ancient earthquake-related human sacrifice occurred in 1700 at the Minoan temple of Anemospilia near Knossos, Crete. The only reason we have record of this event is because the victim and three temple functionaries were buried when the temple collapsed during an earthquake. Thus, it is believed that the sacrifice took place just before the earthquake as a response to foreshocks (Nur and Burgess, 2008).

Ancient Greek Philosophy

One of the first people to propose a non-mythical theory to explain earthquakes was the Ancient Greek philosopher Thales of Miletus (620-564 BCE). Unlike those before him, Thales proposed an explanation that attributed earthquakes to mechanics instead of the gods. He believed that the Earth's crust floats on water and that earthquakes are caused when rough waves shake the floating crust. Although his theory is flawed, it is a rational one, since it does not involve hidden entities. His theory does not mention Poseidon, indicating that Thales moved away from the traditional Homeric views of his people. His earthquake theory was revolutionary and it marked the beginning of Western science (Pollard and Reid, 2007).

Following Thales, the Ancient Greek philosophers Anaximenes of Miletus (580-528 BCE) and Democritus of Abdera (460-370 BCE) both suggested that earthquakes occur during times of drought or heavy rains. Specifically, Anaximenes proposed that the surface of the Earth breaks during times of drought and during times of heavy rainfall. When the crust breaks, areas of uplift, such as hills, and subterranean cavities collapse. As a result, the ground shakes. Conversely, Democritus hypothesized that the Earth is full of water. Thus, during a heavy rainstorm excess water is added to the Earth. This water forces its way into subterranean cavities. During times of drought, water moves from the fuller cavities to the emptier ones. Hence, according to Democritus, the movement of water beneath the surface of the Earth results in an earthquake (de Boer and Sanders, 2005; Wilson, 2013).

The theories of Thales, Anaximenes, and Democritus were all documented by Aristotle in his publication *Meteorologica*. In this publication, Aristotle counters the theories proposed by his predecessors and proposes a new theory (de Boer and Sanders, 2005). He states that earthquakes are caused by winds moving quickly and violently through the Earth's crust (Wilson, 2013). Notably, Aristotle's theory prevailed well into the 18th century (de Boer and Sanders, 2005).

Ancient Earthquake Architecture

The time in which architectural adjustments to make buildings more earthquake resistant were implemented varies greatly across the world. Some civilizations had implemented earthquake-resistant structures in ancient times, while others lagged behind until the 20th century. The Ancient Greek, Incan, Italian, and Japanese civilizations were geographically disadvantaged as they were located in seismically active regions plagued with earthquakes. Let's investigate how each of these civilizations responded to the consequences of their geography using architecture.

One ancient civilization that implemented earthquake-resistant structures was the Incan civilization. The Incan civilization was short-lived yet prolific, lasting from the 13th to 14th century (Moseley, 1993). The civilization was located along the Andes Mountains, and was thus subject to a lot of

Figure 2.9: *This picture shows some of the remarkable architecture that still stands at Machu Picchu today.*

seismic activity. The Incans built with stone, a rigid material that is not very earthquake resistant. Yet, the Incans made some important choices with their architecture in order to increase the resistivity of their stone structures. For instance, they did not use mortar when constructing their buildings. Instead, they finely carved stones, so they fit together tightly without mortar (Moselely, 1993). The lack of mortar made the buildings more flexible during earthquakes as the stones could move without compromising structural integrity (Ferrigni, 2005). This method of construction has been very successful as many of the buildings built by the Incans still stand today despite being subject to numerous earthquakes (**Figure 2.9**).

Unlike the Incans, the Ancient Greeks constructed structures made of heavy rigid stone which were not earthquake resistant. During earthquakes, these structures were known to collapse, crushing those inside (Chappell, 2015). This is likely what led the Greeks to rely heavily on expiatory sacrifices.

Figure 2.10: *This pagoda is part of the Horyu-Ji temple, it was built in 607 AD and still stands today.*

Interestingly, the earthquake-resistant architecture of the Incans was exceptional. Most civilizations did not strive to build structures that could resist earthquakes before the 20th century (Reitherman, 2008). If there was a response to an earthquake before this time, it was in a small area and quickly forgotten (Ferrigni, 2005). For example, in San Lorenzello, Italy, the windows and doors were built in two pieces rather than one for a short period. This building practice was learned after the nearby town of Ceretto was being rebuilt after an earthquake in 1688. During the reconstruction, it was discovered that this technique made the fixtures less likely to crack (Ferrigni, 2005). This technique did not spread across Italy and did not even form deep roots in San Lorenzello as cracked doorways are found both prior to and after the earthquake event in Ceretto (Ferrigni, 2005).

In addition to the Incans, the Japanese also strived to build earthquake-resistant structures. In fact, the Japanese highly influence modern techniques of earthquake-resistant architecture.

The Pagoda

Pagodas are earthquake-resistant buildings built by the Chinese and Japanese. They first appeared in Japan in the 6th century BCE. They are fairly large and complex, having several stories (**Figure 2.10**). The sophisticated earthquake-resistant design of pagodas deserves acknowledgement. Moreover, pagodas are built to allow the parts of the building to be flexible. In both Chinese and Japanese pagodas, the roofs and stories are not rigidly attached to the main structure. This allows the building to sway which helps to dissipate energy during an earthquake (Ferrigni, 2005).

These structures are often not credited for their earthquake-resistant properties due to the difficulty in their modelling. The progression of earthquake architecture was based around rigid structures rather than flexible structures (Reitherman, 2008). Thus, the mathematics and modelling are not fit to model flexible and irregular structures, such as pagodas. Due to these limitations, there is not a mathematical basis that these structures can resist earthquakes well. Despite this, these buildings have survived hundreds of years through several major earthquakes.

Pagodas, although sturdy and beautiful, were very expensive to construct. Thus, for smaller homes, the Japanese made simple wood structures that were very cheap and easy to rebuild (Ferrigni, 2005). Wood is a relatively light material. Hence, if these buildings collapse, they would not cause significant damage to the residents. This combination of flexible materials and simple structures is characteristic of ancient earthquake-resistant architecture. In addition, ancient civilizations that experienced frequent earthquakes often adopted building practices if they were successful. Thus, they learned and developed practices through a sort of trial and error method.

Japanese Seismological Advances

Moving into the 20th century, earthquake-resistant architecture gained major attention around the globe. The forerunner in this area of research was Japan. Japan was far ahead of its time in terms of seismology, building codes, and engineering. Building codes were not adopted in most countries with major seismic activity until the 1930s. Yet, Japan had already instituted building codes by the turn of the century (Reitherman, 2008).

One of the first major breakthroughs in seismology research was the development of more precise seismographs. These were absolutely essential in order to improve our understandings of earthquakes. Without seismographs, calculations of seismic loads would have been greatly diminished. The common countries associated with the advancement of the seismograph are Japan, Italy, and Scotland. However the Scottish scientists made their advancements working in conjunction with Japanese scientists (Reitherman, 2008).

With the advancement of the seismograph, cutting edge engineering techniques soon followed. In the early 20th century, the work in Japan laid the foundation for modern engineering practices. What was seen in Japan during this time period was the application and development of mathematical theorems to describe earthquakes and building stress. The most prevalent theory used to describe seismic activity and buildings is the Equivalent Static Force Elastic Method developed by Riki Sano (1880-1956). The World Wars caused a diversion of resources after major periods of innovation in seismology. Despite this, Japan is still seen as being one of the leaders in seismological research (Reitherman, 2008).

Plate Tectonics

Our current understanding of earthquakes stems from our understanding of plate tectonics. Plate tectonics is the theory stating that the Earth's outermost layer, or lithosphere, is divided into several plates and that these plates move through time (Plummer et al., 2007). The first person to propose that the lithosphere was dynamic was Alfred Wegener, who was discussed in the previous section of this book. Further, the acceptance of plate tectonics allowed scientists to better understand where and why earthquakes occur. Most seismic activity occurs on or near plate boundaries, the place where two plates interact; the plates can either slide past each other (transform plate boundary), crash into each other (convergent plate boundary), or move away from each other (divergent plate boundary) (Plummer et al., 2007). Hence, plate boundaries are areas where there are large amounts of stress and strain. Stress is a geological term that refers to the pressures that a rock may be subject to. Whereas, strain is a geological term that describes the deformation a rock undergoes when it is subject to stress (Plummer et al., 2007). In addition, without plate tectonics, there would be no way to accurately describe how earthquakes occur as the current model relies on the movement of the lithosphere to produce stress and build strain. This will be discussed in more detail below.

Faults and Earthquakes

On March 26, 1872, an earthquake struck the region of Owens Valley, California. The earthquake produced an initial powerful shock which threw down houses, killing many. Lone Pine, California was greatly affected by the earthquake; twenty-one people perished and the town was flattened (Gilbert, 1883). Eleven years after the earthquake, American geologist Grove Karl Gilbert (1843-1918) visited the site of the fault (**Figure 2.11**; Davidson, 1927). His visit resulted in his paper "A Theory of Earthquakes of the Great Basin, with a practical application," which provides a brief description of the seismology of the Great Basin area, proposing a theory to explain earthquakes produced by orogeny, or mountain building (Gilbert, 1883; Davidson, 1927).

Figure 2.11: *American geologist Grove Karl Gilbert in 1906.*

In his paper, Gilbert identifies that mysterious forces are responsible for the vertical movements that build mountains. He also describes the faults of earthquakes. In the Great Basin, Gilbert noticed that the Earth's crust fractures at a particular place and that the land on either side of the fracture behaves differently. On one side of the fracture, the crust lifts up, whereas on the other side, it either sinks or stays fixed. Gilbert proposed that the lifted side is the mountain building side. He also defines a fault to be a fracture in which orogenic movement occurs and a fault-scarp to be the cliff created by the vertical displacement along the fault (Gilbert, 1883).

Gilbert further describes the forces responsible for orogeny and the earthquakes produced by orogeny. He states that there is resistance to the upward growth of mountains; the friction between rocks of the two sides of the fault. Then Gilbert calls upon the physics of friction, specifically the coefficient of static friction, to describe the sudden movement along a fault during an earthquake. He explains that strain along the fault builds over time until it is great enough to overcome the friction between the two surfaces. Once the strain overcomes the friction, sudden displacement takes place (an earthquake), relieving the strain. The earthquake is followed by a long period where no movement occurs. This is the period when the strain slowly accumulates (Gilbert, 1883).

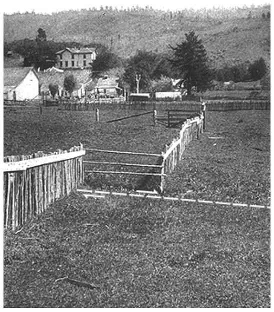


Figure 2.12: *A fence crossing the fault that ruptured during the California earthquake in 1906 can be seen in the image on the right. The arrows indicate the displacement that occurred along the fault during the earthquake.*

Gilbert's paper is significant as it was the first piece to describe that movement along a fault is characteristic of earthquakes (Committee on the Science of Earthquakes, Board on Earth Sciences and Resources, Division on Earth and Life Studies, 2003).

The Elastic Rebound Theory

The widely accepted theory explaining the phenomena of earthquakes is the Elastic Rebound Theory which was developed by Harry Fielding Reid (1859-1994), an America seismologist and glaciologist, in 1910 (Reid, 1910). Reid developed his theory as he was investigating the California earthquake of April 18, 1906. He observed that during an earthquake sudden movements take place near the fault-line and that mysterious external forces causes these movements (**Figure 2.12**). Reid proposed that these forces produce elastic strain in the rocks along the fault. Strain is elastic when the deformation of the rocks is no permanent; the rocks will return to their original shape after stress is removed. Moreover, Reid proposed that this strain is released suddenly when rupture occurs. He coined this sudden release "elastic rebound" (Reid, 1910; Plummer et al., 2007). Moreover, rupture along the fault occurs when the strain exceeds the strength of the rock. The time of rupture is when the earthquake occurs (Plummer et al., 2007).

The Elastic Rebound Theory is very similar to what Gilbert wrote about in his paper "A Theory of Earthquakes of the Great Basin, with a practical application". However, by describing the rocks as elastic, Reid was able to explain what he observed, which was that the rocks on either side of a fault return to their normal shape after the stress was removed and the strain was relieved.

Earthquake Prediction

The acceptance and understanding of plate tectonics has lead us to conclude that earthquakes cannot be prevented. We cannot prevent earthquakes by appeasing the gods simply because they are not the cause. Therefore, since prevention is not possible, today's scientists focus on earthquake prediction.

The modern era of scientific earthquake prediction dates back to Gilbert's 1883 paper. In his paper, Gilbert describes the earthquake of 1872, mentioning that the only homes in Lone Pine that survived the earthquake were made of wood. Hence, the town was rebuilt using wood exclusively. Although this is a logical response, Gilbert did not believe that it was necessary.

"They [the people of Lone Pine] may, indeed, feel feeble shocks propagated from earthquakes centering elsewhere, but in their own locality the accumulated earthquake force is for the present spent, and many generations will probably pass before it again manifests itself…The spot which is the focus of an earthquake (of the type here discussed) is thereby exempted for a long time. And conversely, any locality on the fault line of a large mountain range, which has been exempt from earthquake for a long time, is by so much nearer to the date of recurrence…"

Here, Gilbert touches on the idea of earthquake prediction, stating that earthquakes are less likely to occur at a segment of a fault that has recently ruptured (Gilbert, 1883). This is the basis for The Gap Theory. The Gap Theory uses past earthquake history to make long-term earthquake predictions. It states that if a portion of a fault has been inactive for a long time, then that portion represents a seismic gap that needs to be filled in by an earthquake. As the time since the last earthquake increases, the gap grows in size and needs to be filled in by a larger earthquake (Hough, 2010).

Moreover, The Gap Theory only offers a relative prediction. It tells us that the earthquake is more likely to occur tomorrow than it is today. So, how do seismologist determine an absolute time? By studying the history of earthquakes in a particular area and the rate at which strain builds along a fault, earthquake predictions for a particular time span can be made. For instance, for the past 150 years, earthquakes of Richter magnitude 6 occur along the segment of the San Andreas fault that runs through the town of Parkfield, California about every 22 years (Aki, 1995). It is therefore reasonable to assume that it takes about 22 years for the amount strain accumulating along the fault to surpass the strength of the rock, resulting in rupture. We can predict that future Parkfield earthquakes will occur about every 22 years. However, predictions like this do not always hold true. If faults are clocks, they are not the type you would want to rely on to wake you up each morning as they can be quite unpredictable and very sensitive. The clock of one segment of the fault can be thrown off by the clocks of other nearby segments. When an earthquake occurs, relieving strain at one segment of the fault, it may increase strain at another segment, putting the clock of this other segment forward (U.S. Geological Survey, 1995).

Despite this, earthquakes have been successfully predicted in the recent past. For instance, the Richter magnitude 7.3 earthquake that struck Haicheng, China on February 4, 1975 is believed to be the first earthquake that was accurately predicted using scientific reasoning. An evacuation of the city was ordered after reports of unusual observations, such as changes to the elevation of the land and foreshocks, which were interpreted as precursor events. The earthquake resulted in 2,041 fatalities. However, it is estimated that over 150,000 people would have died if no evacuation was ordered (U.S. Geological Survey, n.d.). Unfortunately, not all earthquakes are preceded by precursor events (Main, 1999).

"It is useless to ask when this disaster will occur," writes Gilbert in his paper. Gilbert goes on to write that people do not know enough about the Earth to offer precise earthquake predictions (those with a precise date) (Gilbert, 1883). Moreover, science still cannot precisely predict earthquakes. For instance, when large scale earthquakes occur, they seem to occur suddenly and without warning, and as a result, they are often deadly events (Main, 1999). Let us not forget the Richter magnitude 7.8 earthquake that hit Nepal on April 25, 2015, killing upwards of 8,000 people (**Figure 2.13**; U.K. Government, n.d.). Currently, efforts are being made to improve the precision, accuracy, and reliability of earthquake prediction. The Parkfield Earthquake Experiment has been studying earthquakes in Parkfield, California since 1985. The goal of this experiment is to determine a scientific basis for earthquake prediction (Langbein, n.d.).

Figure 2.13: *Destruction caused by the Richter magnitude 7.8 earthquake that struck Nepal on April 25, 2015 can been see in the image on the left.*

At the end of "A Theory of Earthquakes of the Great Basin, with a practical application," Gilbert mentions that the only approach society will take to earthquakes is a reactive one. He says that it is not reasonable for people to rebuild their towns of wood as earthquake prediction is unreliable (Gilbert, 1883). Although Gilbert wrote his paper over a century ago, his words still relate to present time. Society aims to take a proactive approach, and precautions, such as earthquake-resistant structures, are in place in many locations. However, due to the unreliability of earthquake prediction, as well as the inaccessibility of precautions (primarily due to financial reasons), society has yet to become fully earthquake resistant (Carroll, 2010). In addition, when predicting an earthquake, the goal is to be able to specify three things: a high probability, a location, and a year (U.S. Geological Survey, 1995). However, doing this has proven to be a challenge as Gilbert's belief that people do not know enough about the Earth still holds true. Although there is ongoing debate regarding whether or not reliable earthquake prediction is a realistic scientific goal, it is evident that earthquake prediction is important (Main, 1999).

A Historical Perspective on the Study of Volcanoes

The phenomenon of volcanic eruptions is one that has fascinated scientists for centuries. Over time, different theories regarding volcanism have come in and out of favour - ranging from mythological stories to scientific hypotheses. In addition, volcanic craters have been extensively studied, and those findings, among others, can be applied to studying volcanoes on other planets.

Volcanoes in Mythology

In ancient times, volcanoes were thought to be caused by gods and angry spirits. In Roman mythology, the god Vulcan was said to live inside a forge in a volcano, causing eruptions as he forged arrows, armour and lightning for other gods (Fisher, Heiken and Hulen, 1998). According to legend, Vulcan would terrorize people with fire, lava, and explosions. To try to appease his anger, once a year the Roman people would have ceremonies at which they would perform ritualistic sacrifices. The Roman philosopher Virgil (70 BCE-19 BCE) also wrote that Mt. Etna in Italy was the location of the underground prison holding Titan Enceladus as punishment for disobeying gods, and volcanic eruptions were caused by him trying to break free. The ancient Greeks believed that Zeus buried giants underneath mountains, and their breathing was responsible for volcanic activity (Fisher, Heiken and Hulen, 1998). Many early cultures around the world considered volcanoes as entrances to the underworld, inhabited by evil forces; Christians believed that volcanic material was produced in Hell and that eruptions were punishments for sin (Marti and Ernst, 2005).

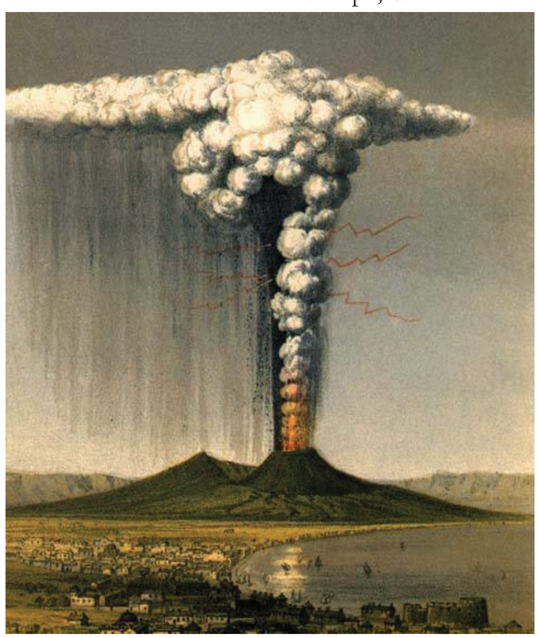


Figure 2.14: *The eruption of Mt. Vesuvius in October 1822, as seen by George P. Scrope.*

Volcanic Eruptions

After traveling around the world to study volcanoes and other geological phenomena, George Poulett Scrope (1797-1876) in his work *Considerations on Volcanos*, chronicles his account of volcanic eruptions. He describes the time leading up to the eruption as having earthquakes in the region, caused by lava swelling and expanding from heat underground, and forcing passage through rock strata (Scrope, 1825). Loud detonations can be heard as the mountains crack and split to allow the lava to escape. According to Scrope, within the chasm of the volcano the lava at extremely high temperatures will bubble and boil, rising and falling until it swells and explodes upwards. The force of the lava launching upwards shatters any rock fragments that may be in the way, creating a shower of lava and rock (**Figure 2.14**). The lava will cool in the air and fall to the ground and solidify as scoria (Scrope, 1825). John Wesley Judd (1840-1916) recounts the sight of a volcano at the time of eruption as being surrounded by a grey cloud of vapour and smoke, referring to the ash emitted from the volcano (Judd, 1881).

Causes of Volcano Formation and Eruption

Over the years, several theories have been put forward attempting to explain the nature of volcanoes. For ages it was believed that volcanoes were chimney-like channels connecting the Earth's surface to its centre

(Hartwig, 1887). The centre, which was thought to be composed fire, would heat and liquefy subterranean earth, forming lava. This was first proposed by the Greek geographer Strabo (64 BCE – 24 CE), who theorized that volcanoes are open craters through which fire can ascend, venting vapours and releasing pressure so that the entire Earth would not experience violent earthquakes (Hartwig, 1887). In this way, volcanoes can be thought of as points of relief, or safety vents, preventing pressure from building too much. This basic theory was widely accepted for centuries, although modified slightly by different scientists. Scrope believed that the heat of the Earth's core would cause the molten lava to expand until the pressure would force it upwards, breaking through the Earth's surface (Scrope, 1825). James Dwight Dana (1813-1895), after studying volcanoes in the Hawaiian Islands, theorized that volcanoes are fissures in the Earth, the points at which liquid interior will accumulate and escape outwards (Dana, 1891). Although Dana was in agreement with the mechanism of Strabo's original statement, he contested the idea that volcanoes were "safety vents" as there was no proof that eruptions were responsible for any decrease in earthquakes. In fact, he said that it was quite the opposite since earthquakes often occur in conjunction with volcanic activity, and as such a more appropriate term would be "indexes of danger" (Dana, 1891)

There have been several theories on the formation of volcanoes themselves. One such theory is called the Elevatory Theory. It was put forward at the start of the 19th century by both Humphry Davy (1778-1829) and Leopold von Buch (1774-1853), saying that volcanic eruptions contort and raise the rock strata previously deposited in horizontal layers (Hull, 1892). It was thought that as the lava expands, and pressure from below would cause it to rise up and push through the sediment layers, altering the previously horizontal shape to form a sloped one (Hull, 1892). This theory was contested however, by Scrope and Lyell, who argued that if it were the case, then the base of all volcanoes would be highly cracked and fissured, which is not observed (Hull, 1892). Scrope believed that volcanic mountains were formed from the deposition of volcanic material (Scrope, 1825). He said that at a new volcanic vent, the lava would force its way through horizontal rock strata, leaving a mound of rock fragments and solidified lava (Hartwig, 1887). After subsequent eruptions, the products of the eruption would continue to accumulate, eventually forming a mountain (Hartwig, 1887). This theory was further supported by Judd, who contributed that it would also explain the formation of craters at the peak of volcanoes (Judd, 1881). The volcanic material erupts upwards, depositing in largest quantities around the edges of the crater, then dipping downwards (**Figure 2.15**). This is because the weight of the dense lava building up will cause the summit of the volcano to sink (Judd, 1881).

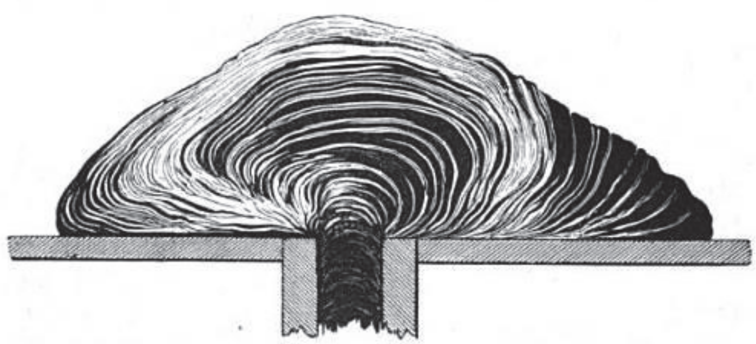


Figure 2.15: *A volcanic cone formed by the eruption of lava.*

Presently, it is known that volcanoes form as result of tectonic plate movement. At a divergent boundary, where volcanic plates are moving apart, rift valleys form (Plummer et al., 2007). Magma from the Earth's molten core can make its way up to the surface at these rift valleys, creating lava flows. At a convergent boundary, an oceanic plate collides with and subducts under a continental plate, forming mountainous volcanoes. As the oceanic plate descends into higher temperature environments, it begins to melt and form magma chambers, which result in volcanic eruptions when they reach the surface (Plummer et al., 2007). Plate tectonic theory was first put forward Harry Hess (1906-1969) and John Tuzo Wilson (1908-1993) as a way to explain the movement of continents (Pullman et al., 1978).

Volcanic Craters

Located at the peak of a volcano is the crater, which contains the volcanic vent. At an active volcano, the crater is constantly changing as ejected volcanic material accumulates around the sides (Hartwig, 1887). The size of a volcanic crater can vary, but generally the bottom of the crater forms a relatively horizontal plain surrounded by high rock-walls, formed from products of eruption (Hartwig, 1887). Craters may also take on a funnel shape, with steep sloping sides descending into the vent of the volcano (Hartwig, 1887).

A History of Meteors and their Origin

The identification of falling rocks to have come from outside of Earth is one that was made well into the past, since the time of the early Egyptians. In fact, it was the Egyptians that were first to suggest rocks were capable of being cast down from the heavens by the gods (Baldwin, 1978). This belief extended well into early Biblical times, as the Bible quotes that God had cast down great rocks from Heaven onto the enemies of Joshua (The Bible, Joshua 10:11). Despite this belief being widely accepted, it was not until the late 18th century that these claims had actually been substantiated with evidence.

Figure 2.16: *A drawing of the Hraschina meteorite from the fall in Hraščina, Croatia. These types of falling objects were the focus of Chladni's studies.*

E. F. F. Chladni (1756-1827) is often considered to be one of the forefathers of the study of meteors and meteor impacts (Sears, 1975). His work started in the late 18th century and helped pave the way for the research that would pick up at the start of the 19th century. Chladni's research considered specifically falling stones and "native irons", which are now known as iron meteorites (**Figure 2.16**). He was one of the first scientists to suggest that these rocks were of extraterrestrial origin (Marvin, 1996). His main reasoning for this hypothesis was due to the physical appearance of these rocks. They all appeared to have been exposed to high temperatures and pressures, but were located in regions far from volcanic or tectonic activity. Since these meteors were found in regions lacking volcanic or tectonic activity, Chladni rightfully suspected that those meteors were not formed in the locations where they were found (Sears, 1975; Marvin, 1996).

As the century drew to a close, Chladni employed the assistance of chemist Edward C. Howard (1774-1816) and mineralogist Jacques-Louis Bournon (1751-1824) to help determine if the chemical composition of these proposed meteorites were similar across all samples (Sears, 1975). After performing a chemical analysis, Bournon and Howard had determined not only that the chemical composition was similar across the meteorites and "native irons", but also that these similar characteristics were exclusive to these structures. Specifically, each sample contained high amounts of iron, and more importantly nickel, which are not found in high concentrations in terrestrial rocks (Sears, 1976; Howard, Williams and de Bournon, 1802). Furthermore, chemical analysis showed that the characteristics and chemical composition were similar regardless of where the sample was found on Earth suggesting that the meteorites shared a common origin. Shortly after this discovery, Howard published his results in 1802. In support of Howard's discovery, two of Europe's most prominent and respected chemists, Louis Nicolas Vauquelin of Paris (1763-1829) and Martin Heinrich Klaproth of Berlin (1743-1817), published results they had obtained independently identifying the same findings (Sears, 1975).

These publications sparked discussion among scientists regarding the source of these extraterrestrial meteors falling to Earth. A year after Howard's publication, French scientists Jean-Baptiste Biot (1774-1862) and Pierre-Simon Laplace (1749-1827) had proposed the origin of these meteors was ejecta falling to Earth from lunar volcanic eruptions (Sears, 1975; Baldwin, 1978). This theory was very popular at the time due to the amount of evidence both on Earth and the moon which appeared to support the claim. The chemical structure of the meteors identified by Howard and Bournon suggested that these meteors had been formed under high temperatures and pressures. At the time, the only known processes capable of producing temperatures and pressures high enough to create these structures were volcanic eruptions. Furthermore, it is likely that the observation of active volcanism on the moon in 1787 by William Herschel (1738-1822) helped generate the basis of this theory (Herschel and Banks, 1787). Lastly, an episode of falling rocks in Sienna, Italy in 1794 coincided with the eruption of Mt. Vesuvius, thus providing a logical source for falling rocks to be ejected from (Sears, 1975; Marvin, 1996). It was also around this time that scientists proposed the craters on the surface of the moon were formed from lunar volcanic eruptions. With this theory in mind, it was not a wide stretch to propose that some craters on Earth were formed by a similar mechanism.

Despite the wide acceptance of this theory, not everyone in the scientific community agreed with this hypothesis. Although some attempts of alternate hypotheses were made, none were taken seriously. It was not until 1829, when Franz von Paula Gruithuisen (1774-1852) proposed that lunar craters were caused by impacts with meteors rather than volcanism, that discussion among the scientific community restarted (Baldwin, 1978). However, this suggestion was quickly dismissed with the publication of *Der Mond* by N. Beer (1797-1850) and J.H. Madler (1794-1874) in 1837. Due to the extensive detailing of lunar surface features included in this book, the public and scientific community started to retreat from the study of the moon as it appeared to be completely analyzed by these scientists (Baldwin, 1978).

Impact Craters versus Volcanic Craters: The Great Debate

Much like the debate regarding crater origins on the moon, the origins of terrestrial craters were also argued among scientists. It was the identification and study of Meteor Crater in Arizona (**Figure 2.17**) in the late 19th and early 20th century which marked the pivotal point in the history of this debate. Analysis of the crater started in 1891 by Dr. Albert Foote (1846-1895), who discovered two main abnormalities when looking at the crater. First, he noted that although the crater appeared to look as if it came from a volcanic explosion there was no evidence of igneous rocks in or around the crater (Gilbert, 1895). Only sedimentary sandstone and limestone were present. Second, he noted the crater was associated with high amounts of iron which, as determined previously, is associated with extraterrestrial meteors. For this reason, Foote proposed that the iron present at the crater was from a meteor shower raining iron meteorites across the area, with one meteor significantly larger than the others (Gilbert, 1895). Foote's results piqued the interest of Grove Karl Gilbert, who had two theories of his own he wanted to test regarding the crater's origins.

Figure 2.17: *An aerial view of Meteor Crater in Arizona. The diameter of the crater is approximately 1,200m and the depth is approximately 170m (Barringer, 1905). Barringer performed extensive analyses on the rocks and ejecta of the crater to determine whether this crater was formed by a meteor impact.*

Once Gilbert arrived at the crater, he went to work collecting data. He suspected that the crater was formed in one of two ways: (1) the impact of a celestial body or (2) an explosion from the build-up of steam beneath the Earth's crust from volcanic activity (Gilbert, 1895). If the crater had celestial origins, then the volume of sediment ejected from the crater onto the surrounding land would be greater than the volume of the crater since parts of the impacting object would have remained inside the crater. If the crater was formed by explosion, then the volume of sediment removed would be equal to the volume of the crater. Gilbert also suspected that if the crater was indeed formed by an impact event, then it would contain high amounts of iron which would produce magnetism and generate local magnetic anomalies (Gilbert, 1895). After collecting his data, Gilbert found that no local magnetic variations existed within the crater and that the sediment ejected was the same volume as the crater. These findings caused Gilbert to reject the collision hypothesis (Gilbert, 1895).

Shortly after this conclusion, Daniel Barringer (1860-1929), unsatisfied with the result, ventured out to Meteor crater to conduct his own tests. He arrived at the same conclusions regarding rock composition as previously stated. To Barringer, this meant that the likelihood of the crater being formed by volcanism or a steam explosion was severely decreased (Barringer, 1905). This was namely due to the fact that no lava or igneous rocks were present in or around the crater. Furthermore, the crater was surrounded by a few very large boulders which were likely too heavy to be thrown the great distances they were by a volcanic eruption. Barringer argued that only the top layers of sediment were ejected from the crater, which would not have happened with a volcanic or steam event (Barringer, 1905). Barringer also noted the lack of fissures and cracks in the surrounding ground that would have been caused by the steam explosion, as well as the unlikelihood of one great steam event which was inactive before and after this single crater formation event.

Figure 2.18: *A shatter cone structure from the Charlevoix impact crater in Quebec. These formations have become the gold standard in identifying impact craters from volcanic craters as these exclusively form under high pressure conditions.*

Barringer believed that the evidence he found supported the impact crater theory so greatly that he was bold enough to say "this crater could have been made only by an extraterrestrial body falling out of space and moving at great speed" in his published results in 1905 (Barringer, 1905). His main supporting fact was the presence of iron and nickel rich meteoritic rocks both surrounding the crater, in the crater basin, and most importantly, below the surface of the crater. Despite this mound of evidence, Barringer's findings were rejected by the scientific community.

Although the theory regarding impact events forming terrestrial and lunar craters was not accepted as soon as it was proposed, scientific evidence supporting this mechanism and the identification of more impact craters slowly surfaced since 1905 (Baldwin, 1978). Barringer continued researching the mechanisms behind impact craters, and his work with ballistics helped substantiate the shape of Meteor crater and the distribution of its ejecta as coming from an impact event. Specifically, he noted that shooting a rifle bullet into mud at high velocities, even at oblique angles, resulted in a near spherical crater with ejecta distributed in the same manner as Meteor crater (Hoyt, 1987).

Shortly after this, the first proposals of high velocity impacts causing an explosion event as meteors hit Earth's surface were made by Ernst Opik (1893-1985) in 1916 and Franklin Gifford (1861-1948) in 1924 (Baldwin, 1978). This theory sparked research into replicating impact events using explosives. In 1968, work with explosives confirmed this hypothesis as detonations of TNT generated craters with similar structures to those generated by suspected meteor impacts. Specifically, the discovery of geologic structures known as shatter cones (**Figure 2.18**) were made in this this set of experiments (Roddy and Davis, 1977; Dietz, 1971). This discovery was very important for the ability to distinguish between impact craters and volcanic craters as shatter cones occur exclusively under high pressure impact events and not during volcanic eruptions. Shatter cones were found in a number of suspected terrestrial impact craters, thus allowing the list of identified impact craters to grow. Even today, shatter cones are used to identify impact craters.

Using Earth Analogues to Find Exoplanetary Volcanism

The search for geological processes on other planets has been occurring for many years and shows no signs of stopping any time soon. In the search for tectonic activity on other planets, the calling card has been volcanism – both in the past and present. Since the processes scientists are looking for may no longer be occurring currently, looking for Earth analogues of the resultant geologic structures has been the gold standard for detection. Exploration of other planets began with Mars, likely due to its proximity to Earth. In order to determine whether Earth and Mars shared some common geological processes, NASA sent a series of rovers to Mars to analyze in detail the structures covering the planet's surface.

In 2004, NASA's Spirit rover landed in Gusev Crater on Mars (Squyres et al., 2004). It traversed the crater, looking specifically for signs of water, while taking observations of other geologic structures along the way. One of the most interesting discoveries made was the identification of volcanic structures within the crater. This was especially interesting as the crater was not suspected to contain evidence of volcanism based on satellite images. Analysis of the lava flows showed they were extremely similar to a'a and pahoehoe flows commonly found on Earth (Squyres et al., 2004). Scientists were then able to deduce that volcanic activity was likely present around the crater in the past, but due to erosion, the source can no longer be identified. This discovery, along with many others, has aided in piecing together the history of Mars.

Although Earth analogues are effective means of identifying exoplanetary volcanism, new detection methods are also being explored. Recently, a group of researchers from Harvard University considered modelling the release of gases from volcanic eruptions on Earth to search for volcanic eruptions on Earth-like exoplanets (Kaltenegger, Henning and Sasselov, 2010). The gas selected for detection was sulfur dioxide (SO_2). SO_2 is one of the most common gases released by volcanic eruptions. Therefore, regardless of the type of volcanic eruption, SO_2 is likely to be produced (Kaltenegger, Henning and Sasselov, 2010). This ensures exoplanetary eruptions are not missed due to a poorly selected identifying molecule. Furthermore, during explosive volcanic eruptions, SO_2 is released into the stratosphere where retention times are longer than at lower altitudes (Kaltenegger, Henning and Sasselov, 2010). This means SO_2 will be present longer before it is removed from the atmosphere, ensuring that proper data is collected regarding the volume of SO_2 released. Lastly, SO_2 is easily identified by looking at atmospheric absorption spectra, thus making it an effective cue to use for identifying volcanism on exoplanets (Kaltenegger, Henning and Sasselov, 2010).

Earth analogues were used to generate a model to determine the change in atmospheric SO_2 levels during a volcanic eruption. In particular, the eruption of Mt. Pinatubo in the Philippines in 1991 served as the basis for the model. The eruption of Mt. Pinatubo released approximately 17Mt of SO_2 into the atmosphere over a 4 day period (Kaltenegger, Henning and Sasselov, 2010). Approximately 170 days later, all of the ejected SO_2 had been removed from the atmosphere by reacting with water to create sulfuric acid.

In order to model more than one eruption type, two model scenarios were developed. The first case assumed a single eruption involving a narrow distribution of SO_2 about 2km in height. The second case involved multiple eruptions over a short time frame which resulted in a wider distribution of SO_2 between 12-25km in height (Kaltenegger, Henning and Sasselov, 2010). Using this model, simulations of exoplanetary eruptions were run in the model to determine the validity of their detection system. They concluded that the model was capable of detecting potential volcanic eruptions based on SO_2 release (Kaltenegger, Henning and Sasselov, 2010). Although the results of true experiments using this model have not yet been published, this method seems to be a promising new study in the field of exoplanetary exploration.

Development of Glacial Theory

There are many geologic features that are studied in depth in order to learn more about the modern world and how the Earth has changed over time. One of the most commonly studied features, particularly in the Northern Hemisphere, is the glacier (**Figure 2.24**). The Arctic landscape, Iceland, and some regions of the northwestern Americas are dominated by these massive formations of ice, constantly moving at rates around one metre per day (Williams, 1998). Their movement and impact have been, and continue to be, studied extensively in countries where they are most apparent (Maizels and Casledine, 1991).

***Figure 2.24**: The Matanuska glacier terminus in Alaska. Modern-day glaciers are an important tool for understanding how the Earth's climate has changed over time.*

Many scientists, dating as far back as the late 17th century, have studied glaciers and worked to develop what is known today as *glacial theory* – the notion proposing that glaciers once occupied the entire face of the Earth. No individual can take total credit for glacial theory's creation and distribution; instead, it is a complex aggregate of contributions whose authors were separated through both space and time.

Early Origins

The framework for glacial theory was laid as early as the 18th century, when a Swiss scholar named Johann Jakob Scheuchzer (1672-1733) discussed glacier formation as the result of accumulation of snow at high elevations in the Swiss Alps. He speculated that they were capable of motion, and further mentioned cracks that formed with booming noise during warmer temperatures (Agassiz, 1967). In 1787, the musings continued when a Swiss minister named Bernhard Freidrich Kuhn (1762-1825) wrote that the Grindelwald glacier had been more extensive sometime in the past. This view was echoed in 1794 by James Hutton (1726-1797), a Scottish geologist who visited the Jura Mountains in Switzerland and remarked that the erratic boulders he saw must have been deposited there by ancient, expansive glaciers (Ben-Menahem, 2009).

1824 saw Jens Esmark's (1763-1839) speculations on glacial theory. A professor at the University of Christiana, he was reluctant to accept the popular scientific opinion of the time that water, not ice, was the medium of transport for large masses such as boulders. He postulated an exposition that refuted water as a possible source of transport for erratic blocks, claiming they were simply too large to be uplifted by the currents of a river. He also showed evidence that glaciers had extended as far as sea level in the past (Krüger, 2013). Esmark's views were known to Reinhard Bernhardi (1797-1849**)**, a German professor who had published papers arguing that the polar ice caps had once spread as far south as central Germany (Imbrie and Imbrie, 1979).

Unification of the Theories

While these early observations were important in underscoring the foundations of glacial theory, their proprietors had no way of advancing any postulations without communicating them to other scientists. Peculiarly, the earliest instance of such a collaboration took place in 1815 by a French mountaineer and trapper named Jean-Pierre Perraudin (1767-1858). He was no scientist, but he hypothesized that the scars and striations on the Val de Bagnes, or Bagnes Valley, were a result of stones embedded in glaciers that had occupied the entire valley in the past. At the present, glaciers were only present at the most northern parts of the valley - Perraudin reasoned that they were the same glaciers that had made these marks in the past, but greatly receded (Kruger, 2013). He detailed his theories to Jean de Charpentier (1786-1855), a German-Swiss geologist in charge of the salt mines in Bex. de Charpentier, though impressed, dismissed Perraudin's ideas on their absence of scientific merit. Disappointed but not deterred, he went on to share his ideas with his friend Ignace Venetz (1788-1859), a cantonal engineer. While Venetz did not outright reject their validity as de Charpentier did, he was still reluctant to accept them. Between 1816 and 1821, he would only discuss Perraudin's ideas as a suggestion that glaciers were simply capable of motion, and not that they had extended to cover a large portion of the Earth in ancient times (Imbrie and Imbrie, 1979).

Challenging Society

In 1821, Venetz underwent something of a revelation as he affirmed his belief in glacial theory. During this year, he wrote a memoir - not to be published until over a decade later in 1833 - discussing ancient glacial motion and its influence on the formation of modern-day moraines (Agassiz, 1967). In 1829, he presented to the Edinburgh Geological Society findings that suggested that immense glaciers had extended from the Alps to cover not only Switzerland, but almost the entirety of Europe. It was this radical affirmation that stirred de Charpentier's faith once more, urging him to reconsider the same theory he had rejected from Perraudin the mountaineer almost 15 years prior (Imbrie and Imbrie, 1979). de Charpentier, initially a skeptic much like Venetz, could not deny the validity of the rising glacial theory when he witnessed firsthand the polished rocks and striations at Val de Bagnes, and further observations of erratic boulders present on the slopes of the Jura Mountains. He, like Esmark, refused to accept that water was a powerful enough medium to transport such massive objects, and came to the same conclusion that they had to have either rode atop or been suspended in glacial bodies (Agassiz, 1967).

Neither de Charpentier nor Venetz possessed the fortitude or aggression to challenge the dominant theory on the transport of erratic boulders and other features suggestive of glaciers. Something of a superpower in the realm of geology, Sir Charles Lyell (1797-1875; see **Figure 2.25**) held authorship of this theory that detailed how boulders could be strewn over such large distances. He reasoned that great masses of rock could be deposited on top of glaciers and icebergs, which would float within ancient lakes and seas. During the widely-accepted event that was the biblical deluge during the time of Noah, the great flood swept the icebergs away and flung their rocky deposits all across the globe in the stochastic disarray seen to date (Lyell, 1970). With staunch academic prowess and both scientific and religious communities lending support, Lyell held firm this theory with an iron grip.

Building Momentum

In 1836, de Charpentier confided the theories of Venetz and himself in his friend, then-ichthyologist Louis Agassiz (1807-1873). Akin to both de Charpentier and Venetz before him, Agassiz was reluctant to believe that present-day glaciers had had greater extents in the past to deposit erratic boulders and other glacial features, let alone cover the entire continent (Bryson, 2003). Nonetheless, he

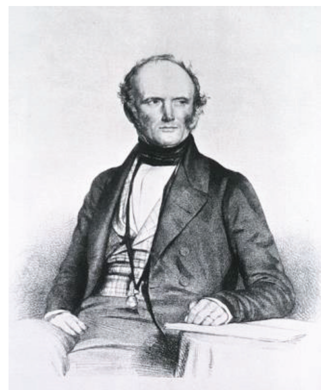


***Figure 2.25**: Charles Lyell (1797-1875) was a renowned geologist of the 19th century, best known for his book Principles of Geology in which he popularised James Hutton's Theory of Uniformitarianism.*

travelled to Bex for a period of five months to study the glacial deposits and evidence with de Charpentier. Shocked by the unmistakable patterns of the erratic deposits, moraine ridges, striations, and paths to the modern-day glaciers, Agassiz returned home to Neuchâtel a born-again believer in the glacial theory. Here, he gave lectures on glaciers during the winter of 1836, and come autumn 1837, he journeyed to the Jura Mountains to observe the boulder-bearing cliffs and polished, striated rocks that served as chief evidence for the theory at the time (Agassiz, 1967).

Agassiz's field studies were with de Charpentier and another colleague named Karl Schimper (1803-1867), a botanist. Schimper, in 1837, was in fact the first to use the term "ice age" - in German, *Eizseit* - to describe a period in the Earth's history when ice sheets and glaciers had overlain not just the Alps, but all of the planet. Not confident enough to present his ideas alone, Schimper gave the notes on his theories to Agassiz to supplement the latter's writings. Over the next several years, Agassiz's publications began to stir the curiosities of the numerous geological societies of the time, but contained no mention of contributions by Schimper or de Charpentier. Left out of some of the most revolutionary research of the century, the two came to develop a great resent for their colleague Agassiz (Bryson, 2003).

Public Reception and Acceptance

Agassiz became possessed by the drive to make the field of glacial theory his own. Leaving all past pursuits behind him, he would proceed to spend the following years undergoing field excursions to various glaciers across Europe, including the Bernese Oberland, the Upper Valais, and the valley of Chamonix (Agassiz, 1967). It would seem that Agassiz chose an opportune time to invest in fieldwork of such great extent, as the concurrent travel back and forth to the Americas provided abundant opportunities for affordable travel. All the while, his observations in the field bolstered the credibility of glacial theory as Agassiz drew increasingly complex inferences of past glacial environments. Chief among these pieces of evidence were the rocky-walled moraines that led like pathways to the modern-day retreating glaciers (**Figure 2.26**), the boulders suspended in rockslides on mountain slopes, and striations that aligned perfectly with retreating glacial trajectories. Perhaps the most significant site of study was the Unteraar glacier, where in 1840 Agassiz established a base camp called "Hotel des Neuchâtelois". Here, he lodged scientists - and even the odd trekker - who wished to see firsthand the evidence of glacial expanses in the past (Lurie, 1966).

***Figure 2.26**: The rocky wall on the left-hand side of the image is a lateral moraine, left behind as a signature of the past movement of the glacier barely visible on the right-hand side of the image. Similar moraines would have been important evidence for proving ancient glacier movement and locations.*

It was this base camp that united Agassiz with some of the greatest contributors to glacial theory. In 1839 William Buckland (1784-1856), dissatisfied with Lyell's popular theory, travelled to Hotel des Neuchâtelois with Agassiz to see the evidence for himself. In tow as well was Charles Lucien Bonaparte (1803-1857), nephew of the infamous Napoleon Bonaparte (1769-1821) - not a scientist himself, Charles had a curiosity for all things natural, and was curious of these glacial features. After Agassiz's tour at Unteraar, however, Buckland wrote to him that he was "as far as ever" from agreeing that glaciers had once covered the whole of the Earth (Imbrie and Imbrie, 1979).

When not in the field, Agassiz was presenting his works to the various geological societies of the time, often to be met with great resistance. The Geological Society of Cambridge, for instance, were especially incredulous to his theories of an Earth covered in ice. In 1840, Agassiz's presentation to the British Association for the Advancement of Science was openly criticized by none other than Charles Lyell (Bryson, 2003). By some strange twist of fate, Buckland was in attendance at the same conference - whether it was Lyell's harsh commentary, or simply seeing the facts in a new light, Buckland realized Agassiz's ideas held great merit, and he became a devout proponent for the glacial theory (Imbrie and Imbrie, 1979). Buckland then took it upon himself to convince Lyell that Agassiz was right - Lyell was at first inconvincible, but Buckland took him to a series of moraines near the Lyell family estate in Scotland. Comparing the position of the moraines to modern-day receded glaciers, Lyell could not deny Agassiz's theories any longer (Bryson, 2003).

Beginning with the support of Lyell, one of the most powerful scientific figures of the time, the following five years saw the solidification of glacial theory. In 1841, the Geological Society of Edinburgh expressed that Agassiz's ideas bore reasonable credibility, the first reputable institute to do so. Agassiz would then travel to America in 1846 to deliver a campaign of lectures on the evidence underlying glacial theory. Harvard University granted him a professorship, as well as constructing a museum in his honor which Agassiz himself would curate until his death in 1873 (Bryson, 2003).

Identifying Causes

Agassiz had obtained the public attention the maturing glacial theory required, but for all the evidence he had compiled suggesting glaciers had covered the Earth in the past, his work failed to give any reason *why* they had done so – and further, why had they disappeared? (Bryson, 2003).

That exact question was posed in an article in *Philosophical Magazine* in 1864, polling its readers for a plausible theory explaining the cause of the major glaciations of the past. Astoundingly, the paper that gathered the most attention from the leading scientists of

Scotland and England was written by a caretaker at the University of Glasgow, named James Croll (1821-1890; see **Figure 2.27**). Croll spent his evenings off of work studying physics, astronomy, and hydrostatics. He employed this self-taught understanding of science in his paper to suggest that subtle changes in the Earth's orbit were cause for the ice ages (Fleming, 2006). He reasoned that the orbit of the Earth changed over time from near-circular to highly elliptical, or eccentric. At this peak of eccentricity, a hemisphere's winter solstice would coincide with the aphelion point – the point furthest from the Sun – of the Earth's orbit, and the winters would be unusually cold and long. Croll postulated that these harsh winters gave rise to feedback mechanisms that disrupted the equilibrium between hot and cold periods - increased snowfall meant more reflected sunlight in the spring, decreased amounts of melted snow in the warm seasons, and the seasonally-indiscriminate accumulation of masses of snow (Hamlin, 1982). With enough snow accumulated, an ice age was a feasible possibility; in this way, the distance of the Earth from the sun had an influence on the present epoch's climate. With a mechanical explanation backing it, the glacial theory began to find more converts across Britain (Bryson, 2003).

The Milankovitch Cycles

When Louis Agassiz died in 1873, there was no one left to publicly propagate the glacial theory, and its popularity teetered on a faltering point. Within only a decade of his death, Agassiz's colleagues at Harvard commented that the glacial theory, which had rang with promise only years prior, now risked being rejected without hesitation and forgotten forever. Furthermore, Croll's computations stated that the most recent of the major glaciations had occurred 80,000 years prior, but field observations contradicted this with evidence that there had been glacial disturbance much more recently (Bryson, 2003). This dangerously implied that either Croll's astronomical theory was incorrect, or the glacial evidence upon which Agassiz had based his theory was.

For the second time, the glacial theory now risked rejection from the scientists upon whom it depended for its validity. 1912 saw the theory's salvation in the work of Milutin Milankovitch (1879-1958), a Serbian scholar of interdisciplinary backgrounds. On reviewing Croll's calculations and works, Milankovitch found them "remarkable". However, he intended to pursue the discrepancies in the glacial theory with the approach of understanding climate in general. Milankovitch noticed that Croll's calculations

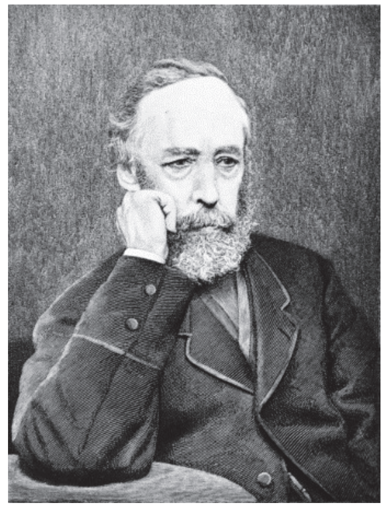


Figure 2.27*: James Croll (1821-1890) was a caretaker at the University of Glasgow, and taught himself principles of physics and mathematics during his evening hours. With little scientific background, he published an impressive paper detailing the influence of minute changes in the Earth's orbit on climate.*

lacked accuracy in their information regarding energy transfer from the Sun to the atmosphere - information that Milankovitch had learned about in the past half-century since Croll initially written his works. He was ready to begin his work (Macdougall, 2006).

Milankovitch began to work tirelessly on computing the inbound solar radiation at various latitudes of the Earth, accounting for variances in the Earth's obliquity, precession, and eccentricity, and used this network of variables to determine ancient temperature cycles (Macdougall, 2014). The beginning of World War I in 1914 might at first have seemed a hindrance to Milankovitch, a Serbian army reservist, but in dissenting to serve he was placed under loose house arrest - in the library of the Hungarian Academy of Sciences. Here, he toiled away on his calculations and manuscripts, described later as "possibly the happiest prisoner of war in history" (Bryson, 2003). His manuscript would be published after the war's end, in 1919.

A prominent German scientist named Wladimir Köppen (1846-1940) saw the relevance of these calculations in understanding changes in climate. Milankovitch's calculations predicted temperatures throughout the past 130,000 years, but Köppen needed more data to calibrate the calculations with the multiple glacial advances and retreats of the Pleistocene Ice Age. He asked Milankovitch to extend his calculations back 600,000 years, but restricted to 55˚ and 65˚ of northern latitude to focus on regions with the most abundant glacial evidence (Macdougall, 2014). After three months of rigorous calculation, Milankovitch delivered his graphs reflecting cyclic changes in temperature at 10,000-year intervals above and beyond the extents Köppen had specified. The oscillations in temperature were in perfect agreement with the glacial advances and retreats suggested by coordinated sets of field evidence from existing glaciers gathered by scientists too numerous to count. They were also in agreement with a glacial timeline produced by Albrecht Penck (1858-1945) and Eduard Brückner (1862-1927). Milankovitch came to refer to these period oscillations as Milankovitch Cycles. Thrilled with the results, Köppen published these graphs with due credit to Milankovitch in his book *Die Klimate der geologischen Vorzeit* (Climates of the Geological Past), which he co-authored with Alfred Wegener (1880-1930). This publication brought Milankovitch, and the glacial theory, worldwide prominence (Macdougall, 2006).

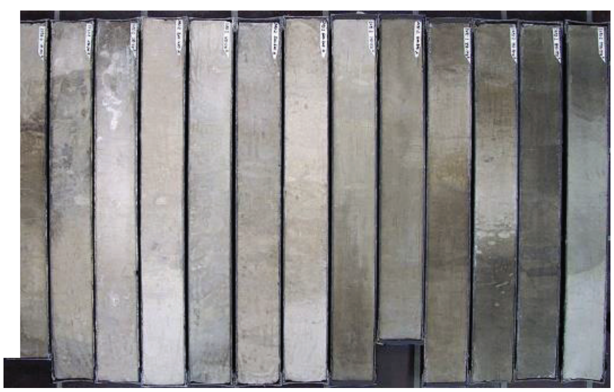


***Figure 2.28**: Deep-sea sediment cores from the Southern Atlantic. The changes in colour across the cores indicate changes in water temperature, a key piece of evidence used to validate the Milankovitch Cycles.*

The Theory's Final Test

After Milankovitch's death in 1958, several discoveries would give the glacial theory its final test: regions thought to record glacial records contained fossils incompatible with a cold climate, and the glacial timescale authored by Penck and Brückner was found to be inconsistent with other field evidence (Macdougall, 2006). Some of the European glacial deposits whose dates aligned the most spectacularly with Milankovitch's glacial cycles were found to not be glacial deposits at all, calling into doubt the primary evidence on which the theory was based (Macdougall, 2014).

The final saving grace of the glacial theory would come over a decade after Milankovitch's death, from the depths of the ocean. Geologists began to consider that ocean-floor sediments, which were presumed to accumulate very slowly over the millenia, might give inference to the Earth's ancient climate (Macdougall, 2006). The 1970s afforded the technology to extract deep-ocean rock cores that extended millions of years into the past (**Figure 2.28**). High-resolution studies of these cores indicated oscillating records of fossils found to exist in either cold or warm climates, as well as temperature records inferred from isotopic oxygen ratios. The records were found to align perfectly with the glacial cycles proposed in Milankovitch's model, with periods of 100,000, 41,000, and 23,000 years. Following precisely his variations in obliquity, precession, and eccentricity, this evidence solidified the climatic periods predicted by the Milankovitch Cycles – the final piece to the puzzle of glacial theory (Macdougall, 2014).

With empirical closure from the works of Milankovitch, Croll, and Köppen, the framework of the glacial theory laid centuries earlier by the likes of Scheuchzer, Kuhn and Hutton came to dissolve into an elegant mosaic that gave sagelike insight into the environments and climates of the past. While oscillations in orbital patterns aren't the sole influence of ancient and modern climates – other factors, such as geographic morphology and its influence on weather patterns – they were able to prove that the Earth was once a much colder place. In concurrence with the evidence of past glacial activity gathered by Agassiz, de Charpentier, Venetz, and others, it could no longer be refuted that the ancient Earth was home to a host of massive glaciers, spanning unimaginable distances across the modern continents. As modern science develops increasingly precise methods of dating ancient cores, the understanding of past environments and climates can only improve. New breakthroughs in glacial theory might still be decades away, or they might be right around the corner. Whatever the future brings, it is safe to say that the development of glacial theory is far from over.

Receding Glaciers

It has been discussed at great lengths how scientists formulated hypotheses about glacier dynamics and deposition based on their observations. It was decided in the 19th century that glaciers had been much more prevalent in the past, particularly in Europe and North America. Scientists, such as those previously discussed, found records of ice sheets covering North America and much larger glaciers in the Swiss Alps that dwarfed the glaciers of the 19th century. In the present day glaciers have receded even further, due mainly to a changing climate. A fine instance of this is Mt. Kilimanjaro in Tanzania, Africa. Over the past two hundred years, the glaciers on the dormant volcano have been steadily retreating. This retreat has been seen to coincide with glacial retreat at mid to low latitudes as well. Incredibly, it is possible that within the next forty or fifty years, there will no longer be any glaciers left on Earth (Thompson et al., 2009).

Identifying and Observing Retreats

Most of the glacial retreat on Kilimanjaro has been attributed to the rapid change in climate in Africa, particularly in the last ten years when over a quarter of the glacial area was lost. This was observed using satellite imaging, a much more sophisticated and accurate technique than the labour-intensive field observations performed during the time of Agassiz. It has been speculated that the rising tropical temperatures are not the only factor responsible for this glacial retreat - other changes in climatological and meteorological factors have been recorded as well, such as precipitation levels, solar radiation, and air temperature. When observing plateau glaciers on Kilimanjaro, climatologists concluded that the melting of these specific types of glaciers was a result of solar radiation rather than more indirect climate changing factors (Cullen et al., 2006).

The glaciers on the west coast of North America are being faced with different environmental conditions and changes compared to the glaciers of Kilimanjaro. On the west coast, in areas such as Washington and British Columbia, glaciers were mostly receding during the first half of the 20th century. Unlike Kilimanjaro, there was a period of relatively rapid glacial advancement in 1945 due to increased snowfall in the winter, and cooler temperatures in the summer (Meier and Post, 1962). The advance and retreat of these glaciers does not determine whether or not they will survive or disappear. Glaciers can reestablish equilibrium even if their terminus is rapidly retreating, as long as the area of the accumulation zone is sufficiently high, where accumulation zone thinning is less than half of the cumulative mass balance. (Pelto, 2010). Tracking glacial advance and recession in the Pacific Northwest, as well as other temperate alpine regions such as the Alps and Iceland (**Figure 2.29**), is of irrefutable importance. As valuable indicators of temporal changes in climate, glaciers provide information about the changes the Earth is experiencing.

***Figure 2.29**: A receding glacier in Southern Iceland. Field sites such as this are invaluable to climatologists and geologists when studying changes in climate and temperature, even over short time scales.*

Utility of Receding Glaciers

Changing climates and glacial retreat have been recorded throughout history, following cyclical periods on the order of tens of thousands of years. The Milankovitch cycles are used to predict these changes and, in light of a rise in global temperatures and worldwide glacial retreat, it would seem that the Earth is moving deeper into its current interglacial period, the Holocene. It is difficult to study the effects of climate change on glacial retreat due to the relatively short lifetime of humans, especially when compared to the timeline of large geologic events. Nonetheless, the snapshots of the present climate afforded in a human lifetime, paired with a seamless record of the planet's past conditions, are invaluable tools for understanding what the Earth's future will bring.

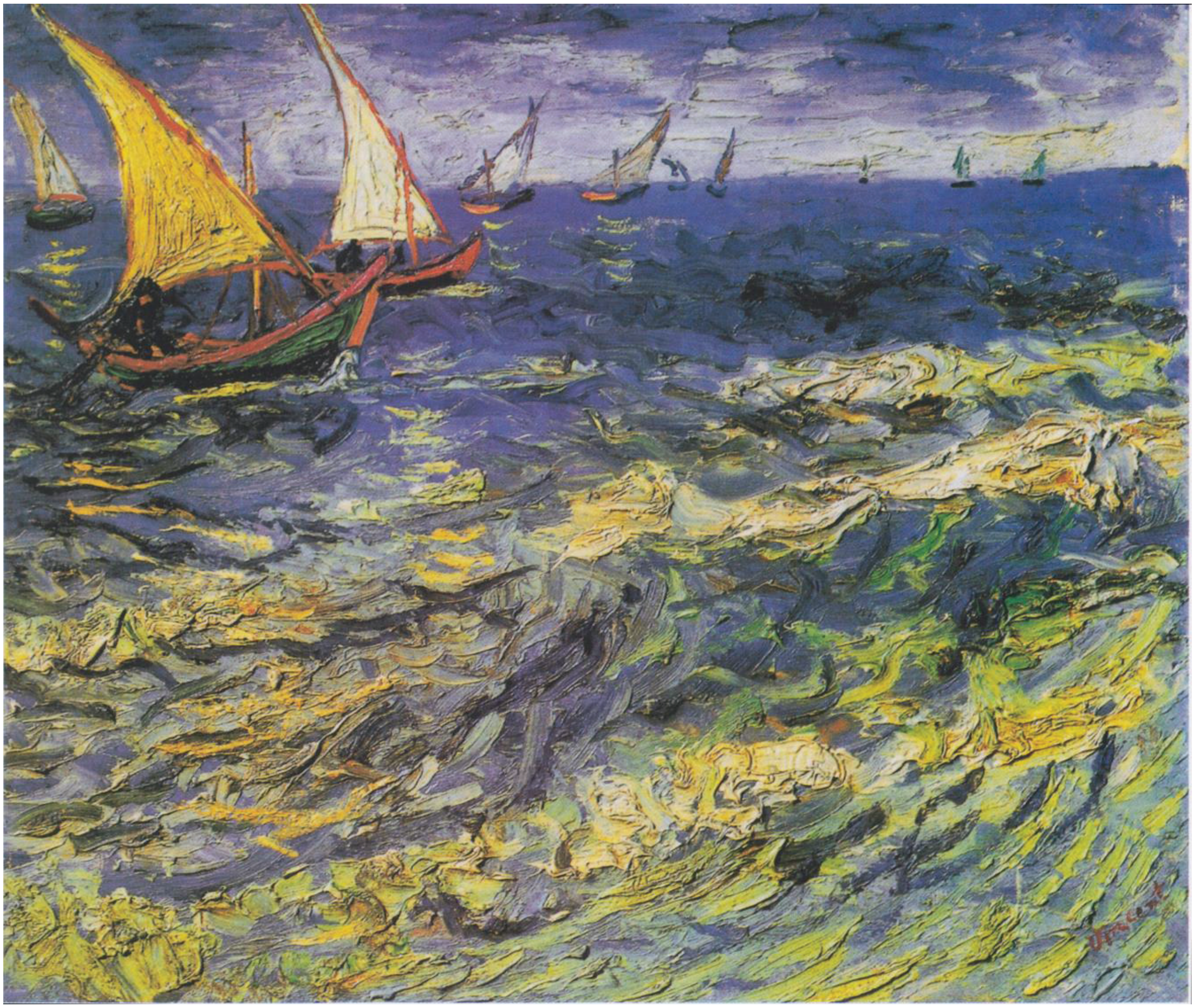


Figure 3.1: *Van Gogh's "Fishing Boats at Saintes-Maries", highlighting humanity's fascination with the Earth, its seas and the sky*

Chapter 3: From Sea to Sky – Exploring and Categorizing

The thirst for knowledge about the Earth is a pursuit that grew alongside the development of the human race. The oldest recorded writings by humans indicate that there was always a need to know more about the planet that humans inhabited. Since the Earth provided countless venues for investigation, and the human race's curiosity was unbounded, various scientific disciplines were created over the course of history.

Humans strived to explore and classify the Earth they experienced on a daily basis. The oceans, which provided food and transport passages, held unknown depths of discoveries below the surface, which human knowledge conquered. The Earth's magnetic field provided direction for explorers, despite the lack of knowledge of geomagnetism – this understanding took centuries of experiments to develop. Humans also sought to analyze the materials of the Earth and the processes associated with them, initially relying on philosophical hypotheses. Alongside with knowing about the current world they lived in, humans wanted to classify the Earth's past, and developed methods of dating material to achieve absolute ages. However, this absolute dating method would not have been possible without the understanding of the properties of materials. Investigation into these properties began with the classification of the physical Earth, such as classifying rocks and minerals. Deeper understanding of the properties of materials came with the development of technological means and scientific experimentation. Further, human exploration and classification did not stay on the Earth's surface but rose to the heavens. The force of weather was easy to observe but hard to predict; despite this, humans noted the patterns of weather and attempted to forecast them.

Scientific method grew from centuries of observation, analysis, thought and hypothesis. Humans still try today to better understand the planet Earth by continually experimenting and investigating the various aspects of it. Although successes and failures have contributed to a, thus far, good understanding of the Earth, many more success and failures are still to come in order to have a slightly better understanding of the Earth.

Oceanography and Exploration

Be it romantic or scientific, humanity has held a fascination for the ocean since its earliest days. To the ancients, the ocean was an impenetrable boundary, encaging man to *terra firma*. This seeded an awe manifested and immortalized in mythos. Through millennia of advancement, humanity has succeeded in breaking through its confines, exploring the extents of the oceans. Despite this, man still retains the ancients' sense of wonder, with continuing expeditions seeking to uncover what other secrets the deep holds.

The Ancient World

Oceanography, the branch of Earth Sciences involved in the study of the ocean and its characteristics, is often indicated to have started with Matthew Fontaine Maury's (1806-1873) 1855 treatise, *Physical Geography of the Sea* (Lyman, 1964; Charlier, Gordon and Gordon, 1980). It is nevertheless important to acknowledge the contributions leading up to the birth of this science, free of the lens of "prescientific", to accurately recount the subject's evolution of thought.

Figure 3.2: *The world according to Homer. Note the "*Oceanus Fluvius*", which translates as "Ocean River", surrounding the three known lands.*

Early reflections on the ocean were largely mythological in nature. Much of it was grounded in fear of the unknown and uncontrollable – storms were the wrath of deities and sailors stayed wary of "sea monsters" such as the Scylla and Charybdis of Greek mythos (Hamilton-Paterson, 1992; Charlier, Gordon and Gordon, 1980). Theology provided an anthropocentric basis for mapping. Shown on **Figure 3.2**, Homer (c.1000 BCE) described the Earth as a flat disk centered on the Mediterranean with the three known lands – Europe, Asia, and Africa – surrounded by the impenetrable ocean (Taylor, 1928; Charlier, Gordon and Gordon, 1980). This theological basis re-arose with Medieval Europe's *mappa mundi*, highlighting "Paradise" to the East (Taylor, 1928).

More rational thought was brought up by the Greek scholars as they tried to recount the origins of the oceans and how water is cycled to maintain constant water levels. Plato (c.427-c.347 BCE) suggested the existence of an ocean in the centre of the Earth, from which water flowed out onto rivers and returned through oceans. Aristotle (384-322 BCE) rejected this, agreeing with a previous theory by Anaxagoras (c.510-c.428 BCE) stating that water is recycled through the atmosphere via evaporation and condensation into rainfall (Vetter, 1973; Deacon, 1971). Where Anaxagoras had theorized that salt was washed from the Earth to the sea, Aristotle replaced with a "dry exhalation" similar in nature to water vapour, thus producing the saltier rains in the south away from the Mediterranean. All these ideas remained accepted until experiments performed in the Renaissance provided conclusive results (Deacon, 1971).

Aristotle created various more theories on marine science, unique among his contemporaries (Deacon, 1971). Much of these are recounted by Strabo (c.63 BCE-c.24 CE), a later Greek scholar. Strabo himself had done significant studies, discovering the erosional actions of rivers, nature of sediment transport to the oceans, as well as giving explanation for the tendency for civilizations to grow on coastlines (Charlier, Gordon and Gordon, 1980). Apart from the Greeks, however, few scholars focused on the importance of the sea (Waldman and Cunningham, 2004).

It is not coincidental that the first recorded studies made about the ocean are from Classical maritime civilizations, such as the Phoenicians, Carthaginians, and Greeks (Lyman, 1964). The Chinese and the Polynesians also rank among the first seafarers, but little of their information has survived to modern day (Charlier, Gordon and Gordon, 1980). These coastal societies have been the dominant forces in both trade and scientific advancement – as ocean travel increased in importance, motivation for maritime study increased. While few scholars apart from the Greeks busied themselves with maritime matters, seamen of all cultures had developed navigational practices, making practical use out of theory. This early era of sea discovery stalled with the rise of Rome and its large focus on landward expansion. Other seafaring civilizations had existed, such as the Norse, but they had not put to record much scientific knowledge (Charlier, Gordon and Gordon, 1980).

The Enlightenment

The revival of ocean-based exploration during the fifteenth century, with the goal of increased European trade with the East, ushered in another age of oceanographic study. Starting with Prince Henry the Navigator (1394-1460), who established the Maritime University of Portugal, various more institutions dedicated to maritime studies were built (Charlier, Gordon and Gordon, 1980; Lyman, 1964). The school also served as a repository for sea charts and any oceanographic data collected by Portuguese captains, giving Portugal the knowledge to become the first enlightenment-era sea power (Charlier, Gordon and Gordon, 1980). The rise of piracy and competition with other European colonial powers, however, forced oceanographic information into secrecy (Lyman, 1964).

Since much of the impetus for oceanographic research during this era was for economics, discoveries dealt little with the nature of the ocean itself; rather, they were involved in the practical utilization of the ocean. Major advancements included Gerardus Mercator's (1512-1594) map projection, which simplified navigation, and Christopher Columbus' (1451-1506) usage of ocean currents to reduce voyage time (Charlier, Gordon and Gordon, 1980). The routes chosen for his voyages to the "Indies" shows that Columbus knew of the existence of the Gulf Stream, though his explanation for its existence was largely speculative rather than scientific (Lyman, 1964; Deacon, 1971). Thereafter, ocean drifts and currents supplemented winds in the sailor's tools.

More scientifically motivated data collection occurred later, pioneered by James Cook (1728-1779). On his voyages, he brought along a staff of biologists and chemists to make observations on characteristics of the sea, primarily temperature measurements and specimen collection.

The 19th Century

The oceans once again became the focus of scientific curiosity, as interests shifted away from utility to admiration of nature itself (**Figure 3.3**). This was the era of large figures in the new scientific field of oceanography, the pioneering two being Matthew Fontaine Maury and Edward Forbes (1815-1854), the first physical and biological oceanographers respectively.

Figure 3.3: *Illustration from Jules Verne's* Twenty Thousand Leagues Under the Sea*, published 1870, showing the era's romantic fascination for the deep.*

Using a deep-sea dredge invented by Johannes Muller (1801-1858), Forbes studied samples up to 600 meters deep in the Aegean Sea on 1841, using them to differentiate eight depth classifications (Charlier, Gordon and Gordon, 1980; Vetter, 1973). He noticed that species diversity decreased in lower depths, leading to speculation of a boundary around 550 m deep below which life cannot exist, dubbed the azoic zone (Vetter, 1973). Although Forbes himself was skeptical, this received popular support from the community due to its connection to temperature measurements taken by Sir James Clark Ross (1800-1862) that showed the deep is uniformly 4°C (Charlier, Gordon and Gordon, 1980). This finding was thought to mean that, in addition to the lack of light and near-freezing temperatures, the deep was also stagnant, having no convection currents to circulate suspended food and oxygen. Thus, this depth was thought to be inhospitable, overlooking the starfish specimen Ross had dredged during his expedition (Hamilton-Paterson, 1992). Both ideas remained relatively accepted until 30 years after, when Wyville Thomson (1830-1882), in a single voyage of the HMS

Bulldog, recorded water temperatures below 4 °C as well as surfacing biota from 4.5 km deep (Vetter, 1973; Deacon, 1971).

The promise of life in places previously thought inhospitable piqued interest in biological oceanography. This was just after Charles Lyell's *The Principles of Geology* (1830), and Charles Darwin's *On the Origin of Species* (1859) were published, bringing up notions of evolutionary missing links being present in the deep (Lyman, 1964). Factors thought to have made such depths sterile were now speculated to hold living fossils, unchanged since fish left water (Hamilton-Paterson, 1992). Dredging expeditions were funded, seeking the creatures that laid in the abyss. Forbes himself, as was Thomas Henry Huxley (1825-1895), was interested in the primordial ooze that was the origin of life, believing to have found it when he had preserved a sample of sea floor in alcohol (Waldman and Cunningham, 2004; Hamilton-Paterson, 1992).

Maury, by comparison, focused little on the biology of the sea, and was more pragmatic with his study of the ocean. He was largely concerned with the application of oceanographic discoveries, lending his efforts with Cyrus West Field (1819-1892) to the laying of trans-oceanic communications cables from 1857-1866. Much of the research was used in his *Physical Geography of the Sea*, which, despite lacking in scientific rigour – having an indefinite line between fact and speculation in addition to missing citations – was largely influential in progressing oceanographic research (Charlier, Gordon and Gordon, 1980).

The Challenger Expedition

The voyage of the HMS *Challenger* is well-known as the first major oceanographic expedition (**Figure 3.4**). Funded by the Royal Society, partly for political reasons, and partly to progress the four facets of oceanography – physical, chemical, geographic, and biological – it sailed from 1872 to 1876, regularly taking a wide range of data such as sea floor depth, temperature, pressure, salinity, among others (Waldman and Cunningham, 2004). Such a vast amount of information had been taken that it took 23 years to compile and publish the final report, totalling 50 volumes (Waldman and Cunningham, 2004). This data was able to clarify much of the disputes present in oceanography at the time, primarily involving the evolutionary nature of deep sea life. Both theories of abyssal life had been disproven – it was neither sterile nor was it a time capsule of prehistoric life. Instead, it was found to contain species far evolved from fossil specimens, with specializations to live in such an environment (Lyman, 1964). Additionally, it found no primordial ooze, instead discovering that the substance found by Forbes and Huxley to be the calcium sulfate precipitate from the reaction of sea water with alcohol. Finally, it rejected the theory that portions of the crust periodically moved up and down, switching between oceanic and continental crust, by showing the chemical distinction between sea oozes and surface chalk, which had been thought to be their remains (Hamilton-Paterson, 1992; Waldman and Cunningham, 2004). This was to the dismay of the biological community, who had attributed the similarity of fossils over various continents to previously uplifted land bridges – it was not until Alfred Wegener's continental drift that an alternate theory was put forward.

Figure 3.4: *The HMS* Challenger *(right), a pioneering expedition in the field of Oceanography.*

Diving Technologies: Submarines and Wartime

Oceanography is a field greatly connected to the development of technology for the exploration of the sea. Like much of early oceanographic sciences, however, most of this development was driven by political and practical purposes, rather than purely for the pursuit of scientific discovery. Ships were developed both for trade as well as war – the latter of which persisting until the latter half of the 20th century. After the Challenger Expedition, the next major step for underwater exploration would be to develop vessels with strong diving capabilities, but retain the mobility of a ship. This would make exploration and recording much more flexible, and at first appearance, it would seem that a vessel that could move underwater at will would be a great asset to scientific endeavours. Unfortunately, the image of this idea, the submarine, was not as well-used by science as one would think. Instead, the submarine would quickly lend itself to military applications and the development of what could be a gem of scientific deep-sea exploration would be almost entirely through the context of war.

The first submarine to be constructed was designed by Cornelis Drebbel (c.1575-1633) in 1624, which was manually powered by oars and achieved depths of 4-5 metres, but was not driven by any particularly useful reason aside from advancing technology (Polmar, 2015). The next major advancement in submarine technology was already related to its application in wartime. During the American Revolution, David Bushnell (1754-1824) invented a submarine that he called "the Turtle" (Roland, 1977). The submarine itself was still manually powered, but the main distinguishing feature was that it was equipped with a drill that was intended to pierce ship hulls and plant gunpowder charges in the holes (Roland, 1977). The submarine ended up unable to pierce the copper on the bottom of the ship hulls, but still represents a major milestone that brought the idea of submarines to be synonymous with war over exploration or science (Roland, 1977).

From here, submarines continued to be used in wartime with extremely limited success. The development of other types of power – steam, electricity, and diesel – led to the development of much more mobile and practical submarines, and torpedoes and mines improved alongside them (Polmar, 2015). At this point, the development of practical submarines was highly political and many nations took keen interest in these crafts, primarily for the purpose of warfare. Leading up to World War I, interest in submarines grew rapidly and the standard design of the submarine soon became based off John P. Holland's (1841-1914) design (Polmar, 2015). This design featured propellers powered by an electric motor while underwater, and a diesel engine while above water to allow the electric motor to recharge (Polmar, 2015). Attached were several guns and a torpedo tube to ensure that this submarine was not only fast, but also dangerous (Polmar, 2015). This design was highly successful in producing a submarine with practical use in warfare, with the basic design being used well into the 20th century (Polmar, 2015).

The invention of sonar would seem to be a large boon for submarines in the context of scientific exploration, but, again, this was not the case. Because of their use in wartime, submarines rarely employed active sonar and instead elected to use passive sonar. Active sonar sends a sound wave signal and measures the time it takes for this wave to bounce back to reveal the location of various objects, while passive sonar simply listens and identifies the approximate location of noisy objects (NOAA, 2014). As submarines required stealth in wartime, the less reliable but silent passive sonar was employed almost exclusively (NOAA, 2014). As a result, submarines could only identify moving objects and objects that vibrated or generated sound. This limited their use oceanographically, so the much less stealthy warships that used active sonar were the ones that led to major oceanographic discoveries such as Henry Hess' (1906-1969) theories on seafloor spreading in the 1960s (Vine and Hess, 1968).

Thus, although submarines in theory would have been the ideal method of studying the ocean in and before the 20th century, history has proven otherwise. Shortly after their inception, people saw greater potential in their applications to destruction rather than discovery, and this idea has mostly stuck in modern times.

Bathyspheres and Deep-Sea Life

Although submarines were not as prevalent in science as one would hope, deep-sea exploration during their advancement did not stop. This exploration tended, however, to be less focused on bathymetry, the measurement of ocean depths, and more on discovery. From 1930 to 1934, William Beebe (1877-1962), a marine biologist, and Otis Barton (1899-1992), an engineer, succeeded in performing several successful dives off the coast of Bermuda to observe deep-sea ocean life in their natural habitat (Ballard and Hively, 2002). These dives repeatedly broke the record for the deepest dive performed by a human (Ballard and Hively, 2002).

The bathysphere was effectively a steel sphere, with the shape maximizing structural stability under intense pressure (**Figure 3.5**; Ballard and Hively, 2002). A quartz window and a simple light bulb were used to make observations of sea life below the twilight zone (Beebe, 1933). During their dives, they recorded detailed observations of sunlight penetration in deep waters, which agreed to calculations they had performed using the Einstein-Smoluchowski theory for light scattering in liquids (Beebe, 1933). The temperature gradient was also recorded both inside and outside the bathysphere during the descents using an ordinary thermometer (Beebe, 1933).

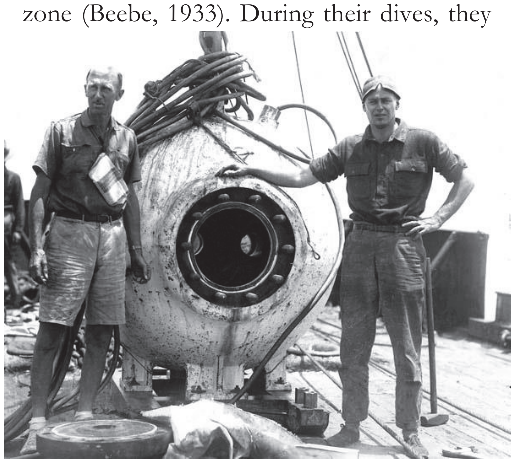


Figure 3.5: *William Beebe (left) and Otis Barton (right) standing in front of their bathysphere before a dive.*

From a biological perspective, the bathysphere allowed for some striking observations of deep-sea life. Several species of fish were seen to possess photophores – organs that fluoresce in deep waters. Some observations were startling as trawling the same specimens showed no fluorescence on the surface. Additionally, a careful record was made identifying fish seen from the surface to 2,200 feet below sea level. Finally, trawling records were compared to Beebe's quantitative observations and it was revealed that trawling fails to capture the larger and more mobile fish, demonstrating that trawling should henceforth only be able to be used as an estimate of deep-sea fish populations (Beebe, 1933).

The bathysphere proved to be a milestone in deep-sea exploration and investigation. It would go on to inspire the creation of bathyscaphes and other submersibles for the advancement of the field of oceanography and marine biology.

The Deepsea Challenger

The history of deep-sea exploration has always been synonymous with both geography and the sciences – particularly life science. The development of the bathysphere began to lead deep-sea exploration into the world of science rather than geography, and developments in the latter half of the 20th century served to affirm this transition. Developments such as sonar made measuring seafloor depths a trivial matter, allowing underwater exploration to focus on other discoveries. Thus, undersea bathyspheres and later bathyscaphes would be developed mostly for studying marine life and sediment formations at shallow ocean depths. In 1960, the bathyscaphe *Trieste* became the first manned vessel to reach Challenger Deep at the bottom of the Mariana Trench – the deepest known part of the ocean on Earth (Schrope, 2012). The pilots were, however, unable to collect samples or do much more than simply observe the fish they claimed to have sighted, although scientists are now quite sceptical of their observations (Gallo et al., 2015).

Deep-sea exploration took another step forward in 2012 with the voyage of the Deepsea Challenger. Piloted by Canadian movie director and experienced deep-sea explorer James Cameron (1954-), the Deepsea Challenger dove to Challenger Deep, but this time vessel was much more prepared for conducting science (National Geographic, 2015).

The Design

The Deepsea Challenger was designed by both James Cameron and Ron Allum (1949-) and possesses a narrow, capsular design (**Figure 3.6**). The shape is intended for hydrodynamic efficiency in diving and surfacing, which allows for quicker rescue if something goes wrong, and otherwise allows more time to be spent on the seafloor (WHOI, 2015). The pilot's chamber is a sphere within the cylinder due to the shape's inherent structural stability under pressure (National Geographic, 2015). A bank of lights above the submarine illuminates the seafloor while HD cameras capture the scenes and creatures that pass by during the dive in both 2D and 3D (WHOI, 2015). The submarine is also equipped with various sophisticated sampling tools such as a slurp gun for collecting fauna, a sediment collector, a water sampler, and a hydraulic mechanical arm for more flexible sampling (WHOI, 2015). With this equipment, samples could be properly taken back for scientific research.

The Exploration

The Mariana Trench is formed at a convergent plate boundary between the Pacific and Mariana Plates. The much older and denser Pacific Plate subducts beneath the Mariana Plate, forming a trench along the boundary (Encyclopaedia Britannica, 2015). Travelling to Challenger Deep gave scientists an up-close look at the plate boundary, the processes associated with the boundary, and the kinds of rocks forming around the boundary.

There is record of a lot of seismic activity at the Mariana Trench, with earthquake strengths ranging from 4.5 to 8 on the Richter scale (National Geographic, 2015). Each earthquake leads to a fresh layer of fine-grained sediment covering the Trench floor, and all tracks that could have been formed by fauna are covered (National Geographic, 2015). Since there is not very much fauna to begin with, the seafloor of the Trench appears very smooth. Using the footage of the seafloor from the Deepsea Challenger's 3D cameras could lead to clues that may be used to predict the occurrence of earthquakes and tidal waves (National Geographic, 2015).

Notably, serpentinization is known to occur in the Mariana Trench, in which serpentinite is formed through intense heat and pressure with by-products of hydrogen and methane gas (Fryer, 2012). These by-products have been shown to support anaerobic life such that microbial mats of entire ecosystems have been recovered and analyzed on unmanned explorations of the Trench (Fryer, 2012). These archaea anaerobically oxidize methane and produce hydrogen sulfide, which sulfide-oxidizing archaea can then use as a food source (Ohara et al., 2012). Thus, a chemosynthetic biological community is formed and even in the extreme temperatures, pressures, and pH, life can thrive (Ohara et al., 2012). It is even theorized that serpentine-hosted ecosystems might have played a large role in the origin of life alongside hydrothermal vents (Ohara et al., 2012). For this to be confirmed, more research on life at these locations is required.

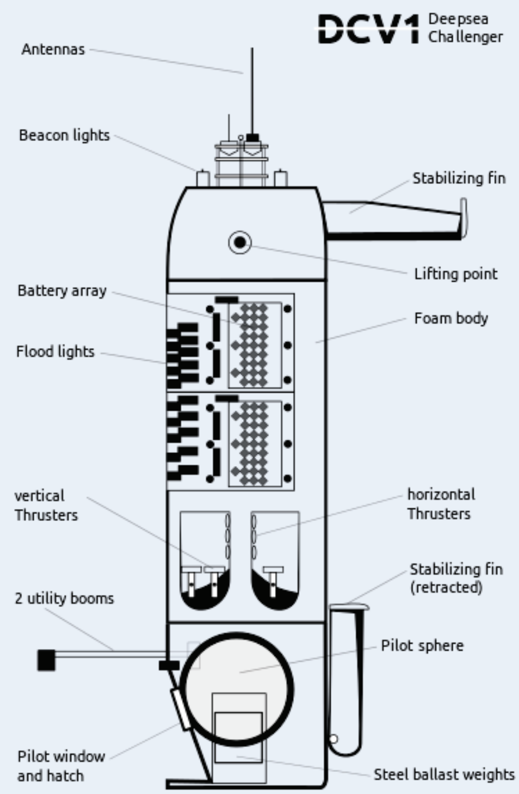


Figure 3.6: *A schematic of the design of the Deepsea Challenger.*

Sadly, the first expedition for the Deepsea Challenger was cut short due to a hydraulics leak in the mechanical arm, and no biological samples and only part of a sediment core were retrieved (Jaggard, 2012). This, however, is not the end, as Cameron plans to return in the future to obtain better samples (Jaggard, 2012). For now, there is the sediment core sample that has been analyzed for new bacteria taxa, and the HD 3D cameras have captured numerous fauna on film and in picture for classification (National Geographic, 2015). Although this is not an ideal first voyage, it was not a complete failure, and that is enough to move the field forward for more scientific finds in future explorations.

Discovery of the Earth's Magnetic Field

Magnetism and the Lodestone

The study of magnetism predates modern scientific methods and experimentation. The first writings about the force of magnetism can be found in ancient Greek and ancient Chinese texts associated with descriptions of a strange rock called lodestone (Blackman, 2006). Lodestone is a rock consisting of a form of iron oxide called magnetite (Verschuur, 1993). The word "lodestone" comes from Old English (Merriam-Webster, 2009), but is not a direct translation of the ancient Chinese or ancient Greek name for the rock. The ancient Chinese named the rock *tzhu shih* or "loving stone" based on the attraction of the rock to other objects (Merrill and McElhinny, 1983). The ancient Greeks named the stone *magnet*, acquiring its name, according to the Roman philosopher Lucretius (c. 99-55 BCE), "because it has origins in the hereditary bounds of Magnetes … in Thessaly [Greece]" (Gilbert, 1600). Lucretius wrote about magnets in the 1st century BCE, but the Greeks were aware of them even earlier. The Greek philosopher Thales (c. 624-546 BCE) was first to write about the lodestone and magnetism (**Figure 3.7**) (Merrill and McElhinny, 1983). The first observations about the stone were simple, and included guesses about the origin of the stone's attractive force. For example, it was noted that while two objects, when rubbed against each other, could become attracted to each other, iron was attracted to lodestone without rubbing (Verschuur, 1993). This result was unexplainable with just earthly reason, so for centuries people turned to unearthly superstitions.

***Figure 3.7**: A Greek postage stamp with the portrait of the Greek philosopher Thales who is credited with the first observations on lodestone.*

In the 13th century CE, the Englishman Bartholomew wrote that the lodestone had the power to restore marriages, cure sicknesses like dropsy, and oust unfaithful spouses (Verschuur, 1993). While many people focused on the supposed supernatural effects of the lodestone, certain individuals focused on advancing scientific thought about the lodestone. In 1269, the Sicilian soldier Peter Peregrinus (c. 1230-1280 BCE) wrote a letter, later named *Epistola de Magnete*, to his friend about his observations on the lodestone (**Figure 3.8**) (Verschuur, 1993; Merrill and McElhinny, 1983). Peregrinus described shaping a lodestone into a sphere and placing a needle nearby. The rotations of the needle led Peregrinus to discover two magnetic *poli*, or poles. During this time period, lodestones were believed to align themselves in the direction of the mines they were taken from, but Peregrinus believed otherwise. He hypothesized that lodestones did not align with poles found on the surface of the Earth, but with some celestial pole. Peregrinus also hypothesized that spherical magnets should rotate about their axis at the same rate as the observable night sky rotates around the Earth; however, Peregrinus related that he did not have the appropriate tools to investigate this (Verschuur, 1993). Despite his preliminary understanding of the force of the lodestone, Peregrinus presented all his current understandings coherently and succinctly, and is considered to have authored the first modern scientific treatise (Merrill and McElhinny, 1983).

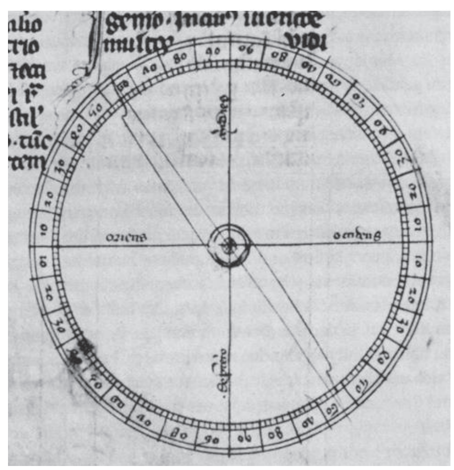


***Figure 3.8:** A 14th century drawing of a compass based on Peter Peregrinus' descriptions from Epistola de magnete*

Magnetism as Tool

While there was an incomplete understanding of the Earth's magnetism, people were not dissuaded from using magnetism as a tool. The use of compasses for determining direction was first recorded in ancient Chinese texts from the 1st century CE, and later recorded in European texts in the 12th century CE (Merrill and McElhinny, 1983). Early compasses were needles magnetized by lodestones, and it was believed that the needles always pointed towards the lodestar, otherwise known as Polaris, or the North Star. Compasses generally directed people where they wanted to go, although there was a methodical error associated with them. This error is now known as magnetic declination. Magnetic declination is the difference between the North the compass needle points to and the true geographic North (Verschuur, 1993). The first hypothesis about a compass error related to the compass' location on the Earth was suggested in 1510 by Georg Hartmann (1489-1564), the vicar of Nurenburg; however, his hypothesis was rejected. Magnetic declination was "rediscovered" in 1576 by hydrographer Robert Norman (c. 1545-1600), who built compasses. Norman considered it an art to create compass needles which minimized magnetic declination, and wrote a treatise in 1581 about this passion of his. Magnetic declination, although an inconvenience for some, is said to be the reason that Christopher Columbus (1451-1506) discovered North America in 1492 (Verschuur, 1993).

Columbus' obliviousness to magnetic declination was a lucky mistake; however, many explorers of the time period wished to adjust their bearings by including magnetic declination. In 1538, Spanish explorer João de Castro (1500-1548) was the first to build an instrument to quantify magnetic declination (Merrill and McElhinny, 1983). De Castro sailed to a certain altitude and measured the Sun's angle in the sky with respect to his compass' magnetic North. The differences between the angles in the morning and afternoon at that latitude corresponded to the magnetic declination at that location. De Castro devoted whole voyages to Southeast Asia to make these measurements in order to aid his fellow seamen. While de Castro's method worked for some time, it was not sufficient to map a greater area. Edmund Halley (1656-1742) built on de Castro's preliminary work and created the first geomagnetic map during his voyages across the North and South Atlantic Oceans in 1698 and 1700, respectively. Later in the 18th century, Johann Carl Wilcke (1732-1796) published the first magnetic declination map of the entire Earth (Merrill and McElhinny, 1983).

William Gilbert's Experiments

As the initial correlations of the lodestone and its several primitive uses were widely acknowledged, it was not until the beginning of the Early Modern Period in 1600, when the English physician, William Gilbert (1504-1603), made a mark on the history of geomagnetism. In 1600, Gilbert published a highly influential scientific work titled, *De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure* (On the Magnet and Magnetic Bodies, and on That Great Magnet the Earth) alongside his colleague, Aaron Dowling. With Gilbert and Dowling's success, they were able to conduct an impressive series of experiments to prove their investigations of the utter most unknown, misunderstood force at their time – magnetism.

They began their investigations by studying magnetic bodies, unraveling the Earth's layers inside out, first within stony matter on the surface and worked towards the Earth's core. According to Gilbert, the lodestone possessed "peculiar" actions that drive forces of attraction, polarity, and revolution of the Earth (Gilbert, 1600). Gilbert truly believed that the lodestone had an all-encompassing capacity to direct forces within nature and that it was a perfect, absolute portion of "true earth" (Gilbert, 1600). A strong lodestone can therefore be found to be of the innermost earth and is able to control the direction of the Earth's movements. On the other hand, a weak lodestone was seen as a fissile rock that shows evidence of degradation from weathering, decay, or other environmental causes. The lodestone of course became a useful resource of interest that even thieves in Gilbert's time thought of it as a tool, a love potion, a cure for gout and spasms, and "that it makes one in favor of princes" (Verschuur, 1993). It was believed to be the stone that can satisfy your wildest fantasies and your deepest desires. Also, other human superstitions arose saying that the lodestone can get rid of the devil and other evil sorceries hence, restore purity in one's life. Thus, in these times of misconceptions and uncertainty, people considered the lodestone as a magical attracting body of rock that was so powerful that it could attract gold from the depths of the Earth (Verschuur, 1993).

However, in order to put these superstitions to rest, Gilbert used different scientific experiments to demonstrate the magnetic properties of the lodestone, not as a tool of magic but a physical force of the Earth itself. Gilbert proposed a model of the geomagnetic Earth using a spherically cut lodestone, which he referred to as the terrella. This was the beginning of a new age for people's understanding of the Earth's terrestrial magnetic field. Through this terrella, Gilbert was able to decipher how forces of magnetism interacted at different points of the sphere as it would on the Earth's different hemispheres. Firstly, he observed that in the equatorial division of the terrella, the magnetic forces are equally distributed between the two parts of the hemisphere, whether they differ in magnitude and direction. Additionally, he observed that no matter the shape of a lodestone, there would always be two vertices or poles where it attracts best, as it conveys the strongest force perpendicular to the poles rather than obliquely (Gilbert, 1600).

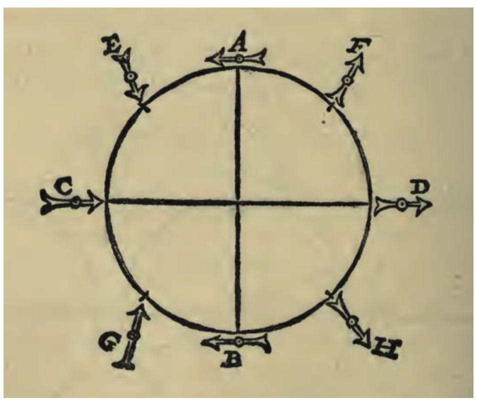


Figure 3.9: *A depiction of the magnetic dip of the Earth at different regions of the hemisphere, drawn by William Gilbert.*

After establishing these properties, Gilbert explored the dip or inclination of the magnetic needle to show the different angles that can be made with the horizontal by the Earth's magnetic field. Immediately, he recognized and deduced that the magnetized needle tilted with respect to the Earth because of the fact that the Earth itself is magnetic, which he later found to be the correct deduction (Verschuur, 1993). He saw this by putting an ion bar balanced on the middle of its axis and exciting this iron bar with a lodestone, from one side of the terrella to the opposite pole. Through this experiment, Gilbert was able to determine that the Earth does indeed magnetically dip, tending to its center. It has a different dip angle on each region of latitude and the needle's lowest dip angle is that of the horizon or the equator **Figure 3.9**). Gilbert shows that inclination is evident when the magnetic needle turns to the body of the earth, its south end pointed to the north, in any latitude away from the equator (Merrill, McElhinny and McFadden, 1996). Gilbert's observation of the Earth's magnetic dip using the lodestone and its properties proved to be untimely accurate hence, it was the basis of world's earliest-improved and most accurate navigational compass.

The main factor that sets Gilbert's scientific writings apart from other physicians is the manner in which his investigations are organized in his publication. Not only does it exemplify much understanding and application of magnetism but it also mirrors the sole purpose behind his experiments. Gilbert's work was essentially a culmination of centuries of thought and experimentation in magnetism. His conclusions put an immediate stop to the wild superstitions and speculations concerning the magnetic needle and magnetism in general (Merrill, McElhinny and McFadden, 1996). His curious and intricate mind paved the way for a newfound geomagnetic Earth.

Magnetism and Rocks

After Gilbert's monumental work, scientists all over the world acknowledged the importance of understanding magnetism; however, not many advances were made throughout the 18th century. Isaac Newton (1642-1728), in his treatise *Philosophiæ Naturalis Principia Mathematica* (1687) mentions Gilbert's work, but does not provide any of his theories on the magnetic force (Segrè, 1984). Other physicists of Newton's time period described the magnetostatic force, but few attempted to describe the Earth's magnetism. One of the notable achievements in geomagnetic history was German mathematician Carl Fredrich Gauss' (1777-1855) *Allgemeine Theorie des Erdmagnetismus* from 1838. Gauss used measurements from Johann Carl Wilcke's magnetic declination map of the Earth, mentioned previously, to create a mathematical description of magnetic declination, and to predict where the geomagnetic poles were (**Figure 3.10**) (Merrill and McElhinny, 1983). Although his predictions were not correct, Gauss paved the way for others to investigate further into geomagnetism.

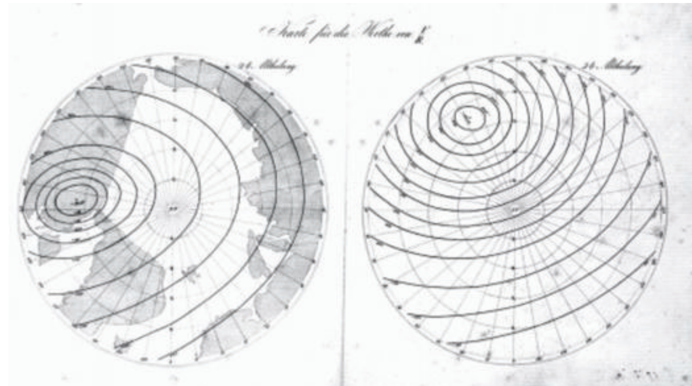


Figure 3.10: *Gauss' predictions of the geomagnetic poles superimposed on the geographic North (left) and South (right) poles.*

The 19th century brought great innovations in the general theories of magnetism, and in the more specific theories of geomagnetism. Although rock magnetization was known since ancient times, it was only near the end of the 18th century that theories were being proposed about the origin of rock magnetism. Alexander von Humbolt (1769-1859) suggested in 1797 that rocks get permanently magnetized due to lightning strikes (Merrill and McElhinny, 1983). Later, studies of rock magnetization led Achilles Delesse (1817-1881) and Macedonio Melloni (1798-1854) to independently discover that rocks magnetize to align with the Earth's magnetic field. This discovery inspired Guiseppe Folgheraiter (1856-1913) to suggest that perhaps rock magnetization is tied to the creation of the rock itself; he started looking into the magnetization of rocks that undergo extreme temperature such as the clays that are used to make pottery. Folgheraiter hypothesized that if one knew the location of the clay inside the kiln, the magnetization of the clay would follow the Earth's magnetic field in that location. This experiment, although very primitive, led to more investigations of rocks created at very hot temperatures. In 1904, Pierre David (c. 1870-1935) found that old igneous rocks created by lava flows had opposite directions of magnetization compared to younger rocks. Bernard Bruhnes (1867-1910) discovered the same occurrence during his research in 1906. These two scientists hypothesized that the rocks indeed magnetized to align with the Earth's magnetic field, however, the Earth's magnetic field was reversed at the time of the rock's creation (Merrill and McElhinny, 1983).

David and Bruhnes' findings sparked an interesting proposition on the topic of periodic geomagnetic reversals. If the Earth's magnetic field reversed, as suggested by David and Bruhnes' rock samples, then rock samples from all over the Earth should display such reversed magnetization. This fact was affirmed by Paul Mercanton (1876-1963) who, in 1926, found that reversed rock magnetizations could be found in rocks from different parts of the world (Merrill and McElhinny, 1983). He also found that similarly magnetized rocks were dispersed all over the world, and hypothesized that these rocks were once close together. Mercanton's hypothesis was similar to the Continental Drift Theory that Alfred Wegener (1880-1930) proposed in 1924, and in fact, Mercanton supported Wegener's theory. Mercanton's suggestion to use rock magnetization to study the Earth's geologic past, including the movement of tectonic plates, is a branch of study called paleomagnetism (Merrill and McElhinny, 1983). Although paleomagnetism is seen as a useful tool by current scientists, paleomagnetism took almost thirty years to be accepted into the scientific community of the early twentieth century. Patrick Blackett (1897-1974), in 1954, stated his opinion that paleomagnetism could be useful: "to test experimentally the much discussed and highly controversial hypotheses of Continental Drift and of Polar Wandering" (Blackett, 1954).

The Origin of the Earth's Magnetic Field

Besides commenting on the validity of continental drift, Patrick Blackett was interested in the heart of geomagnetism: the origin of the Earth's magnetic field. The first theory into the origin of the Earth's magnetic field came in 1919 from Joseph Larmor (1857-1942) (Merrill and McElhinny, 1983). Larmor proposed that the Earth's magnetic field was a result of mechanical energy transforming into electrical energy, and that electrical energy induced a magnetic field. The transformation of electrical energy from mechanical energy was called a dynamo, and Larmor's theory was called the Dynamo Theory. Larmor's theory was debated hotly, and rejected by Thomas Cowling's (1906-

1990) theoretical findings in 1934. For years, there was an "anti-Dynamo" perspective in the earth science community, which included Patrick Blackett. Blackett attempted to find a different origin of the Earth's magnetic field. In 1947, Blackett proposed that the two poles of the Earth's magnetic field were related to the Earth's rotation. He set an experiment up not unlike the experiment suggested by Peregrinus in 1269, who suggested that spherical magnets should rotate at the same rate as the Earth. Blackett's experiment consisted of trying to measure a magnetic field produced by rotating a sphere of gold at the same angular frequency, or rate, of the Earth. Sadly, Blackett did not achieve significant results, despite having state-of-the-art instrumentation to measure the minutest magnetic field (Merrill and McElhinny, 1983).

At the same time that Blackett executed his failed experiment, more support for the Dynamo Theory arose. In the late 1940s, Walter Elsässer (1904-1991) and Edward Bullard (1907-1980) both provided mathematical support for Larmor's theory, although amending it slightly (Merrill and McElhinny, 1983). When Larmor proposed the Dynamo Theory, dynamos were created via mechanical energy from rigid bodies such as wires and discs. Elsässer and Bullard proposed that the mechanical energy was produced by the Earth's constantly moving molten iron core, and this mechanical energy transformed into electrical energy which induced a magnetic field (Merrill and McElhinny, 1983). Not too long after, Blackett agreed with Elsässer and Bullard's proposition, calling it, "the most plausible" theory (Blackett, 1954). Blackett also commented that in that year 1954, the tools available to scientists could only allow for the understanding of the concept behind Dynamo Theory, but not to quantify it or directly experiment with it (Blackett, 1954). Blackett's comment rang true for another twenty years; the Dynamo Theory was not fully supported with experimentation until the 1970s (Merrill and McElhinny, 1983).

The Earth's magnetic field is still not completely understood today; however, with current technology, great strides are being made into understanding geomagnetism, including providing more evidence for magnetic reversals and the Dynamo Theory. The history behind the study of geomagnetism involved countless theories and many brilliant minds, even if those minds sided with superstition rather than science

Geomagnetism as a Hazard to the Modern World

The Earth's magnetic field is neither simple nor easy to predict. It has a complex structure that continuously changes, subjecting the Earth to numerous dynamic influences over time. Since Gilbert's discovery of the unchanging, permanent magnetic field of the Earth, many technologies have been developed for further surveillance regarding the naturally occurring geomagnetic phenomena on the Earth's surface. These recent developments allow the detection of the several dangers that geomagnetism brings forth from core to crust. Geomagnetic hazards include magnetic storms, geomagnetically induced currents (GICs) and with these hazards, direct applications and effects can be seen through the practice of directional drilling. While there has been no established tactic to prevent these hazards, the field of geomagnetism and geophysics continues to study how the ever changing magnetic field of the Earth can be applied to minimize geomagnetic hazard.

Magnetic Storms

This geomagnetic phenomenon is a major disturbance of the Earth's magnetosphere that occurs when high-energy solar wind shock waves interact with the Earth's magnetic field (**Figure 3.11;** Merrill, 2010).

As the earth's exosphere is exposed, effects such as radiation are able to predispose humans, fauna and flora, and satellite systems to damage. However, these storms cause many disturbances that can be forecasted by observing space weather conditions.

The largest magnetic storm recorded in history is referred to as the 'Carrington Event' (Bell and Phillips, 2008). It occurred over a period of eleven days from August 27th to September 7th in 1859. This extreme deviation in the Earth's natural magnetic field was recorded at the Greenwich Observatory in London, England (Bell and Phillips, 2008).

There have been several recent technological advances that make monitoring magnetospheric irregularities easier and more efficient. Instruments such as magnetometers, particle detectors, and radio sounders have made it possible to interpolate magnetic patterns and their responses to interplanetary variations (Merrill, 2010).

Geomagnetically Induced Storms

Geomagnetically induced currents (GICs) are primarily driven by an impulsive geo-electric stimulation during events of disturbances in the Earth's magnetic field, such as a geomagnetic storm (Love and Swidinsky, 2014). When these disturbances in the magnetosphere reach high levels, they are reflected at ground level causing GICs to flow through electrically conducting power line transmissions, which can further lead to geomagnetic induction on the Earth's crust (Philips, 2010).

The effects of this occurrence can be exemplified through the geomagnetic storm of 1989 in Québec, Canada. GICs caused nationwide blackouts throughout the Canadian Hydro-Québec power grid for approximately six million civilians (Love and Swidinsky, 2014). As a result, the overall

electrical infrastructure of the city was highly disrupted and damaged due to a shock to the whole system.

Directional Drilling

Directional drilling is a mechanistic practice that relies on the orientation of boreholes relative to the magnetic field of the Earth (Inglis, 1987). It is heavily influenced by the Earth's magnetic field as it involves a specialized navigation method that makes use of magnetic tools to determine the orientation of boreholes drilled into the Earth's surface at multiple angles. Directional drilling has been an integral part of the petroleum industry since the 1920s (Buchanan et al., 2013).

Problems arise with this method of drilling as it is difficult to accurately determine the exact positioning of the Earth's magnetic field as it is constantly changing. This is particularly evident after the occurrence of a geomagnetic storm where magnetic north becomes skewed from geographic north by an angle called declination (Inglis, 1987). In order to navigate accurately, it is necessary for drilling companies to understand how declination varies over distance and time.

Thus, the magnetic field of the Earth can have a major effect on directional drilling either by damaging the metal equipment used or drilling in a misleading direction (Buchanan et al., 2013). By drilling into the crust, the geomagnetic field beneath the Earth's surface is considered a hazard and must be carefully surveyed prior to this geologic practice.

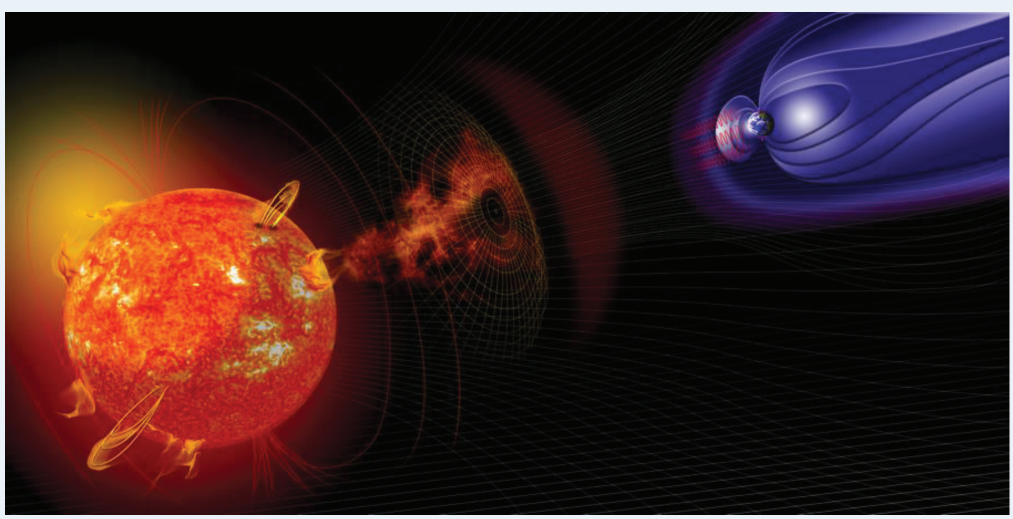


Figure 3.11: *Solar wind radiating from the Sun and disturbing the Earth's magnetosphere during a geomagnetic storm.*

Chinese and Greek Thought on Nature

Today, the study of nature of the universe is somewhat reserved to physicists in multi-billion dollar endeavors. However, the question of the underlying basis of matter and phenomena is one of the first topics that arise in the pursuit of understanding the world. In ancient civilizations, where academic disciplines were largely undifferentiated, all-encompassing theories of the universe and matter contemplated not only the natural world, but also religion, politics and medicine. Theories of this time were therefore often influenced by a multitude of societal factors in their respective civilizations. In spite of this variation between great ancient societies and their pressures and motivations for study, there exist parallels between thought in different civilizations, which makes their theories all the more interesting to consider.

Ancient China

Thought in premodern China can generally be divided into several philosophical schools that emphasized different approaches of study and enforced a different worldview. Throughout history, schools of thought such as Taoism and Confucianism phase in and out of popularity, sometimes simultaneously, which presents a challenge for historians, since the use of similar terms can may have different connotations depending on the text.

A recurring theme in Chinese thought is the interrelatedness of phenomena and analogy of man, society, and nature. The idea of acting in accordance with nature and its processes is deeply rooted in Chinese thought. *Chi Ni Tzu*, an early text from the 4th century BCE, stresses the importance of following the cycles and celestial objects and seasons, citing the importance of preserving people's livelihoods (Needham, 1969). It is hypothesized that early attempts to explain phenomena came from efforts to understand the will of Heaven during the Warring States period in the 4th century BCE (Nakayama, 1966; Yosida, 1973). Rulers would enlist court astronomers to track the movement of celestial bodies to predict future calamities, wars, and shifts in the political landscape (Yosida, 1973). This eventually led to a formalization of underlying fundamental principles of the Chinese intellectual framework: the ideas of Yin-Yang, and the Five Elements, or *Wu hsing*.

The constructs of Yin and Yang is eventually seen throughout all traditional Chinese schools of thought, and were used to universalize fundamental dichotomies such as heaven and earth, and act as two underlying universe-driving forces (Nakayama, 1966; Needham, 1969). All systems and individuals were thought to move through Yin and Yang periodically in a dynamic equilibrium (Sivin 1976). Taoists in particular felt that all of nature and human affairs could be analogized with life cycles of organisms. Most notably, birth and death, night and day, and the rise and fall of dynasties are analogous phenomena in the Taoist worldview. However, these phenomena, while analogous, were not thought to necessarily happen simultaneously or synchronously. On the contrary, one of the most important themes in Chinese thinking is organismic view of the universe, which sees the universe as a spontaneous cooperation and harmony of wills, and every entity goes about cycles in their own "Way," or *tao* (Sivin, 1976; Bodde, 1991).

There was undoubtedly heavy cross-influence between the Chinese schools of thought. Although applied differently, major concepts of this time were ubiquitous in Chinese texts, making it difficult to track their origin and evolution. For example, the cyclic thinking central to Taoist thought is often attributed to Tsou Yen (350-270 BCE), who is referred to as the father of Chinese Naturalist school of thought (Needham, 1969; Ho and Lisowski, 1993). In the transition from Feudal to Imperial China, political and military motivations may have allowed these thoughts to gain traction quickly and simultaneously in different areas, as political rulers became interested in correlations between war successes and symbolic correlations (Needham, 1969).

The concept of *Wu hsing* also served as a system of symbolic correlations, following the common scheme of comparing nature, man, and society. This complementary concept was also discussed by Tsou Yen, among other previous thinkers, and is of comparable importance to Yin Yang, but is somewhat less well understood by historians. While many translate this concept as material elements in a similar sense to that of the Greeks' Four Elements, others more recently would argue that the more accurate interpretation would be the five "phases" or even "processes" (Yosida, 1973; Aylward, 2007; Sivin 1976). The two interpretations are also not necessarily mutually exclusive; both the Greek elements and *Wu hsing* are often compared to modern conceptions of the states of matter. It is probable that both translations are neither strictly correct nor wholly captures the abstraction of *Wu hsing*, and it is therefore probably more useful to think of them as abstractions. In any case, the idea likely stemmed from observations by early astronomers of the five planets visible at the time: Mercury, Venus, Mars, Jupiter, and Saturn, which led to a notion of primacy of the number five. Based on correlations between seasons, terrestrial events, and celestial movements, entities and sensations were classified into a five-category system (Yosida, 1973; Nakayama, 1966).

An early record of this concept appears in the "Monthly Ordinances" chapter of the *Li chi* ("Record of Rites") that was written on beliefs and customs held in the Zhou dynasty (1046-256 BCE). In this text, the Five Elements and their relationships are described in two cycles: Mutual Production and Mutual Conquest (**Figure 3.12**). The former describes a constructive, creative process: Wood gives rise to Fire, Fire yields Earth (ash) Metal is produced by growing in the womb of the Earth, and so on. The latter describes a destructive process, in which Fire melts Metal, Metal cuts and carves Wood, etc. (Yosida, 1973; Ho and Lisowski, 1993). From these basic interactions also emerged indirect cycle-regulating processes by which elements are replenished and conserved (Ho and Lisowski, 1993). The Principle of Control refers to the repressing of processes, while the Principle of Masking refers to reversion of the net effects of some processes. For example, the process of Fire conquering Metal can be controlled by Water by undermining the effect of Fire, and "masked" (i.e. undone) by Earth, since the Earth was thought to produce more Metal. As will be discussed later, the overarching theme of balance and symmetry in the system is certainly not unique to the Chinese, and recurs in modern ideas of biogeochemical cycles and ecological balance.

While each of the Five Elements had a sense of character common throughout the schools of thought, they were applied to distinct areas. Tsou Yen and the Naturalists were arguably the closest to the modern notion of a scientist, with their interest in physical world. To them,

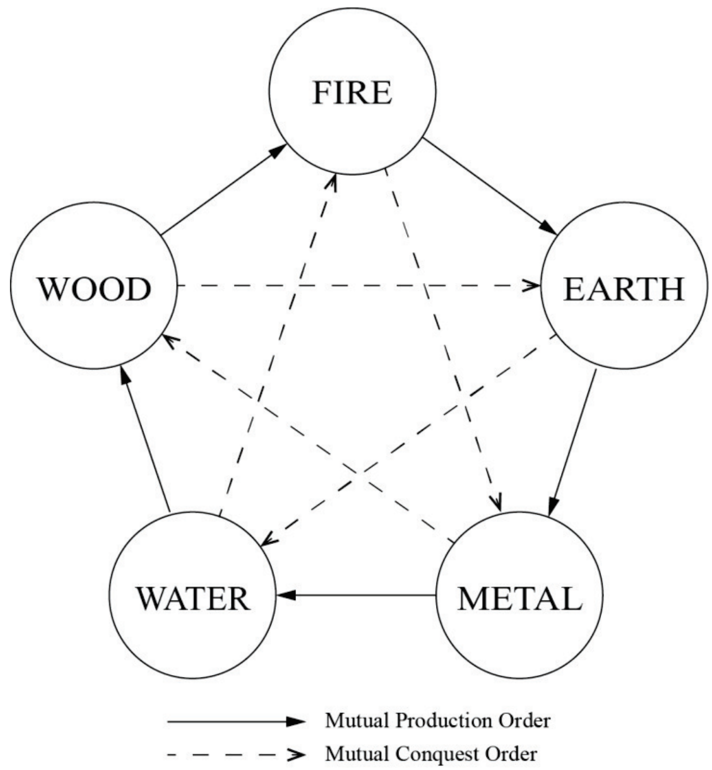


***Figure 3.12**: The Mutual Production Order and the Mutual Conquest Order of the Five Elements, as proposed in the Record of Rites.*

Wu hsing was a system under which the natural world was classified (Needham, 1969). For example, under this system the seasons followed the ideas of conquest and production: spring is associated with Wood and growth, which then yields summer, the time of peak activity characterized by Fire. Late summer, associated with Earth, is a period of declining growth, which leads into autumn, a period of harvest characterized by Metal. Finally, winter is a period of stability and calmness associated with Water (Yosida, 1973). The school of Confucianism, on the other hand, was primarily concerned with applications to self-development and morality, using natural phenomena and the elements as analogies for moral and social behavior. The quality of benevolence, for example, could be learned by observing the life-giving aspect of water (Bodde, 1991).

The relationship between Yin-Yang and *Wu hsing* is somewhat ambiguous. While often mentioned subsequently in literature, it is often left to interpretation how exactly these concepts fit together. Some historians, in their translation of *Wu hsing* to mean the Five Elements as basic constituents of matter, would be inclined to believe that Yin and Yang act as forces on matter made up of the five elements (Needham, 1969), others that translate *Wu hsing* as Five Phases have proposed *Wu hsing* to be a finer subdivision of phases in Yin and Yang that show rise and decline in activity (Sivin, 1976). Given that these abstract concepts were broadly, yet consistently applied across different disciplines of ethics, alchemy, and medicine, it is probable that some aspects are lost in translation or are absent in western culture.

Parallels in Greek Thought

Relative to the Chinese, early Greek thinkers took a more academic approach to the interpretation of natural phenomena in the modern sense. The early Greek philosopher Thales of Miletus (624-565 BCE) was among the first to ask the question, "what is the world made of and how is it made?" (Ginestra, 1961). This is in stark contrast to Chinese thinkers whose study of phenomena came primarily as a byproduct of other pursuits. The Chinese approach is principally concerned with finding correlations and resonance, whereas the Greek way was based on demonstrability and discussion (Lloyd and Sivin, 2002). This makes it all the more interesting to note the apparent parallels between thoughts in the two civilizations.

Thales of Miletus speculated that water was the underlying substance of all things in the universe. He reasoned that water, in its different states composed all matter, and its transformations and changes gave rise to all phenomena (Ginestra, 1961). His initial interpretation of all matter in the universe as a single substance became a catalyst for Greek discussion and philosophy on this topic (Bose, 1971). Anaximander (610-546 BCE) later put forward the construct of *apeiron* – an abstract idea of an infinite, inclusive, and undefined substance that was in constant motion (Kahn, 1994). In its motion, opposites of hot and cold in the substance separated as the world came into being. In his view, the world was temporary and would cyclically return to *apeiron,* and again form new worlds (Evans, 2014). These initial ideas about the universe, though vague and largely hypothetical, were important in catalysing discussion in Grecian times on theories of nature.

One of the most enduring and influential theories to emerge of ancient Greece is that of the Four Elements. Contrary to popular belief, Empedocles (490-430 BCE), not Aristotle, is generally acknowledged as the forefather of the thought on the four Greek primordial substances (Pullman and Reisinger, 2001). In his key work, *On Nature*, he wrote that these elements were "the roots," composing all other objects in the universe, and were eternal and equally balanced forces. However, this idea of persistent, fundamental constituents of matter dates further back to Parmenides (515-460 BCE) who first brought up ideas of elements successively combining to form objects and separating (Parry, 2012). The four elements identified by Empedocles, Earth, Water, Air, and Fire, were also intimately linked with two pairs of opposite states, which can be loosely thought of as two spectra on which things fall: cold and hot; wet and dry (**Figure 3.13**). The ancient Greeks also used the Four Elements to describe their geocentric cosmic model. At the centre was the mass of Earth, surrounded on the surface by Water then Air, and finally Fire was at the periphery as the distinct entity of the Sun. The Four Element view was later adopted by Aristotle (384-322 BCE), who also eventually proposed a new, fifth element upon considering stars and souls and mind. This fifth element called Aether also explained the movement of the heavens, which in his view were not accounted for in Empedocles' four originally proposed elements (Chroust, 2015). However, Aether is commonly not included when referring to classic Greek elements.

The elements of Fire, Earth, and Water recur in both the Greek and Chinese theories of elements, which also share motifs of balance and symmetry. It can be seen how the historical study of the Greek elements might have influenced earlier translations and interpretations of the Chinese *Wu hsing* as strictly physical, non-changing elements. At large, the occurrence of other homologous constructs could have led to a biased interpretation of Chinese texts that leans towards better understood Greek constructs, as opposed to an autonomous, independent interpretation.

In both Greek and Chinese societies, their respective themes of the elements permeated throughout nearly all disciplines. This is perhaps best illustrated in the field of medicine. In ancient Greece, Hippocrates' four humoral theory of physiology resonates with the four states (cold, hot, wet, and dry) between the Four Elements (Clendening, 1960), just as different parts of the body were associated with *Wu hsing* (Ho and Lisowski, 1993). The importance of symmetry in the ancient world can once again be seen here, as in both cases, disease was thought to come from an imbalance of element-associated aspects in the body.

A dichotomy of two opposite fundamental forces was also present in Greek thought. In *On Nature*, Empedocles proposed the fundamental universe-driving forces of Love and Strife, which were inspired by the thoughts of Parmenides. The mixing and combining of elements was attributed to the force of Love, while the separation of elements was Strife (Lloyd and Sivin, 2002). Immediately, one can draw the resemblance to Yin-Yang. This thought, however, was not universally supported. Aristotle's opinion was that these were a misguided attempt to identify causes of events. Instead, Aristotle said that the interactions of the four material elements were responsible (Parry, 2012). It could be argued that the original Four Elements have an innate dichotomous nature and therefore act as opposing forces in themselves: Fire with Water and Earth with Air.

Matter

A rarely discussed topic in Chinese thought is the notion of a universal basic constituent of matter, which perhaps might have undermined ideas surrounding *tao* and of every entity having their own "Way" and form. While some believe that certain schools of thought in China were more inclined to ideas about the atom, and there were brief ideas of infinitely small time periods and division of matter, overall there was little to say on this topic (Needham, 1969). In Greece however, decades after Empedocles, Democritus (460-370 BCE) proposed a primitive theory of atomism. Democritus is most intimately associated with the birth of atomism discussions by about 420 BCE. At this time, previously held ideas of continuous change seemed to be contrary the idea of permanent reality. To resolve the conflict, Democritus offered the atom: the unchanging unit composing all entities and responsible for all change. This phase in Greek atomism is respected as a significant phase in the growth of atomic thought. However, about 60 years later in *Timaeus*, written 360 BCE, Plato elaborated on Democritean atomism (Cornford, 2014). In *Timaeus*, Plato's proposition of a single matter was consistent with the single uniform composition of Democritean atoms. However, he deviated from the thinking of Democritus in claiming that each of the four elements is composed of distinct, geometrically regular particles that defined their physical properties and characteristics.

The proposition of the atom fell out of favour as the highly esteemed Aristotle developed a more dynamic view of physical change. He stated that the elements, when in

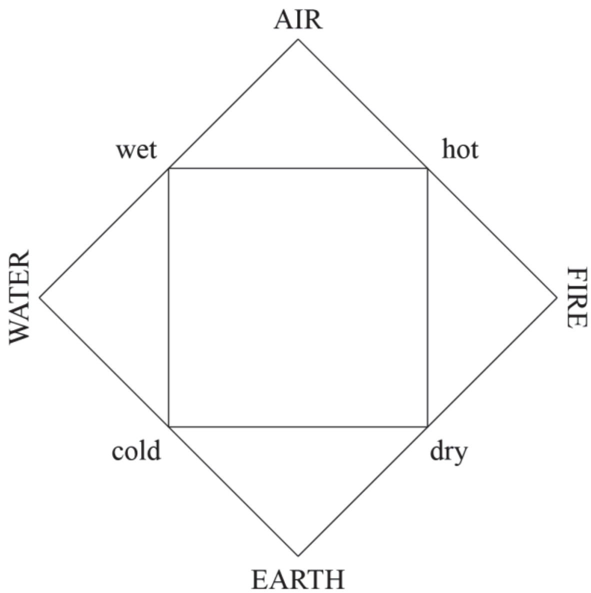


***Figure 3.13**: The Four Elements as identified by Empedocles: Earth, Water, Air, and Fire; and the two pairs of opposite states: cold and hot; wet and dry.*

composition with each other, form new compounds in which they cannot be individually distinguished. Instead, they are "everywhere" in the compound, which opposes Democritus' belief on the unchanging nature of atoms (Melsen, 2004). At the time, Democritus' proposition of the atom was also perceived as too materialistic (Melsen, 2004). This garnered sharp opposition from thinkers in later centuries as many refused to reduce the wealth of the human mind to a system composed of only moving atoms. Ideas about the atom did not resurface in western thought until the 18th century in Daltonian atomism (Gregory, 1931).

The Periodic Elements

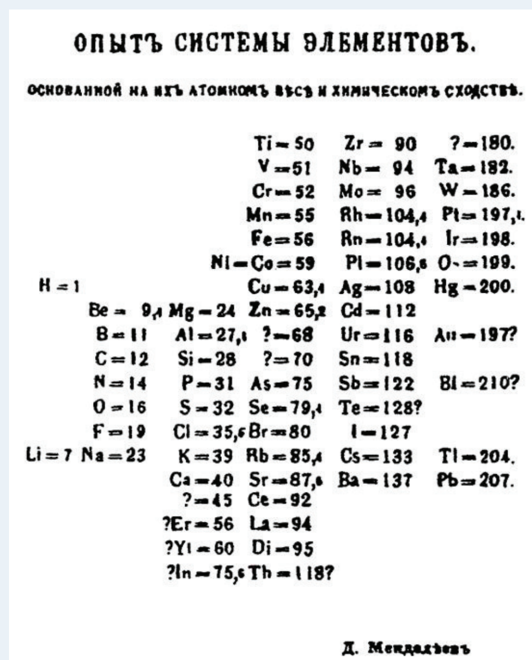
The elemental theory of Empedocles and Aristotle in Greece, and its Chinese counterpart persisted for nearly two millennia in their respective societies. It is difficult to pinpoint what retarded the development of the physical sciences, but it is likely because these theories stayed closest to experience and intuition. Inquiry on this topic would also implicate similar themes in other disciplines and require a major shift in thinking. It would take the development of new experimental methods to properly challenge the theories of old and establish a completely novel way of viewing matter and substance.

Atomic Models

The late re-emergence of thought leading to modern atomic theory occurred mostly in 19th century Europe. As mentioned previously, the major concern with the ancient Greek model of the atom was its inability to distinguish between the types of atoms between the elements. English chemist John Dalton (1766-1844) addressed this major concern directly with the notion of an indivisible entity carried directly from the work of Democritus. With Dalton's model the calculations of masses and the establishment of combinatorial relations became possible. Despite its later success, the atomic model was initially ill-received and, ironically, considered radical by many for its allusions to the ancient Greek model. Dalton's model provoked thought in chemists and physicists from the late 19th century onward, leading to the development of several atomic models (Justi and Gilbert, 2000). The Bohr model of the atom, developed by Danish physicist Niels Bohr (1913), is widely used and accepted today (Bohr, 1934), despite technical inaccuracies concerning electron orbit.

The Periodic Table of Elements

Dalton's theories also allowed for experimental verification and built the foundation for a library of experimental data on atomic mass (Hettema and Kuipers, 1988). Using these available data, many scientists attempted to develop a classification system for the elements, which appeared fruitless until the Russian chemist, Mendeleev (1834-1907). Mendeleev was able to formulate a classification system (**Figure 3.14**) in 1869 that was an early version of what we now recognize as the periodic table of elements (Hettema and Kuipers, 1988).



ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ.

ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.

			Ti=50	Zr=90	?=180.
			V=51	Nb=94	Ta=182.
			Cr=52	Mo=96	W=186.
			Mn=55	Rh=104,4	Pt=197,4.
			Fe=56	Rn=104,4	Ir=198.
			Ni—Co=59	Pl=106,6	Os=199.
H=1			Cu=63,4	Ag=108	Hg=200.
	Be=9,4	Mg=24	Zn=65,2	Cd=112	
	B=11	Al=27,4	?=68	Ur=116	Au=197?
	C=12	Si=28	?=70	Sn=118	
	N=14	P=31	As=75	Sb=122	Bi=210?
	O=16	S=32	Se=79,4	Te=128?	
	F=19	Cl=35,5	Br=80	I=127	
Li=7	Na=23	K=39	Rb=85,4	Cs=133	Tl=204.
		Ca=40	Sr=87,6	Ba=137	Pb=207.
		?=45	Ce=92		
		?Er=56	La=94		
		?Yt=60	Di=95		
		?In=75,6	Th=118?		

Д. Менделѣевъ

Figure 3.14: *(right) Mendeleev's original periodic table, where the elements are arranged the elements in vertical columns with increasing atomic weights, so that the horizontal rows contain similar elements, again in increasing weight order.*

The central theory of Mendeleev's periodic table is the periodic law: when elements are ordered by their atomic masses, their chemical behaviour follows from their ordering. The translation of this law into the periodic table was not without its share of faults. At first, copper appeared twice, once in the first and eighth column, and fluorine appeared above manganese instead of chlorine. These errors were corrected by Mendeleev in future revisions of the table. In 1879 he stated his table was used for classification for elements, a systematic account for the properties of known compounds, determination of atomic masses of elements, prediction, and examination of unknown elements and their compounds (Hettema and Kuipers, 1988). The periodic table was quickly accepted due to its ability to easily classify newly discovered chemical elements based on atomic mass and other properties.

The periodic table has since dramatically changed and grown from Mendeleev's original 63 elements. The discovery of periodic elements has a strange history, in which new elements were often discovered in quick succession (Scerri, 2006). Some elements, like iron, copper and gold have been known since ancient times, and others such as sulfur, mercury, and phosphorus played roles in alchemy. In modern times, electricity has enabled isolation of many more reactive elements that could not be obtained by heating their ores with carbon. Electrolysis has led to the isolation of as many as ten elements which include calcium, barium, magnesium, sodium, and chlorine. A variety of techniques and discoveries collectively contributed to the periodic table of elements that we have today (**Figure 3.15**) (Scerri, 2006).

Radioactive Elements

Notably, the study of radioactive materials has filled in many gaps in the periodic table, and has been important to our understanding of the atom (Scerri, 2006). However, these materials have historically been a challenge to the development of the periodic table (Greenwood and Earnshaw, 2012), since the temporal variation in the relative concentration of isotopes creates a varying atomic weight. It is now known that the weight of radioactive elements depends on the initial relative abundance of the isotopes and the half-life of the element, and so the original concept of a "normal" atomic weight does not apply. At least 19 elements that were not initially considered radioactive elements, were found to have naturally occurring unstable isotopes (Greenwood and Earnshaw, 2012). The discovery of radioactive elements revolutionized the fields of geology, paleontology, and archaeology through the emergence of radiometric dating, which uses the fixed rate of decay of radioactive elements to effectively act as a geological clock.

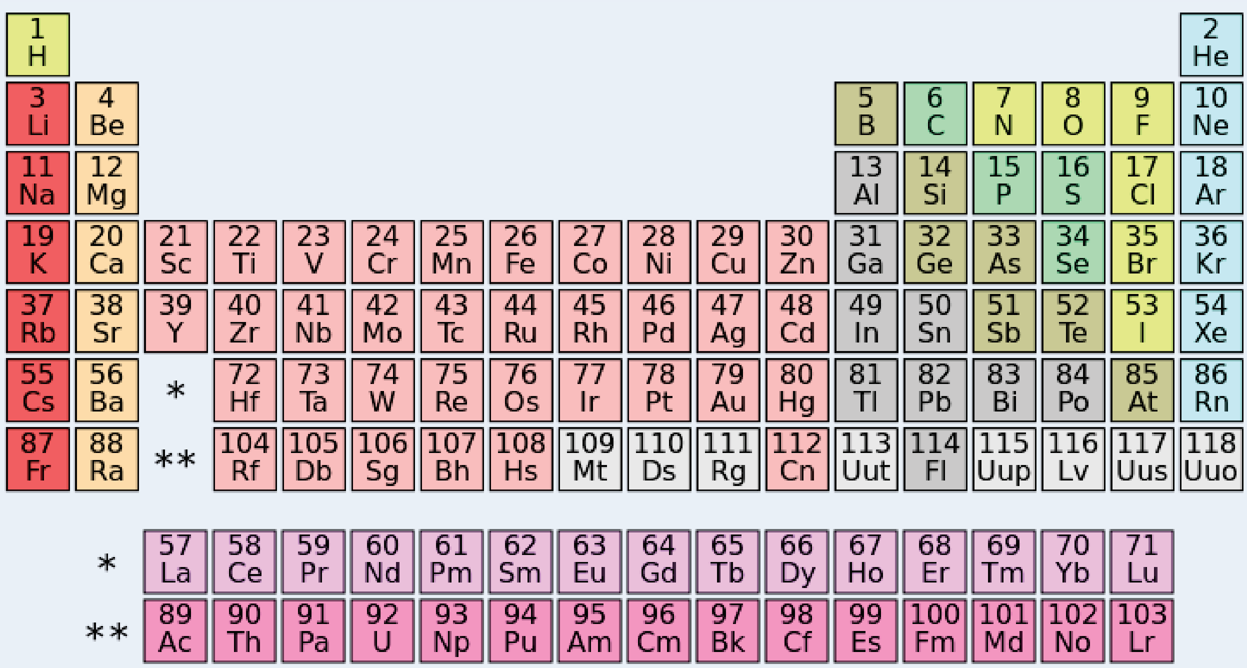


Figure 3.15: *The modern periodic table. Chemical elements are arranged in horizontal rows with increasing atomic weight, and vertical columns contain elements with similar properties, increasing in atomic weight going down.*

Development of Radiometric Dating

The significance of radiometric dating became apparent within the last few decades as researchers realised the importance of determining the age of fossils and the time scale of eras. Various methods of radiometric dating have evolved to measure not only specimens on the Earth, but also features on other planetary bodies. Initially, geochronology focused primarily on relative dating; the age of specimen was determined through its relative locations in geologic formations and the presence of indicator fossils. The development of the radiometric method in the 1900s advanced the field of absolute geochronology. Researchers were able to use this method to obtain the true age of specimens through the radioactive decay of radioisotopes. The development of the radiometric dating method is shown through the birth of various techniques. Its importance is outlined by its contribution to the development of the geological time scale, as well as its use in proving the existence of important historical events. Despite many of the developed dating techniques being highly effective, the ones which are of particular interest in relation to the development of geology are: uranium-lead, rubidium-strontium, potassium-argon, and carbon-14.

Uranium–Lead Method

Uranium was the first element that was used in radiometric dating. Its radioactive action was discovered by Henri Becquerel (1852-1908) in 1898 (Becquerel, 1896) but it was not employed in geometric dating until a study was conducted by Ernest Rutherford (1871-1937) in 1906 (Rutherford, 1906). This initial study used the decay relationship between uranium and helium to calculate the age of rocks (Rutherford, 1906). Helium is produced in the decay of most radioactive minerals, thus Rutherford believed it was the most logical pick for the decomposition product of uranium. Using this technique on different samples, Rutherford found the age of the Earth to be 40 million years old (Ma) later revised to 500Ma (Armstrong, 1991). Rutherford understood that helium was capable of escaping from the minerals so acknowledging his underestimation of the Earth's age, he suggested lead as a more appropriate decay product (Rutherford, 1906). Bertram Boltwood (1870-1927), like Rutherford, was also searching for uranium's final decay product (Boltwood, 1907). He believed that the most suitable decay product would be one that would, for minerals formed at the same time, have a constant proportion of decay product to parent product. And, the proportion of the disintegration product would be greater for older minerals. In 1907, he proved that lead was a decay product which followed all the criteria he set (Boltwood, 1907). A similar report was given by Arthur Holmes (1890-1965) in 1911, confirming that the ratio of lead and uranium is nearly constant for similar minerals of the same age (Holmes, 1911).

Though the previous articles involve studying isotopes, the term was not coined until 1913 by Frederick Soddy (1877-1956) (Soddy, 1913) which was used to describe substances with identical chemical structure but different physical properties. This discovery was an issue for the field of radiometrics; in previous measurements, researchers did not account for the different isotopes of lead. Many of the minerals that were studied contained all the isotopes of lead, but only one specific isotope was produced as a decay product. This meant that the researchers used an incorrect amount of produced lead in their equations. This issue would not be resolved until the mass spectrometer was invented.

Until the 1920s, all the measurements had been calculated through chemical means and since isotopes were chemically similar, this method was unable to separate the various isotopes. Thus, it was rendered obsolete when the first mass-spectrometer was developed in 1919 (Armstrong, 1991). However, it was not until much later that a mass-spectrometer worked well enough to detect the three different isotopes in lead: lead-206, lead-207, and lead-208 (Aston, 1929). With the new knowledge on isotopes, Rutherford wrote an article in 1929 classifying lead-207 as the final decay product of uranium-235 (Rutherford, 1929). Using this new information and the mass

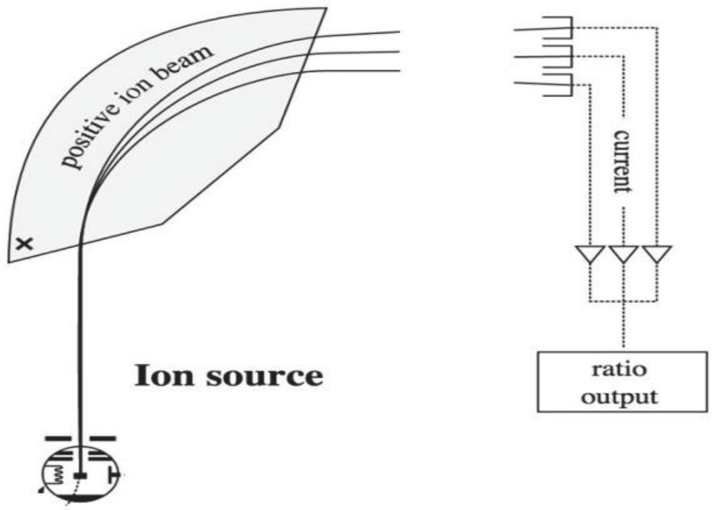


Figure 3.16: *A schematic for a mass spectrometer. Ions are emitted into a magnetic field where they deflected into receptors. The amount of deflection changed with the mass of the isotope.*

spectrometer, Rutherford suggested that the Earth could not be older than 3.4 billion years old (Ga) (Rutherford, 1929).

The development of the uranium – lead technique was sped up by the start of World War II where research into uranium as a weapon allowed scientists to develop a method for separating solid uranium into its isotopes. Spearheaded by Alfred O. C. Nier (1911-1994), the mass spectrometer continued to develop into the late 1930s (**Figure 3.16**). In 1939, Nier, using his mass-spectrometer and a technique involving counting alpha-particles, measured the isotopic composition of uranium isotopes and was able to calculate their decay constants (Nier, 1939). The development of this decay constant allowed for much simpler calculations to be done to determine the age of the Earth. The development of the mass spectrometer also led to the discovery of the uranium-238 – lead-206 and thorium-232 – lead-208 decay chains, which is used alongside the uranium-235 – lead-207 to verify all measurements; this is commonly referred to as the uranium decay series (Nier, Thompson and Murphy, 1941). Nier also measured the isotopic compositions of differently aged lead samples and found that there were large variations in lead compositions (Nier, 1939). This led him to hypothesize that all samples had primeval lead, which is an initial and static isotopic composition present during mineral formation. The difference between the primeval and sample lead isotopic composition would be due to the radioactive decay of uranium. If researchers knew the primeval isotopic concentration of lead, they could calculate the amount that has been produced due to radioactive uranium isotope decay. Using this information and the decay constant calculated by Nier, they would be able to determine the age of the sample. Using a sample from Greenland, with low amounts of radiogenic lead as an model isotopic composition for primeval lead, E. K. Gerling(c.1910-c.1990) performed a study to calculate the age of the Earth (Gerling, 1942). Subtracting the amount of primeval lead from his samples, he was able to determine the amount of radiogenic lead produced by decay. Using this method, Gerling determined the Earth's age to be about 3.23Ga (Gerling, 1942). This estimate would not be challenged until Clare Patterson (1922-1995) published a paper in 1956 suggesting that meteorites, in orbit around the Sun, and the Earth had formed at a similar time, as well as were composed of lead with the same isotopic composition as early Earth(Patterson, 1956). Assuming meteorites acted like closed systems, he extrapolated the decay of uranium over time for three stony meteorites and two icy samples. Patterson discovered that the meteorites were all formed at the same time, 4.5Ga, with similar isotopic lead composition (Patterson, 1956). This initial composition was determined to be the most accurate measurement for the primeval conditions of Earth. Since it was assumed these meteorites and the Earth were formed at the same time, the Earth also had to be aged at about 4.5Ga (Patterson, 1956).

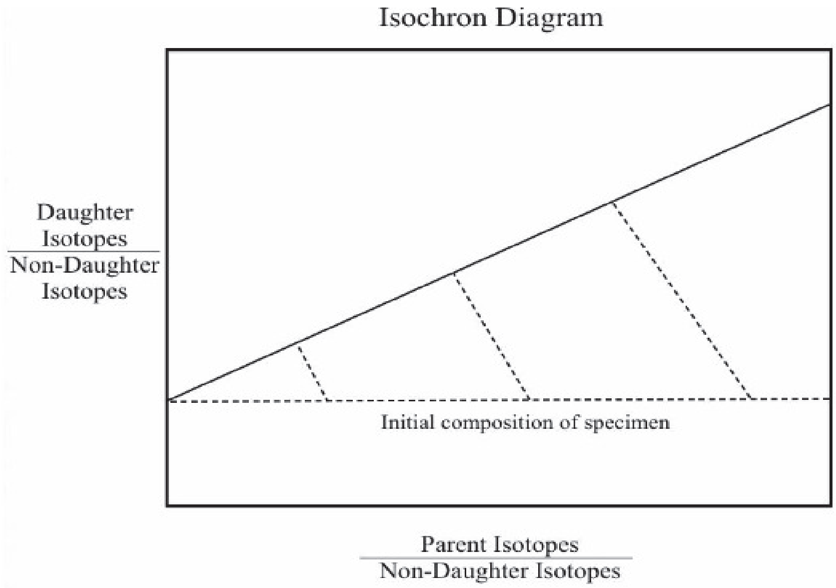


Figure 3.17: *Isochron diagram depicting the slope (solid line), and the aging of a specimen (dotted lines). The point of intersection of the solid and dotted lines represents the age of the specimen at its specific point in time.*

Developments to the mass-spectrometer and the isotopic separation technique allowed for different minerals to be tested, most important of which being zircon. Zircon is a very robust and common mineral that has an abundant amount of uranium. It was considered the ideal mineral for study due to its minimal primeval lead content and resistance to any lead loss. Zircon minerals are also very interesting as they would undergo color changes depending on theiruranium content and age (Heaman and Parrish, 1991).

Rubidium –Strontium Method

The rubidium – strontium method is different than the uranium - lead method as it uses a different starting material and isochron diagrams to determine the age of minerals (**Figure 3.17**). It started development in 1905 when J.J. Thomson (1856-1940) determined that the emission of rubidium differed from other metals in terms of emitting negative ions (Bowmen, 1988). A year later, Norman Robert Campbell (1880-1949) and A. Wood (c.1870-c.1960) discovered that rubidium was a radioactive element and in 1921, Francis William Aston (1877-1945) determined that the two isotopes of rubidium were rubidium-85 and rubidium-87 (Bowmen, 1988; Dickin, 1995). However, it wasn't until 1937 that rubidium-87 was identified as the radioactive isotope (Bowmen, 1988). The rubidium – strontium method consists of dating rocks in which rubidium-87, a group-1A alkali metal, decays to strontium-87. A year after the radioisotope was discovered, the possibility of dating Rb-rich minerals was hypothesized by Otto Hahn (1879-1968) and E. Walling (c.1870-c.1960) (Dickin, 1995). This possibility was later confirmed in 1943 by Hahn and colleagues (Bowmen, 1988).

Rubidium decays to strontium with the emission of a beta particle and an anti-neutrino (Dickin, 1995). The rubidium – strontium method was initially used to date igneous rocks (Dickin, 1995). Through a decay equation, scientists were able to determine the amount of daughter atoms which were produced from the decay of rubidium-87 using the equation:

$$87Sr = 87Sr_i + 87Rb(e^{\lambda t} - 1)$$

in which $87Sr_i$ indicates the initial amount of strontium-87 atoms, and 87Sr represents the amount of strontium-87 atoms in the sample (Dickin, 1995). Since it was complicated to measure the specific abundance of a nuclide, the equation was converted into a ratio for simplicity:

$$(87Sr/86Sr) = (87Sr_i/86Sr) + (87Rb/86Sr)(e^{\lambda t} - 1)$$

Since the rubidium-rich minerals had the tendency to develop extremely high ratios of 87Sr/86Sr over geological time, the initial ratios of strontium isotopes in rubidium-rich minerals was determined to be 0.712 (Dickin, 1995). The rubidium – strontium method was also used on other rock minerals such as potassium-feldspar, muscovite, and biotite, however the initial ratios of strontium isotopes had to be calculated first. In 1959, W. Compston and P.M. Jeffrey realized that the initial ratios of strontium isotopes in specific minerals was higher than 0.712 and the previous equations were not accurate (Dickin, 1995). Through this, the isochron diagram was invented to determine the age development of rocks without the need of an initial ratio. In this diagram, the slope of the line ($e^{\lambda t}$– 1) is used to determine the age of the minerals and young geological rocks (Nicolaysen, 1961). This method further evolved in 1958 due to innovations by G.D.L. Schreiner (c.1920-c.2000), who used it to not only date minerals but also date whole-rock sample (Dickin, 1995).

Although the rubidium – strontium method was very popular with minerals that were rubidium-rich and igneous rocks, it was discovered that this method could also be used to date meteorites due to the presence of both strontium-87 and strontium-86 (Bowmen, 1988). The first measurement that appeared to be accuratewith initial ratios of strontium isotopes in meteorites was made by Dimitri Papanastassiou and colleagues on basaltic achondrites in 1969 (Dickin, 1995). In 1970, Petermanused the rubidium – strontium method and measured the ratio of 87Sr/86Sr in shell carbonates (Peterman et al., 1970). His findings determined that the seawater strontium ratio decreased during the Palaeozoic Era, was at a minimum during the Mesozoic Era, and began to increase from there onwards (Dickin, 1995; Peterman et al., 1970). While E. Jäger was working on the central European Alps in 1973, he made the discovery that metamorphic rocks that were located around the exterior of the Alps preserved rubidium-rich minerals such as biotite and muscovite. Therefore, he could apply the rubidium – strontium method to obtain information about the metamorphic terranes (Dickin, 1995).

In 1990, the rubidium – strontium method evolved to be able to date specific ore deposits, as Nakai S. Hallidaymade the first isochron diagram to determine the age of a lead-zinc deposit in Tennessee (Dickin, 1995). He determined that the deposit had to form during the Acadian orogeny, which occurred 380-350Ma (Dickin, 1995). In 1999, Veizeranalyzed and used data from approximately 1,450 cases of brachiopod shells along with belemnites from around the world to create a strontium evolution curve for the Mesozoic and Palaeozoic Era, which was inspired by Jonathan Burke in 1982 (Dickin, 1995). The evolution curve is a graph depicting the correlation between the age of a specimen, x-axis,and its relative strontium-87/strontium-86 ratio, y-axis (Lanphere, 1964).

The evolution of this method shows its ability to determine many important geological dates throughout history, specifically through the dating of igneous rocks, meteorites, seawater floors, metamorphic terranes, and through determining boundaries of different eras (Dickin, 1995).

Potassium–Argon Dating

In 1935, potassium-40 was discovered by Nier, but its radioactive nature was not introduced until a paper was published by William R. Symthe (c.1900-c.1990) and Arthur Hemmendinger (1912-2012) 2 years later (Hemmendinger and Smythe, 1937). There was not much initial hope for this method as potassium-40 would decay into calcium-40 which is a common element found in all rocks (Harper, 1973). However, this changed when Carl F. von Weizsacker (1912-2007) suggested that a different isotope was also produced during potassium decay (Weizsacker, n.d.). He suggested that if the potassium nuclei could capture an orbital electron, it would evolve into an argon-40 atom. This suggestion was verified by F. C. Thompson (c.1910-c.1980) and S. Rowlands' (c.1910-c.1980) study (Thompson and Rowlands, 1943) where they were able to create argon-40 from potassium-40 in a laboratory setting using Weizacker's suggested electron capture method. Thus, the dual decay model of potassium was developed; potassium-40 could evolve into calcium-40 by beta emission or argon-40 through electron-capture (Thompson and Rowlands, 1943) (**Figure 3.18**).

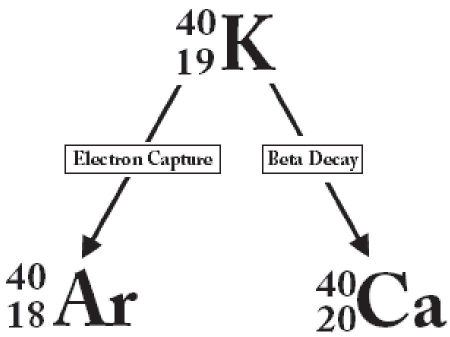


Figure 3.18: *Decay model for potassium shows two possible outcomes. Electron capture will result in argon-40 forming while beta decay will result in calcium-40 being formed.*

After this promising discovery, many independent research groups studied the viability of this method. This technique seemed to be promising as it would have been useful in dating the potash-feldspar mineral which is common in igneous and metamorphic rocks. However, a study done in 1955 showed that the potash-feldspar minerals would be dated a different age than the mica minerals in the same rock (Wetherill, Aldrich and Davis, 1955). Known as the "mica-feldspar discrepancy", this phenomenon was studied by J. H. Reynolds (c.1920-c.2000) and he demonstrated that argon was able to diffuse out of the feldspar at elevated temperatures(Reynolds, 1957). Even with this issue, the potassium– argon method continued to develop and still functioned to perfectly date hornblendes and low-potassium feldspars (Hart, 1961). Due to this, it was chosen as the best method to develop the Cenozoic Time Scale (J. Evernden and K. Evernden, 1970).

Carbon-14 Dating

Natural radioactivity was initially looked into by Willard Frank Libby (1908-1980) in 1933, who was particularly interested in the radioactivity of carbon-14. In 1934, A.V. Grosse (c.1890-c.1980) discovered that the mineral, eudialyte, which consisted of calcium and sodium was radioactive (Bowmen, 1988). With the aid of Libby he showed that cosmic rays would interact with elements such as oxygen and could result in radioactivity (Bowmen, 1988).Understanding this concept, Libby and Grosse hypothesised that radioactive species such as carbon-14 are formed by the interactions between cosmic rays and neutrons in the upper atmosphere (Bowmen, 1988).

The discovery of cosmic-ray neutrons in 1933 by G.L. Locker (c.1890-c.1980) led to C.G. Montgomery (c.1910-c.2000) and D.D. Montgomery (c.1910-c.2000) to suggest that the interaction between cosmic rays and the neutron of a nitrogen-14 atom in the atmosphere produced carbon-14 (Bowmen, 1988). In 1940, M.D. Kamen (1913-2002) performed an experiment where he confirmed that carbon-14 was a radioisotope (Kamen, 1963).

Carbon dioxide molecules are distributed evenly throughout the atmosphere, some of which would contain the radioactive carbon-14 isotope. These molecules would enter plant tissues through the process of photosynthesis (Parsons and Strickland, 1961) and since they were present in plants, they also became present in organisms that consumed these plants (Parsons and Strickland, 1961). This uptake would, however, stop when the organism died. The presence of carbon-14 and its rate of decay could be used to calculate their time since death (Bowmen, 1988). The specific formula used on decaying samples is:

$$A = A_0 e^{-\lambda t}$$

in which "A_0" represents the initial predicted presence of radioactivity, and "A" represents the measured activity of this decay (Bowmen, 1988).

In 1946, Libby proposed that enough carbon-14 would accumulate in living creatures to allow for this method to be viable as a method of radiometric dating (Bowmen, 1988). In 1962, H. Godwin declared that the half-life of carbon-14 was about 5,730 years, which in 1982 was corrected to about 5,568 years (Bowmen, 1988). In 1973, H. Erlenkeuser (c.1930-present) analyzed the growth rings of marine shells and found that carbon-14 activity differed in various regions of the specimen (Gillespie and Polach, 1979). By grouping the different specimens by patterns of carbon-14 activity in their shells, researchers were able to determine if different marine-species lived in close proximity to each other (Gillespie and Polach, 1979).

Modern Radiometrics

Though the radiometric equations have been updated to allow ease of use, the core ideas which form the basis of radiometric dating have not changed. The ideas from 50 years ago are still relevant and due to the broad nature of radiometric dating as a dating technique, it is easily integrated into many different fields of study.

Radiometrics in Space

Researchers at Colgate University recently attempted to verify the age of the Zagami meteorite (Hays, 2011). Samples of basaltic shergottite from the Zagami meteorite were used with resonance ionization mass spectrometry (**Figure 3.19**). This technique allows for neutral atoms within the specimen to be emitted by laser ablation. These atoms are then ionized by photons and are then accelerated into a high transmission mass spectrometer. Rubidium-87 and strontium-87 have equivalent masses, requiring rubidium-87 and strontium-87 to be separated prior to dating the specimen. After separation, thermal resonance ionization mass spectrometry was used to confirm the age of the Zagami meteorite to be about 360Ma (Hays, 2011).

Figure 3.19:*A basaltic shergottite of a Martian meteorite found in 2011, located in Morocco.*

While the rubidium-strontium technique is used to date meteorites, the potassium-argon method aids in dating a planet of immense interest – Mars. The current estimate of the general age of Mars is based around the number of its craters and the crater formation rate of the Moon (Farley et al., 2013). Mars, unlike the moon, is geologically active and surface processes can remove traces of craters. Since Mar's weather can reduce the number of visible craters, all of which are required for an accurate age estimate, scientists are aware that their current estimate is not accurate (Cassata, 2014). In 2013, Farley et al. suggested an improvement to the existing potassium – argon method which allows scientists to determine the absolute age of key locations on Mars (Cassata, 2014).Through this information, they are able to estimate the age of the surrounding geologic features (Cassata, 2014). The successful implementation of this project would allow researchers to learn more about significant geological events related to aqueous and volcanic activity on Mars (Farley et al., 2013).

Radiometrics on Earth

In an article published in 2010, researchers adopted the uranium–lead method to study the growth patterns of the deep sea coral: *Enallopsammia rostrata* (Houlbrèque et al., 2010). This coral has distinct growth bands and by dating them researchers are able to calculate their growth rate. Additionally, by measuring the growth of this coral in a set amount of time and comparing this to their average growth rate, researchers were able to use these corals as a proxy to identify times when deep sea water was less favourable for growth (Houlbrèque et al., 2010).

Apart from dating corals, other forms of radiometric dating such as carbon-14 dating has been used to determine the age of a late Pleistocene human skeleton, named Naia. The skeleton was found at the bottom of a submerged cave in the Yucatan Peninsula(Chatters et al., 2014). Though well preserved, her skeleton proved difficult to date because the usual carbon-14 method of dating requires collagen but her bone collagen had leached out into the surrounding water. Therefore, scientists were originally only able to date her by noting her relative position in the megafauna graveyard she was surrounded by (Chatters et al., 2014). Determined, researchers were eventually able to successfully perform carbon-14 dating on the enamel on one of her teeth; this method determined her age to be about 13 000 years old (Chatters et al., 2014). This discovery was important for radiometrics and paleontology. By dating the skeleton and by analysing her mitochondrial DNA, researchers confirmed that Paleoamericans were originally migrants from Beringia who would later develop into Native Americans.

The History of Rock and Mineral Classification

Humans have valued rocks and minerals for millennia. Since the earliest recorded ancient societies, humans have been interested in them for their many unique and aesthetically pleasing appearances, as well as their practical uses in a wide variety of applications. For that reason, people have been classifying and categorizing rocks for a very long time. Back in ancient Greek society, philosophers like Theophrastus (371-287 BCE) and Pliny the Elder (23-79 CE) were keenly interested in how to distinguish different rocks and minerals. Theophrastus wrote about the subject in great length in his treatise, *On Stones*. Pliny the Elder had more of a passing interest. He sought to bring together the scientific knowledge of his time and collect it into a book, which he named *Naturalis Historia* (Natural History). However, he did little original research himself and mostly just used Theophrastus' research. In somewhat more recent times, Freidrich Mohs came up with a convenient system of classifying rocks based on their relative hardness, a method that is still used today in situations where modern analytical techniques, such as x-ray diffraction and x-ray fluorescence, are unavailable.

Theophrastus and Ancient Greek Classification

One of the earliest known collections of information on the classification of rocks is the treatise *On Stones*, written by the Ancient Greek philosopher Theophrastus (Caley and Richards 1956). Theophrastus lived in Athens and studied under the infamous Aristotle. He was one of his few students to fully embrace Aristotle's interdisciplinary nature. Theophrastus was known to have studied physics, politics, geology, history, and many subfields of biology. Partly due to his diverse interests, he was made the head of Aristotle's university, Lyceum, when the older philosopher retired in 323 BCE. Under Theophrastus' leadership, Lyceum received its highest student enrolment rate until the eventual fall of the Ancient Greek society.

Figure 3.20: *Three specimens of quartz with different colours*

In order to actually classify rocks and minerals, Theophrastus examined a wide number of characteristics. One of the characteristics that he used was colour, which is now known not to be the most reliable method of classification (Theophrastus 325-301 BCE) (Mange and Maurer 2012). Some minerals like quartz can come in several different colours (**Figure 3.20**). A more historical example is how Theophrastus used the term anthrax to refer to red garnets, red spinels, and rubies which all look similar but have very different chemical compositions. This was not detrimental to his classifcation though, as spinels and garnets do have some similar properties. They look alike and are fairly close in hardness with garnet tending to score between 6.5 and 7.5 on Mohs Hardness Scale, and spinel falling between 7.5 and 8. They also react similarly to fire (provided they are not heated to too high of a temperature). The ruby on the other hand is much harder with a rating of 9. Note that the values of Mohs scale are non-linear; the nature of it will be more precisely looked at in the section on Freidrich Mohs(1773-1839).

Theophrastus also looked at density, however he does not mention it very often, with *On Stones* only containing four references to density. He may have found density less useful or more tedious to calculate than other more qualitative methods. He could have had a difficult time calculating density since stones generally have irregular shapes and he likely did not know about the Archimedes Principle since Archimedes was born in the year Theophrastus died (287 BCE) (Hasan 2005).

Theophrastus made note of the hardness of rocks. Referring to it as the "power of not submitting to treatment" according to Caley, an English translator of *On Stones*. Theophrastus found that some stones were very soft and could be scratched very easily (likening them to solid earth). He seemed very confused that some stones could not be scratched by iron tools, but could be scratched by other stones. Unfortunately a lot of what Theophrastus said about the subject of hardness was very poorly preserved so the bulk of his findings on the subject are lost.

Theophrastus' rock classification tools included fire. He noticed that different rocks would react differently to being burned. He thought that the response that rocks and minerals had to being burned had to do with the amount of moisture contained within them. Theophrastus observed that certain rocks will melt when exposed to fire, while some rocks, instead of melting, will fracture and break when heated as though they resisted being burned. According to him, the rocks that melt would have a large amount of moisture in them but the rocks that fractured would have very little moisture. This hypothesis was supported by a rock that he referred to as *spinos*. *Spinos* was likely some form of asphaltic bitumen, a semi-solid material containing large numbers of combustible hydrocarbons. Theophrastus observed that when *spinos* was cut up and piled on top of itself, it would burn when exposed to sunlight. Adding water to it actually speeds up the burning rather than stopping it. These observations are consistent with what researchers see from asphaltic bitumen. The burning of *spinos* would follow Theophrastus' logic that the more moisture a rock has, the less resistant it is to burning. *Spinos*' reaction to water is similar to pouring water on any kind of oil or grease fire. Rather than smothering the fire like it would a wood fire, when water is poured on an oil or grease fire it does not mix with the oil (or in this case, bitumen). Since the water cannot prevent the reaction, the heat quickly turns it into steam and all of this rapid movement and formation of gases moves CO2 away from the fire and, comparatively, more oxygen-rich air into the fire causing it to burn more strongly. Theophrastus also found that certain rocks that normally would not absorb water like, obsidian (or as he called it, the Liperean stone), became more porous and would absorb water after having been burned. This also supports his hypothesis about moisture determining a rock's susceptibility to being burned.

Finally, Theophrastus also made observations about the "power of attraction" that some minerals have. He noticed that some minerals like lyngourion (an amber of solidified lynx urine) and lodestone (also called *Heraclean*) had this strange property that they would attract iron. He was, of course, observing magnetism. He did not discuss it very much though he did observe that amber made from the urine of tame animals was more weakly magnetic than that from wild animals, but he did not attempt to explain why this was.

The Ancient Greeks had several uses for rocks and minerals. One of the most frequently discussed usages in Theophrastus' *On Stones* is the making of seals. A seal is essentially a hard substance with an image carved into it such that it can make an impression of the image if pressed into a soft substance (Wilson 2013). Seals were often made in the image of their owner (if the owner was rich) or of important people. They were considered to be a sort of luxury item, like a Rolex watch only made of rocks. Theophrastus, being a famous philosopher, naturally had an interest in which minerals would make the best seals. He made particular note of the *smaragdos* as being a rock good for seals, citing its hardness and its seemingly magical effects on the human body. At the time, it was thought that looking at *smaragdos* would improve one's eyesight. It is ambiguous as to what exactly *smaragdos* was. However, it is known to have been a green, precious stone. Though the modern word for emerald is derived from *smaragdos*, some authorities in this area (Caley and Richards 1956) do not believe that Theophrastus' *smaragdos* was actually emerald. Pliny the Elder (another Greek Philosopher interested in stones) stated in his work, *Naturalis Historia*, that there were twelve kinds of *smaragdos* with varying properties (including hardness), further confusing the issue since Theophrastus talks about it as though it is one type of stone.

Freidrich Mohs and 19th Century Classification

While the field of geology was still heavily studied between Theophrastus' time and the 19th century, another key figure in the classification of rocks did not appear until Freidrich Mohs came about. Mohs was a German geologist (Bressan 2014) born in 1773 to a small town in Germany. Another interdisciplinary scientist, Friedrich Mohs decided to go to the University of Halle in 1796 in order to study chemistry, mathematics, and physics. However at school he found that his real interests lied within the fields of geology and mining so after graduating from Halle, he went to the Royal Saxon Mining Academy of Friedberg. At Friedberg, Mohs studied under the famous geologist Abraham Werner (1749-1817). Mohs was very impressed by one of Werner's papers where he used basic physical characteristics in order to classify rocks rather than the more complicated analytical chemistry tools they had at the time. Mohs was so fond of this approach that in 1804 he published what he considered to be a simple “student's guide” to rock and mineral classification where he discussed aspects like crystal shape, colour, and density, amongst other things. In 1824 Mohs published *Essentials of Mineralogy* which contained his famous mineral hardness scale that is still used today.

Mohs hardness scale is based on a simple geological principle. If one mineral is harder than another one then, if the two minerals are rubbed against each other with sufficient force, the harder one will scratch the softer one (Mohs 1825) Mohs took ten minerals of varying hardness and assigned them a value based on which ones they scratched and which they were scratched by out of the other nine minerals. Mohs used talc, gypsum, calcite, fluorite, apatite, orthoclase feldspar, quartz, topaz, corundum, and diamond and assigned them hardness values of one through ten respectively. Mohs' scale is somewhat arbitrary though. It does not follow any sort of mathematical relationship. For example, fluorite's hardness relative to calcite is not proportional to gypsum's hardness relative to talc. While now humans have instruments such as the Turner-sclerometer to tell us the absolute hardness of minerals, it can be much cheaper and more convenient to use Mohs’ scale instead, especially since hardness is not the only characteristic used to classify minerals. An image of a typical kit containing Mohs' ten minerals is included (**Figure 3.21**).

Figure 3.21: *A typical kit containing Mohs’ ten minerals, often used for scratch tests in the field*

Mohs had a particular interest on the optical properties of minerals. Mohs looked heavily at lustre, colour, streak (which he noticed was sometimes different than the colour of the mineral), and diffraction. Mohs classified minerals based on five different categories of lustre, the categories being metallic, adamantine, resinous, vitreous, and pearly, with some of those categories breaking up into two or more subcategories. Like Theophrastus, Mohs also thought that the colour of a rock or mineral was a good predictor of what it was. Luckily, Mohs went a step further from just looking at colour and also looked at the streak. The streak of a rock or mineral is the colour of the powder produced when it is scratched. Unlike the colour, the streak remains constant for all minerals, so if one mineral has a certain streak, then all minerals of that type have the same streak. This makes streak a valid identification and classification tool.

Mohs also mentioned transparency, however he did not seem to think that it was very useful for classification purposes. He did say though that transparent minerals become less transparent when they are impure, which is in agreement with what Theophrastus wrote about transparency in *On Stones*.

It seems that Mohs had a much greater propensity for licking rocks than Theophrastus did. While Theophrastus briefly mentions the scent of a few rocks and never brings up taste, Mohs went as far as to categorize many different possible scents and flavours rocks and minerals could have. Mohs identified rocks that would produce the smell of garlic, empyreumatic odours (burning organic matter), or other odours when rubbed together. Also in discussing taste Mohs broke down the flavours of rocks into eight categories, comparing each one to a certain substance (e.g. he described that a saline flavour is like table salt, a sour taste is like an acid, etc.). He stated that rocks were usually flavourless, and that all acids and salts would produce a flavour, so the taste of a rock would be indicative of the presence of a salt or acid.

Modern Analytical Techniques

With modern times comes more modern techniques. Rather than having to rely on qualitative observations like Mohs and Theophrastus, humans now have a number of techniques capable of determining what type of rock or mineral is being examined.

X-ray Diffraction

One of these techniques is x-ray powder diffraction (Dutrow and Clark 2015). X-ray diffraction is used to determine the elemental composition of a certain substance. However, since rocks are a combination of minerals, this technique does not work very well on rocks. Instead, x-ray diffraction is used to identify or determine the composition of minerals. The applications of x-ray diffraction are not limited to geology and it sees widespread usage in other fields as well. Conducting x-ray diffraction requires a few things. It requires a cathode ray tube for generating x-rays, an x-ray detector, and some sort of surface or container for the sample. Depending on the type of mineral being analyzed, a different piece of equipment will be required to grind it up. For example, some softer clay minerals can be ground up by hand with a mortar and pestel, whereas harder minerals will require more specialized equipment like a ball mill or a shatterbox. The substance being analyzed also needs to be very pure or else the data gathered will not make much sense.

Essentially, x-rays are fired at the target material and the detector is used to check at which angles there is constructive interference between the x-rays (Dutrow and Clark 2015). Constructive interference between the x-rays occurs based on how far the x-rays travel into the substance. This depends on two things, the angle the x-rays are being fired at, and the spacing between the layers of atoms in the substance. As the x-ray beam is rotated around, certain spots of constructive interference will be found (where the x-rays constructively interfere there will be large peaks in the amount detected). Since the angle the x-rays are fired at, and the wavelength of the x-rays are known values, the spacing between the atoms can be calculated using the Bragg condition ($2d\sin(\theta) = n\lambda$). Where d is the spacing between the atoms, θ is the angle of incidence, λ is the wavelength of the x-rays, and n is some positive integer. The value of n is known based upon which peak in the graph is being looked at, so d can be solved for. This d value is unique for different substances, comparing it to known d values can determine what the material is made of.

X-ray Fluorescence

Another technique used to analyze the composition of rocks is x-ray fluorescence (Wirth and Barth 2015). X-ray fluorescence works better on mixtures than x-ray diffraction and, as such, can be used on both rocks and minerals. Usually rocks and minerals are ground into a fine powder in order to analyze them using x-ray fluorescence. X-ray fluorescence works by firing high energy x-rays at a substance. When this happens, the inner electrons in the atoms become excited and can ionize. When the inner electrons ionize, outer electrons will lose energy and "fall down" to where the inner electrons were. The energy lost by the outer electrons is released in the form of more x-rays. This will cause the material to then release a spectrum of x-rays. Each element has a unique spectrum of x-rays that will be released and so the composition of the substance can be determined (both what is there and how much of it). The only problem is that it works at the atomic scale and not the molecular scale, so for substances like calcium carbonate (with the molecular formula $CaCO_3^{2-}$) the oxygen spectrum will be three times as strong as the carbon and calcium spectra for that molecule. Since the final spectrum recorded will be the sum of all of the spectra from all of the atoms in the substance, a wavelength-dispersive x-ray spectrometer (WDS) may be used. A WDS uses a crystal to isolate only the x-rays of interest. Once certain atoms have been identified with WDS, their unique spectra can be subtracted from the total spectrum found, then that spectrum can be further analyzed for characteristics of other atoms. X-ray fluorescence is often used in geology labs when other techniques are either wouldn't work or are unavailable. For example, while it would normally be preferable to use x-ray diffraction over fluorescence due to its high accuracy and simpler equipment, diffraction can not handle mixtures like fluorescence can.

History of Metallurgy in Europe

The towering pagodas of China, expansive temples of Greece, and monumental pyramids of Egypt all showcase the ingenuity of humankind when it comes to harnessing materials from the Earth. Metals have been the most important substance in advancing structures, agriculture, warfare, and transport throughout human history. The process of extracting and refining metals is known as metallurgy, a process that has changed tremendously over time. Before the 18th century, metallurgy was defined as the melting, smelting, and working of metals, and the spread of this knowledge varied greatly between civilizations (Tylecote, 2002).

The Opening of the Doors

Given the immense value associated with acquiring and refining metals, techniques associated with metallurgy have long been kept hidden from the masses. For much of European history, ruling families engaged with these industries constituted part of a tight-knit community that tended to pass down information and skills discreetly from one generation to the next (Aitchison, 1960).

Over time, a few individuals have documented these secretive trades. As "outsiders" of the industrial families, these writers have opened the eyes of much of the world to the knowledge and techniques of metallurgy (Aitchison, 1960).

Ancient Rome

Metal working in Ancient Rome (c.8th century BCE-4th century CE) is notable for its compilation and dissemination of the best techniques throughout the Roman Empire, which allowed for the successful development of the metal industry (Tylecote, 2002). Considerable military and civil demands for metals led to substantial increases in production. Lead, which had little use in pre-Roman times, was required in large quantities for plumbing (Habashi, 1997). In addition, copper-based alloys and gold were used extensively in coinage. One of the main requirements from both a civil and military point of view was for iron, which was used to create swords, tools, and structural foundations. Knowledge of precious metals extraction and refinement was also explored by the Romans (Williams, 2012, Tylecote, 2002).

Pliny the Elder

One of the first written records of metallurgy comes from the ancient Roman Scholar Gaius Plinius Secundus (Pliny the Elder, 23-79 CE) (**Figure 3.22**).

Figure 3.22: *(right) Illustration of Pliny the Elder (23-79 CE, a Roman scholar and author of* Naturalis Historia*, which included a thorough overview of Roman metallurgy (Morello, 2011).*

Born into an elite family, he was afforded the opportunity to gain military experience and a well-rounded education. After the revolt against Emperor Nero in 65 CE, Rome was plunged into civil strife (Brunt, 1959). Pliny successfully allied himself with the new emperor, Vespasian (Healy, 1999, p.2), and was rewarded with a series of procuratorships (Maxwell-Stuart, 1995) that provided him with the opportunity to govern over a number of Rome's provinces. Although the exact locations of these positions are subject to some scholarly debate, Pliny's role as procurator was instrumental in allowing him to observe and collect information for inclusion in his seminal work *Naturalis Historia* (Morello, 2011), a detailed collection of botany, philosophy, and the physical sciences, including a thorough overview of Roman metallurgy.

Among many other subjects, Pliny presents a view into the world of gold mining in deep

Spanish mines (*arrugiæ*). In particular, he describes how workers separated ores from rocks by heating up the surfaces and then immediately poured vinegar within them, inducing cracks in a process now known as fire-setting (Secundus, 77a, p.101).

To prevent excess smoke from appearing in the *arrugiæ*, miners more frequently smashed large pieces of iron against rocks to crack them and extract the gold ores (Secundus, 77a, p.101). In cases where beds of rock were too thick, iron wedges and hammers were used to scrape exterior layers. Large basins of water were then gathered via aqueducts at higher elevations outside of the mines; the basins were released into the mineshafts and galleries, clearing out any debris and leaving behind pure gold deposits (Secundus, 77a, and p.102-104). It is this level of detail that truly separates *Naturalis Historia* from other works of the time and contributed to its legacy as a formidable text.

Perhaps the most important aspect of Pliny's work is his desire to make his writing accessible to as many people as possible. As he notes, the book's extensive table of contents is designed to ensure that "any one may search for what he wishes, and may know where to find it" (Secundus, 77b, p.11) without needing to consult the entire source (Morello, 2011, p.163).

The Middle Ages

The Middle Ages occurred after the decay of the Roman Empire and spanned the 5th to the 16th centuries. Several technological advances during this period led to the ability to extract great quantities of metals of higher purity (Tylecote, 1990).

Notably, furnaces used to isolate metals from ores experienced a surge in improvement. For the first time, water power was harnessed to provide the necessary air flow for ironworking. This arose through investments from monastic institutes, which were the only bodies in Europe with enough capital and interest to fund the iron industry. Water power was essential for building larger bloomeries, the iron smelters of the time (Espelund, 2013). This development paved the way for the introduction of the blast furnace into Europe, one of the most interesting subjects in the history of ferrous metallurgy. However, blast furnaces originated in China long before their usage in Europe. It is possible that the Europeans independently developed them, but their introduction into European society occurred when contact between the East and West was well established and information could have easily travelled (Tylecote, 2002). Silver production also increased in the Middle Ages due to the insurgence of silver coinage (Blanchard, 2001).

Bartholomaeus Anglicus

New pieces of writing describing the nature of metallurgy were not significantly seen again until well into the Middle Ages. Of particular importance during this later period was the encyclopaedia *De Proprietatibus Rerum* (*On the Order of Things*) (**Figure 3.23**), written by the English Franciscan friar, Bartholomaeus Anglicus (c.1203-1272). Just as Pliny is best known for his *Naturalis Historia*, so too is Bartholomaeus most remembered for his significant literary contribution (Seymour, 2004).

Figure 3.23: *(left) Image of early French version of* De Proprietatibus Rerum*, and encyclopedia of the natural world written by Bartholomaeus Anglicus (c. 1203-1272) (Seymour, 2004)*

Despite the importance of *De Proprietatibus Rerum*, few details of Bartholomaeus' early life are known. As a young man, he may have studied at the University of Oxford prior to his arrival in Paris in 1224 (Seymour, 2004).

Bartholomaeus then moved to Saxony, where he began teaching theology at the School of Magdeburg. It was during this time that he wrote *De Proprietatibus Rerum*. An important religious figure, Bartholomaeus held many other titles during his life, including Minister of Austria (1247) and Bohemia (before 1255). His influence within the Catholic Church continued to rise; in 1256, Pope Alexander IV appointed him as the Church's leader in Bohemia, Moravia, Poland, and Austria. He was later appointed bishop of a cathedral in Łuków, Poland. However, Mongol raids in the region prevented him from serving out this position (Seymour, 2004).

Figure 3.24: *(right) An example from the Middle Ages of a gold-plated jewellery piece. Note the possible difficulty in discerning this from one made of solid gold.*

After its completion in Latin by Bartholomaeus in 1250, *De Proprietatibus Rerum* was later translated into several languages, including French, Spanish, Dutch, German, and English (Hunt, 1975). Given the many versions and potential modifications of this encyclopedia, it can be difficult to discern the true words and intent of Bartholomaeus. Yet, all translations of *De Proprietatibus Rerum* highlight the unique nature of this text: despite his lack of experience in metal work, Bartholomaeus was a rare member of a group of individuals responsible for discerning information surrounding metallurgy and other areas of interest to society (Aitchison, 1960a).

Since the days of Pliny, there had been little change in the process of gold extraction and metallurgy. However, a persistent problem for purchasers of gold had been ensuring that the product was genuine rather than simply a thin layer of gold placed on top of the base of another, less valuable metal (Aitchison, 1960a, pp.313-314). Bartholomaeus' journey through France, Flanders, and Holland prior to his arrival in Saxony took him past many goldsmiths. Along the way, he is thought to have observed the practice of plating a thin sheet of gold onto a plate of silver, a process that he refers to as "meddling" (**Figure 3.24**). In particular, Bartholomaeus warns that the "joyning [of gold and silver] is inseparable, so that they may not afterward be departed asunder", highlighting the notion that joining of the two metals was a permanent and deliberate trick by certain goldsmiths (Hunt, 1975, p.27).

The inclusion of this precaution indicates the commonplace nature of meddling at the time of *De Proprietatibus Rerum's* publication (Hunt, 1975), an expression of Bartholomaeus' desire to educate readers about this form of deception. In response to frequent reports of fraud, royal authorities began to play a more significant role in ensuring consistent quality of gold, including the institution of stiff punishments for those caught committing this act (Aitchison, 1960a). Notably, in 1260, the Provost of Paris outlined a number of measures designed to regulate the goldsmith industry, which had failed to stop the proliferation of this problem (Cripps, 1881). Similar reforms were enacted in London during the early 14th century, with the establishment of formal regulation of the London guild of goldsmiths (Cripps, 1881, pp.21-22; Aitchison, 1960a, p.316). In 1327, a royal charter from King Edward III banned goldsmiths from using silver in their businesses in an effort to prevent the continuation of meddling (Cripps, 1881, p.22).

In light of these ideas, Long (1979) argues that the true motivation of Bartholomaeus' work lies in his epilogue, where Bartholomaeus explains that "the simple and the young…can readily find their meaning herein - at least superficially" as an alternative to consultation of Biblical texts for guidance (p.1). Whether Bartholomaeus truly wrote this part of his work is disputed; other epilogues have been found to have been written by local publishers (Duff, 1906, pp.4-5). Yet, this idea certainly contains elements of truth, since *De Proprietatibus Rerum* can be thought of as the story of a pious man seeking to enlighten a world that may not be able to glean such knowledge from the Bible. In a world full of deceit, Bartholomaeus likely imagined himself as a redeemer of corruption, with his religious background providing the backbone for the creation of his work.

The Renaissance

Less than 300 years after Bartholomaeus' death, Europe found itself on the cusp of the Renaissance (c.14th century-17th century), gradually turning its back on the Middle Ages and the legacy of alchemy. The Renaissance forever shaped the nature of the continent, propelling a number of great literary works including those of William Shakespeare, Francis Bacon, and Thomas Moore. Metallurgical developments in the Renaissance laid the foundations for the Industrial Revolution in the 18th century. Blast furnaces spread to most areas of Europe and huge improvements were seen in their construction, size, and quality of metal production (Tylecote, 2002).

Georgius Agricola

For metallurgist enthusiasts and the general public, this period of time also brought perhaps the greatest single contribution to the documentation of metallurgy: *De Re Metallica* (*On the Nature of Metals*) by the German physician Georgius Agricola (1494-1555), the father of modern metallurgy (Aitchison, 1960b, p.290).

Similar to both Pliny and Bartholomaeus, Agricola lacked the traditional background in metallurgy or mining common among most individuals with knowledge of the field. An educated man, he graduated from the University of Leipzig in his early twenties with a Bachelor of Arts. Agricola then held a position as a teacher at a school in Zwickau, Saxony (Wilson, 1994, p.137). In 1524, he travelled to Italy in 1524 to complete his medical degree (Weber, 2002). He later became the appointed physician in Joachimsthal, a mining town in Saxony. It was there that Agricola's knowledge of mining and metallurgy developed, devoting any free time that he had to the mines, smelters, and workers of Joachimsthal (Wilson, 1994, p.138). Despite living in Germany during the time of the Reformation, Agricola remained a devout Catholic, a remnant of his education in Italy. A well-respected man even within the Protestant community, he held several political positions including Burgomaster (chief magistrate) of Chemnitz (Wilson, 1994, p.138).

De Re Metallica is a thorough collection of metallurgy of the time, with a specific focus on the dominant German metallurgic industry (Aitchison, 1960). Perhaps the most defining features of Agricola's work are the elaborate illustrations of many metallurgic methods (***Figure 3.25***), included purposely to "delineate their forms, lest descriptions which are conveyed by words should either not be understood by men of [the time], or should cause difficulty to posterity" (Agricola, 1556, p.xvi). Agricola's desire to ensure clarity for all readers within his works is akin to efforts seen in prior works by Pliny and Bartholomaeus. Yet, in the case of *De Re Metallica*, the significance of illustrations cannot be understated: for the illiterate individual, images provide insight when words cannot.

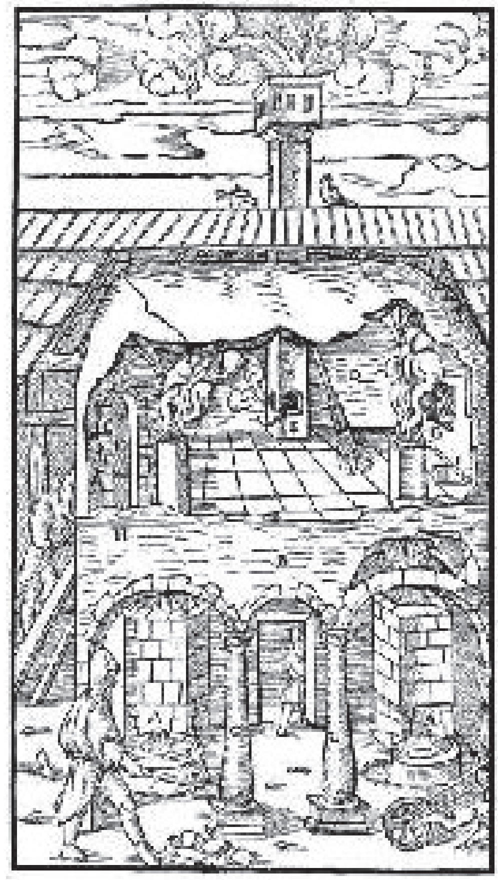


Figure 3.25: *An example of an illustration from* De Re Metallica*, a very influential book on metallurgy by Georgius Agricola (1494-1555).*

Similar to the cautions expressed by Bartholomaeus, Agricola warns of the deception associated with plating a layer of silver over gold. Much of this caution is reserved for Agricola's distrust of alchemy, warning that some within the field would even go so far as to "colour [base metals] to represent gold or silver" (Agricola, 1556, p.xxix). Yet, at other times during his work, it appears that Agricola understands the unique transitions taking place within Europe. The arrival of the Reformation and Renaissance coincided with Europe's gradual shift from alchemy towards the notion of scientific investigation. In the context of smelting, he describes how workers "combine in right proportion the ores, which are part earth...

pour in the needful quantity of water…modern with skill the air from the bellows…[and] throw the ore into that part of the fire which burns fiercely" (Agricola, 1556, p.380), cleverly interpreting each of the four traditional elements within the context of practical production of metals (Aitchison, 1960a, p.379).

One of the many descriptions provided by Agricola surrounds smelting, a process used to isolate metals like copper, lead, and iron from ores. Of particular interest is Agricola's description of a special shaft furnace designed to catch valuable metal residues from being emitted as fumes into the air (Agricola, 1556, p.396). In this furnace, two shafts release metal fumes into a dust-chamber, which prevents the loss of minerals known as *cadmia*. which are later scraped off the walls and sprinkled onto the ores. Although not explicitly stated, *cadmia* is believed to have been a zinc oxide known as furnace calamine (Agricola, 1556, p.394), which can react with copper metal to form an attractive alloy of brass (Martinón-Torres and Rehren, 2002).

De Re Metallica remained the dominant metallurgic text for centuries, its vivid descriptions and illuminating images captivating tradesmen and interested readers of all stripes (Aitchison, 1960a). Like others before him, Agricola was a complicated man, living in a time of transformation as the world began to shake off the yoke of the Middle Ages. The significance of mining and processing metals would only increase in the coming years as society advanced forward. At times, it is easy to diminish the significance of these works, given how accessible information remains in today's information age. In this respect, it is essential to realize the true value of literature by writers like Pliny, Bartholomaeus, Agricola, and others in eras where industrial knowledge was a closely guarded secret.

Metals in the Modern Age

From the gears that keep machinery running to the trains, boats, and planes that move people back and forth with ease, down to the very foundations that support homes and other buildings, it is clear that metals form the framework of the modern world.

Ubiquitous Metals

Given the myriad of applications associated with metals, they are essential components of many different systems present throughout society.

Metals such as zinc, copper, and magnesium are vital for physiological processes (Tapiero and Tew, 2003) and most pharmaceutical preparations contain these or other metallic substances (Cole, May and Williams, 1983). Some skin care products and cosmetics also utilize precious metals such as gold and silver (Thomas, 1987).

The use of metallic molecules in medicine has been growing, and can be seen in advances such as metal-based cancer drugs (e.g. cisplatin, auranofin; Milacic, Fregona, Dou, 2008), or in gold and silver nanoparticles as a novel method for drug delivery and biological imaging (Zhang et al., 2007).

In the transportation industry, metals remain essential. Commercial aviation would not have flown off without aluminum, a light-weight metal with high tensile strength. Trains, ships, buses, and cars are usually comprised of steel alloys and aluminum for similar reasons. Aluminum and tin are also often the material of choice for the packaging of goods and materials (Landner and Reuther, 2004).

Most, if not all, of the structures and buildings we encounter are made of various metals such as carbon steel, stainless steel, aluminum, and copper (Landner and Reuther, 2004).

In quite the literal sense, metals power the world. Copper in cables allows the movement of electricity over large distances. Lead, nickel-cadmium, and lithium-ion are the key components in batteries, a form of portable power. Lithium-ion batteries are most commonly used for consumer electronics. Electronics themselves contain various precious metals, such as copper, silver, palladium, and gold. They are all excellent conductors, with gold in particular being widely used in the wiring and circuitry of motherboards (Harper, 2004) (***Figure 3.26***).

Impacts of Metal Extraction

Despite their many benefits, the widespread usage of metals has led to a number of negative environmental impacts.

Figure 3.26*: An image of a gold circuit board.*

Metal ores are obtained from the Earth through mining and quarrying, which involves excavating and processing large volumes of rock. Issues with mining and quarrying are that these processes generally leave the landscape scarred, resulting in habitat fragmentation or destruction, and the loss of biodiversity in the surrounding environment. Processing and metal extraction from the ores generates a large amount of pollutants, such as the release of carbon monoxide from the blast furnace extraction of iron, and sulphur dioxide gas through copper extraction from sulphide ores. There exist many methods to aid in reducing these pollutants, such as gas scrubbing which can recover compounds (Dudka and Adriano, 1997).

Improper Recycling

One of the biggest problems involving metals is the improper recycling of electronics (Guo et al., 2009). Due to rapid advances in technology, consumer electronic products are experiencing an unprecedented turnover rate. However, electronic products are not easy to recycle and an astoundingly large number of them end up in landfills, posing many environmental risks (Graede, 2010).

Almost all electronic devices contain lead, a highly toxic heavy metal (Harper, 2004). Lead can leach out of landfills and enter groundwater systems (Brown, 2004). Cadmium, nickel, and lithium are also toxic heavy metals that are found in electronics, specifically batteries (Harper, 2004). Studies on leachates in landfills with electronic waste found significantly higher concentrations of heavy metals as compared with areas lacking electronic waste (Kiddee, Naidu and Wong, 2013). Toxic heavy metals tend to persist in living systems and prolonged accumulation can cause serious deleterious effects (Singh et al., 2011).

With lax environmental regulations and improper screening of recycling processes, many electronic waste recycling facilities in developing countries utilize crude and harmful techniques for extracting precious metals, such as gold, from the waste. Much of this waste is a result of large numbers of illegal exports from developed countries. Unregulated burning, melting, and usage of chemical baths have caused severe contamination of toxic heavy metals into terrestrial and aquatic ecosystems, as well as vastly decreasing atmospheric quality in the area. Near these unregulated electronic waste facilities, heavy metals have been shown to contaminate the soils and induce contamination of harvested crops. The accumulation of relatively low levels of heavy metals can lead to organ malfunction and chronic syndromes (Fu et al., 2008).

Metals are extremely important in the modern world and have allowed for the development of structures, machines, medical products, and electronics. However, there exist negative consequences of this widespread usage. Improving the extraction and processing of metals, as well as increasing electronic waste recycling, is a major challenge that needs to be addressed in this century, lest we impart irreparable damage on the environment.

Weather Forecasting

Meteorology, the study of weather, is commonly seen as one of the least exact sciences. Its foundations lay in discerning the future. The history of meteorology is filled with curious individuals compelled to look upwards for clarity. The pioneers of this field are some of the most innovative minds in science. Unlike other fields where controlled experiments can be created and measurements can be taken, it is impossible to directly measure the underlying processes that control our atmosphere. As a result, the study of meteorology is founded in detailed observations as no tangible substances, sparing rain, can be collected.

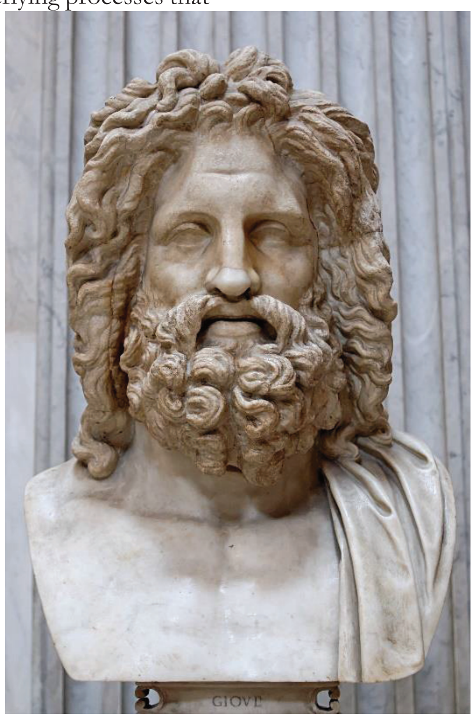


***Figure 3.25**: Bust of Zeus, Otricoli (Sala Rotonda, Museo Pio-Clementino, Vatican). Religion was a highly pervasive principle at the time. Explanation of natural phenomena as the actions of the Gods was rampant. Respect and deference to these deities existed in both artistic and scientific spheres. These beliefs hindered investigation as statements to the contrary could be seen as sacrilegious. However, when philosophers began to question these facets of society theories that did not explain phenomena with Godly actions began to develop.*

The skies have been attached to ethereal connotations throughout history shrouding this already distant arena in mystery and lore. These connotations likely arose from respect and fear as predicting the weather can have lifesaving effects. Knowledge of when a storm is near, or when the next rainfall will arrive can prevent large scale fatalities. Curiosity around what drives these events is a uniting factor between those that have contributed to unraveling the mystery of the skies.

Perspectives from Ancient Greece and Rome

Insights into ancient notions about the weather are found in the earliest extant ancient Greek works, the Homeric and Hesiodic poems (a prominent example being The Odyssey), include many references to meteorological phenomena. These archaic Greek ideas inferred a deliberate interpretation on how the concept of weather was viewed as a purely theological concept; a method of Gods to impact man. These mostly used theories of gods and goddesses such as Zeus and Kalypso as a means of describing control of the weather (**Figure 3.25**). Both poets are quoted later by numerous authors on meteorology (Taub, 2003; Rosen, 1997). One poem called *The Works and Days* was influential in correlating astronomical phenomena with seasons and weather events (Taub, 2003). Another work, *The Iliad* notes the annual cycle of recurrent seasons and assigned weather characteristics such as late summer to early autumn as having violent rain and flooding, the time of the star known as Dog-of-Orion, as well as being a time of harvest and fever.

A topical question that was raised and debated by great minds of the time was regarding the relationship between the 'signs' and 'causes' of weather. Some authors suggested a causal relationship, accepting that celestial events had seasonal and meteorological influence. A specific theory, for instance, was that since the Sun controlled the year's seasons (a commonly accepted theory at the time), that each of the stars also had a force of its own to create effects on the Earth. A commonly mentioned point in these discussions was looking at rainstorms associated with Saturn and heat accompanying the rising of the 'Dog-star', called Sirius (Taub, 2003; Buchan, 1868). Other writers disagreed. Some acknowledged that although the view was well-established, it was wrong. That there was no causation, and that the star only served to mark when the heat of the Sun is greatest.

Finally, a more vehement rejection of any significance with astrological signs existed. Epicurus (342-271 BCE) argued that there were too many variables to be able to draw lines of correlation. That there may be multiple possible causes rather than a single explanation for natural phenomena (Taub, 2003; Gregory, 2013). It is important to note that although these theories couldn't be empirically substantiated, rigorous, serious and widespread observation methods were established in the field of study for astro-meteorological theories at the time (Taub, 2003).

Aristotle (384-322 BCE) wrote many works relating to different aspects of human life. In these, he indicated the order in which he studied, using a "top-down" approach, beginning with astrology, moving to meteorology and then turning to animals and plants. Within this hierarchical treatment of nature, meteorology having a central position was to reflect the mediating role these processes serve; caused by motions of celestial regions and in turn affecting living things on Earth (Taub, 2003; Aristotle, 347 BCE).

In his works that specifically pertain to weather, he introduces most with a disclaimer that alludes to the frustration of the time which is that, in regard to meteorological phenomena, in some cases he was not certain whether or not his hypotheses were correct. He notes that concepts he outlines would be difficult, and maybe impossible to grasp. This was due to the common problem of information accessibility when it came to weather phenomena. Factors such as distance and difficulty of observation (for example, in the case of clouds) and rarity of occurrence (lunar rainbows) limited the ability to observe the phenomena (Taub, 2003).

Aristotle's main hypothesis was that the elements themselves (Earth, Fire, Water, and Air) are material causes, coupled with the motion of ever-moving bodies (in the celestial sphere) should be regarded as the efficient cause of terrestrial events. For a specific example, in the topic of rain, Aristotle maintains that the Sun's revolution is the moving cause (Taub, 2003). This topic of rain is quite interesting as he put forward a view offering a conjunctive explanation, incorporating both the traditional beliefs of the time (Zeus and other Gods), with a physical cause (water as it is heated by the Sun rises, cools and condenses, falling to the earth as rain). It has been observed that this could have possibly been Aristotle's subtle way of trying to shift understanding from acts of god to a purely natural process (Taub, 2003).

For Greek and Roman meteorologists, trying to explain meteorological events was almost a shared project, motivated by a number of collective concerns such as the desire to understand frightening and dangerous phenomena. Ancient authors were participants in an extended intellectual community, who built upon each other's ideas, observations and prognostications. They supported and contributed to projects of predicting and explaining meteorological phenomena moving humanity from leaning only on theological debate to expanding to include questions on physicality of large phenomena (Taub, 2003).

Development of Meteorological Instruments

Figure 3.26: This barometer was approximately created in the late 1800s and so has the more elegant design of the manufactured era. This barometer would be used in a home, with categories that are easy to understand to allow for general usage.

Measuring instruments marked the beginning of scientific, empiric study of weather. One of the very first being the invention of the mercury barometer in the mid-17th century by Evangelista Torricelli (1608-47), who was an Italian physicist-mathematician. Another important and nearly concurrent development was that of a reliable thermometer. Who was the primary creator of the thermometer is a matter of contention as it depends on at what point the device in question can be considered a thermometer (Encyclopædia Britannica Online, 2015; Middleton, 1964).

A succession of notable achievements by chemists and physicists of the 17th and 18th centuries contributed significantly to meteorological instrument research. The formulation of the laws of gas pressure, temperature, and density by Robert Boyle (1627-91) and Jacques-Alexandre-César Charles (1746-1823) created great strides in the necessary understanding required to create reliable measurements. It was only

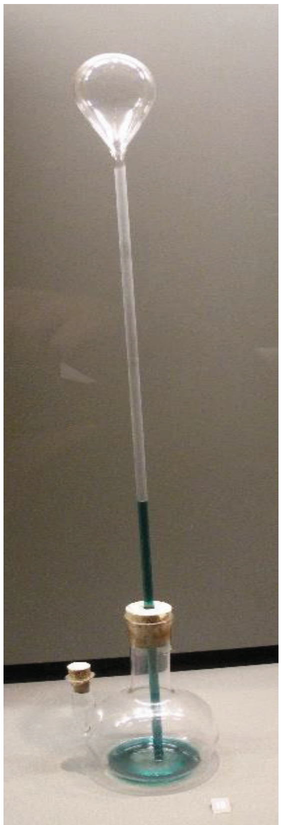


Figure 3.27: The thermoscope depicted contains a coloured liquid to allow for ease of observation. As the temperature of the system decreases the air within the bulbous section of the instrument contracts and the liquid rises. As the temperature of the system increases the air expands and the fluid lowers. These pre-thermometers were useful at examining changes in temperature but not actual values of thermal energy.

during the 19th century that these ideas began to produce results in terms of useful weather forecasting tools (Encyclopædia Britannica Online, 2015).

By deriving its Greek roots, *baros*, weight and *metron*, measure, it becomes clear that the barometer is an instrument used to measure air pressure (**Figure 3.26**). In early 17th century Italy there were many Italian scientists independently working on the principles of vacuums and air pressure, however, it was Torricelli that first publicized his experiments in 1643 with what became known as the first working barometer. This instrument utilizes the principle of a vacuum to measure the weight of the air (Ellis, 1886).

At first, water was used to measure air pressure. It is important to note that Torricelli's mentor, Galileo (1564-1642) is recognized as the first to experiment with a water type vacuum apparatus in early 1642, but his primary objective was to simply ratify the "vacuum theory", and he did not extrapolate his findings to deduct that changes in the weather correspondingly caused air pressure fluctuations. Torricelli was the first to notice that air pressure changes, related to weather changes, indeed caused the water level to rise and fall within a thirty-five foot tube experiment he set up within his home (Ellis, 1886 and Middleton, 1964).

To try and make this instrument smaller, Torricelli thought to use a liquid heavier than water, mercury, creating a shorter tub of only thirty-two inches. It wasn't until about the year 1670 that barometers were being produced and sold as a weather instrument to be used in private homes. By the end of the 17th century, many clock makers, furniture makers, and opticians began to market ornately designed barometers for personal use (Ellis, 1886 and Middleton, 1964).

For the next two hundred years, the mercury barometer became very popular, and a societal connotation began where to possess one was a symbol of great achievement. Records show there were over 3,500 registered barometer makers between 1670 and 1900. Today, it is a rarity to even discover a working mercury type barometer, as most were destroyed or replaced by the current day aneroid type barometer (Ellis, 1886).

The thermometer, a similar meteorological instrument to the barometer, evolved from a device known as the thermoscope. The distinction being the thermometer possesses a scale while the thermoscope does not. The invention of the thermoscope is often credited to Galileo in 1607 however, Sanitorio (1561-1636), Drebble (1572-1633) and Fludd (1574-1637) are sometimes also cited as the inventors (McGee, 1988). The development of the thermoscope highlights the collaborative nature of discovery as new ideas from chemists and physicists were sparking innovation by other great thinkers and vice versa.

A thermoscope is a device which traps air in a bulb so that as the air expands or contracts in response to a temperature change it moves a liquid column within an adjoined tube (**Figure 3.27**). These devices were not sealed and were therefore not subject to constant pressure and suffered from evaporative losses. These devices were expansions upon experiments originally conducted and recorded by ancient Greeks: Hero (10-70 CE) and Philo (25 BCE-50 CE) of Byzantium in the first and second century BCE (McGee, 1988). In 1613 Sagredo (1571-1620) used the thermoscope to compare the temperature of different sized lakes as they cooled in the winter and found that smaller water bodies cooled faster. He also compared the responses of the instrument to winter snow and summer heat denoting his readings as degrees of heat, making this the first true thermometer (McGee, 1988).

After this innovation the issue of standardization became a primary concern. Every thermometer craftsman produced a unique instrument and as a result comparisons could only be made by researchers using the same model. Over time technologies and techniques improved the calibration of the thermometer and standardized scales like Kelvin and Celsius were created. By defining temperature as the level of thermal energy and therefore the driving force of heat flow, these standardized systems could be created (McGee, 1988).

On the Modifications of Clouds

Despite the ability to now measure the effects of weather meteorologists still knew little about the processes themselves. Luke Howard (1772-1864), an English chemist and pharmacist with a passion for meteorology, provided new insight into the field through his work on the categorization and naming of clouds. Howard spent large portions of his school career looking observing clouds through the window. Like everyone else at the time Howard had little idea how clouds were formed, what kept them aloft or what drove them through their seemingly endless transformations. Howard's unbounded curiosity however, led him to previously unfounded insights (Thornes, 1999).

In December of 1802, Howard presented his findings after years of observation to the Askesian Society of London. Howard's classifications demonstrate the interdisciplinary nature of scientific progress (Hamblyn, 2001). His naming follows that of the Linnaean model, which he was previously familiar with through his work studying pollen in the summer of 1795 (Linnaean Society, 1855). Howard had observed that clouds were subject to certain distinct modifications, produced by the general causes which affect all the variations of the atmosphere; they are commonly good visible indicators of the operation of these causes. These modifications referred to the structure or method of aggregation and not the exact form or magnitude, which in many clouds is constantly changing (Thornes, 1999). In 1803, Howard published these findings on what were then the seven modifications of clouds, in an essay titled *On the Modification of Clouds*.

Howard's proposed there existed three simple modifications of clouds: the cirrus, the cumulus, and the stratus, titles still used today. Cirrus clouds are characterized by parallel flexuous or diverging fibres that may extend in any direction. Cirrus clouds were noted to have the least density the greatest elevation, and the greatest variety in extent and direction. Howard also observed that they were often the first to form after serene weather and that they had shorter durations when they formed at lower heights and in the presence of other clouds. Cumulus clouds are characterized by convex or conical heaps which increase upwards from a horizontal base. Howard noted that these clouds appeared the densest, were formed in the lower atmosphere and travelled with the same currents experienced on the Earth's surface. When forming they build off of a small irregular spot and continue to increase in size with the temperature before they begin to dissipate. Stratus clouds are characterized by a widely extended horizontal sheet that increases from below upwards. Stratus clouds appear to have a mean degree of density and are the lowest of clouds often resting on the Earth. Contrary to the cumulus clouds, Stratus clouds begin to form at sunset and will dissipate with dawn (Howard, 1803).

Figure 3.28: *Photograph of a solar halo. This is a phenomena that often forms with Cirro-Stratus modifications. These phenomena often precede severe weather and as such were used as warnings before a storm. Neither the cloud modification nor the halo cause the weather however, it is underlying atmospheric processes that cause both.*

In addition to the three simple modifications put forward, Howard also identified two intermediate modifications: the Cirro-Cumulus and the Cirro-Stratus, which too are still used in modern meteorology. The Cirro-Cumulus modification is characterized by small, well defined, round masses, in close horizontal arrangement. This modification was noted to be most common in the summer and is created as the tendrils of Cirri collapse into clumps. The Cirro-Stratus modification is characterized by horizontal or slightly inclined masses attenuated around a part or all of their circumference and found separately or in groups consisting of small clouds. Howard noted that this modification often precedes wind or rain and is almost always seen in the intervals of storms. In addition the Cirro-Stratus most commonly and completely exhibits the phenomena of solar and lunar halos, the Parhelion and the Paraselene (**Figure 3.28**; Howard, 1803).

Lastly, Howard, proposed two final compound modifications: the Cumulo-Stratus and the Cumulo-Cirro-Stratus or Nimbus, which akin to the five previous modifications are still in usage today. The Cumulo-Stratus occurs when a Cirro-Stratus blends with a Cumulus and appears either intermixed with heaps of the Cumulus or with a superadded wide spread structure on its base. This modification is formed in the interval between the appearance of the cumulus and the commencement of rain. The

Nimbus cloud is defined as a cloud or system of clouds from which rain is falling. It is a horizontal sheet, above which the Cirrus spreads, while the Cumulus enters it laterally from beneath (**Figure 3.29**) (Howard, 1803).

Howard's observations had widespread impacts on both art and science. His naming of the clouds sparked a wave of poetry and paintings. By providing a way to categorize clouds he provided poets with the language to write about the previously enigmatic. Howard's curiosity sparked artistic exploration in the works of Goethe (1749-1832) , who wrote a series of poems in gratitude to him, Shelley's (1792-1822) poem *The Cloud*, and John Constable's (1776-1837) paintings and studies of skies (Thornes, 1999). In addition to sparking artistic innovation his categorizations also propelled the field of meteorology. With terminology to classify and more accurately observe the skies, meteorologists could now explain some of the connections Howard theorized in addition to many new ones. Clouds are the observable products of atmospheric processes and by allowing for the detailed study of them Howard provided opportunity for the explanation of the underlying processes as well (Howard, 1803). Howard's system of classification was adopted and popularized by Ralph Abercromby (1734-1801) and Hugo Hildebrand Hildebrandsson. Hildebrandsson (1838-1925), upon request from the International Meteorological Committee, co-created the International Cloud Atlas in 1896. The Atlas continues to use Howard's framework and has been essential in the training of meteorologists and encouraging the consistent use of vocabulary when describing clouds, both important for early weather forecasting. To date Howard's original modifications are continuing to expand with new clouds continually being named (Hamblyn, 2001).

In addition to his seminal work on clouds, Howard was also a pioneer in urban climate studies. In similar fashion to his observations on clouds, Howard made several detailed daily observations of meteorological conditions in London publishing *The Climate of London* in 1818–20. This contradicted the leading theory on rain at the time, proposed by James Hutton (1726-97), which stated rainfall depended directly on the humidity of the air as well as the mixing of different air masses in the upper atmosphere. In addition, this text included the first mention of the heat island effect, showing that temperatures in London, compared to those simultaneously measured in the surrounding countryside, were 3.7°C warmer at night, and cooler during the day. Howard attributed what he referred to as high concentrations of city fog (now called smog) as the cause of this phenomenon. This is one of the first observations that humans could have effects on modifying climate (Thornes, 1999).

Howard's meticulous observation on clouds demonstrate not only the necessity of categorizations to the study of science but how interdisciplinary approaches and curiosity drive innovation. Howard's work provided a foundation for modern meteorology. His naming of the clouds inspired both artists and scientist to look up to the sky.

Figure 3.29: *Howard's illustrations of Nimbus Cloud. Above which cirrus spreads, while the Cumulus enters it laterally from beneath.*

Interpreting Current Weather Models

Since the advent of computers has dramatically changed the way humans can calculate minute changes in atmospheric conditions in such a way that is consistent and mathematical. This shift to numerical weather prediction models brought many new computer specialists and experts in numerical processing and statistics to work collaboratively with atmospheric scientists and meteorologists. This enhanced capability to process and analyze weather data pushed meteorologists to aspire to secure more observations with greater accuracy. Since the 1960s, there has been a growing reliance on remote sensing, particularly the gathering of data with satellites orbiting the Earth. By the late 1980s, local activity was interpreted by specialists through radar and satellite measurements. Larger than small city locale's forecasts were based on determinations of numerical models integrated by high-speed supercomputers.

Radar Models

Along with many other fields, weather forecasting experienced a very important breakthrough during and immediately after World War II. Before that, radar technicians had noticed "ghost echoes" on their relatively primitive scopes but did not realize at first that they were caused by thunderstorms (NOAA, 2006). The microwave radar was used in the 1930s by the British for monitoring enemy aircraft, but later its use it was found to give excellent detection of raindrops at certain wavelengths (5-10cm). This allowed the possibility of tracking and studying the evolution of individual showers or thunderstorms. It also allowed the modelling of precipitation structure in larger storms, such as rain bands (not clouds) in a hurricane (Encyclopædia Britannica Online, 2015). The size and violence of a hurricane on September 15th, 1945, in conjunction with its closeness to the Spring Lake, New Jersey radar station, resulted in observations of these types of structures. These observations later substantiated many general characteristic of hurricanes (NOAA, 2006). Throughout the period when this specific hurricane was near Florida the general shape of the disturbance was seen using radar to be identified in the shape of a figure six with clockwise spiralling "tails." At one time six distinct "tails" were observed, three of which were detached and were moving northward ahead of the storm's center. These were deduced to be rows or rings of rain-bearing storm clouds, or "line squalls," eight to ten miles in width and from three to five miles apart. When the hurricane was basically on top of the radar station, with the center only a few miles away, the radar revealed that the eye of the storm, the calm area in the center, was 12 miles in diameter, and the lack of echoes proved that there was no precipitation within it. The height-finding radar set revealed that the dense cloud masses surrounding the eye extended up to an average of 18,000 feet (NOAA, 2006).

Since this initial application in meteorological work, radar has grown as contributing to forecasting as well. Virtually all tornadoes and severe thunderstorms over the United States and in some other parts of the world are monitored by radar (Meischner, 2004). Radar observation of storm characteristics, including growth and motion, provide clues as to their severity. Modern radar systems use the Doppler principle of frequency shift associated with movement toward or away from the radar transmitter/receiver to determine wind speeds as well as storm motions (Doviak and Zrnić, 1984). Using radar and other observations, the Japanese American meteorologist Tetsuya Theodore Fujita (1920-98) discovered many details related to severe thunderstorm behaviour and of the structure of the violent local storms common to the Midwest of the United States (Encyclopædia Britannica Online, 2015). His Doppler-radar analyses of winds revealed microburst gusts (Doviak and Zrnić, 1984). These gusts cause the large wind shears (differences) associated with strong rains that have been responsible for some plane crashes. Other types of radar have been used increasingly for detecting winds continuously, as opposed to twice a day. These wind-profiling radar systems pick up signals reflected by clear air and so they can function in the clear skies (Encyclopædia Britannica Online, 2015).

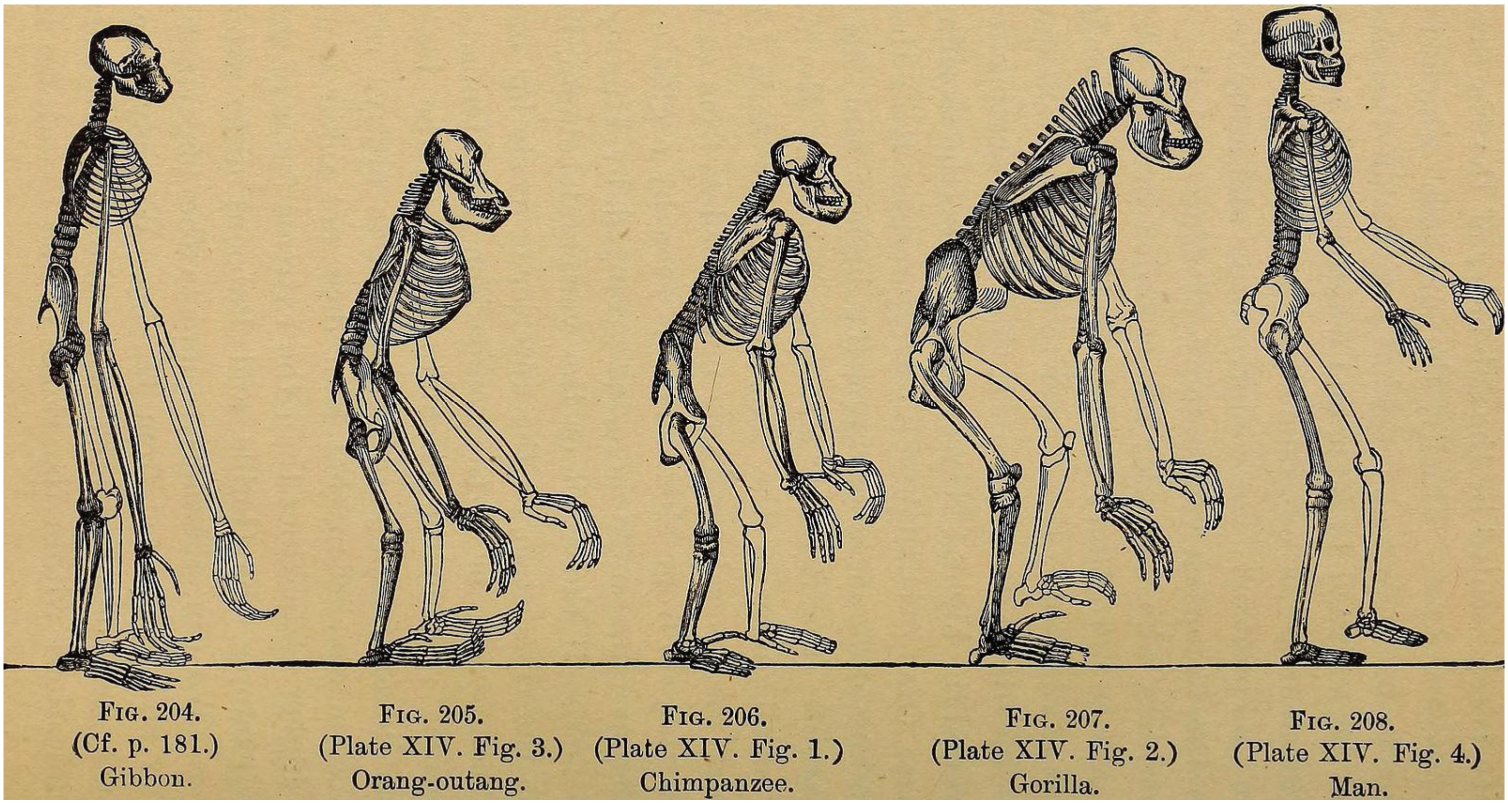


***Figure 4.1**. The progression of Homo sapiens through evolutionary history.*

Chapter 4: Origins of Life on Earth

The origin, evolution, and anatomy of man have been relentlessly studied to generate a modern understanding of *Homo sapiens*. From theories of spontaneous generation and Darwinian principles, to the discovery of the structure of the body, the progression in evolutionary thought will be discussed throughout this chapter.

The origin of life remains a mysterious phenomenon. For centuries, philosophers and scientists alike have contributed to theories accounting for the origin of life, including creationism, spontaneous generation, and chemical evolution. The theory of spontaneous generation, proposed by Aristotle, will primarily be discussed.

A thorough understanding of human anatomy has developed through the progression of theories. It was initially postulated that the four classical elements, air, water, fire, and earth, functioned as the basic necessities required to sustain life, and that all living tissue was composed of each of the four elements in varying proportions. Following the "Scientific Siesta" spanning from the 8^{th} to the 15^{th} century, Leonardo da Vinci rose to prominence with his iconic anatomical depictions, which further solidified anatomical discoveries.

Historical evolutionary thought has developed into modern ecological principles based on Darwin's *Origin of Species*. The scientific discoveries leading up to this publication involve postulates from the likes of Aristotle, Linnaeus, and Lamarck. Darwin's *Origin of Species* legitimized and revolutionized the scientific discussion of evolutionary mechanisms, and set the precedent for modern ecology.

However, the understanding of evolution is not strictly limited to the understanding of biology. Cuvier, von Humboldt, and Nopcsa were among the first to integrate fields of biology and earth science to better understand evolutionary history. Their works introduced the study of paleobiology, enabling scientists to evaluate previous theories from a new perspective. Evolutionary principles could thus be proven incomplete based upon new paleobiological discoveries.

Theories of human origin have been developed across a myriad of different perspectives beginning as early as 7^{th} century BCE. Through the constant integration of new and opposing viewpoints, our understanding of the origin of life only continues to be refined.

Theories on the Origin of Life

The origin of life is a perplexing and alluring phenomenon. While still under much uncertainty and debate today, accepted theories on this subject have evolved over several millennia. Philosophical and religious views played a large role early on and are still relevant today, which carries the belief that a supernatural force from the act of a deity formed the basis of life. On the contrary, the scientific study on the origin of life is only a few centuries old. For these early scientists, bridging the gap between life and death proved to be very difficult. From the time of Aristotle (384-322 BCE) to the early 19th century, most people accepted the view that life could spontaneously arise from a collection of nonliving matter within a matter of days. Louis Pasteur (1822-1895) eventually disproved this with his nutrient broth experiment in 1862, which left many feeling perplexed. Scientists continued to speculate on the fundamental difference between life and the nonliving. The scientific field took a sharp turn when Alexander Oparin (1894-1980) and John Haldane (1893-1981) proposed that the origin of life could be explained by the chemical and physical processes occurring in the early Earth environment. This was supported by work from Stanley Miller (1930-2007) and Harold Urey (1893-1981) in 1953, which sparked a renaissance period in the scientific study of the origin of life. It appeared to be only a matter of time before the mystery would be solved, but this was not the case. Although many great theories have been proposed and developed since then, it is clear today that the problem is far from solved.

Figure 4.2: *God creating the heavens and the Earth*

In this section, a timeline of the different theories associated with the origin of life will be discussed. This ranges from historical theories, such as Creationism, Spontaneous Generation, Eternity of Life, Panspermia, Chemical Evolution, and Early Earth environment, to the modern topics, including the Ribonucleic Acid (RNA) World and Deep-Sea Hydrothermal Vent Hypotheses.

Creationism

Before scientific thought, religious beliefs and faiths were used as a means to explain the origin of life. Even today, many people still show strong support for this perspective (Raven and Johnson, 2002). The most popular theory that surrounds Creationism is the Theory of Special Creation, which explains that a divine or supernatural force (e.g. God) created the Earth and the living organisms in it (Raven and Johnson, 2002). This theory encompasses the core of what many religions believe today. An example of one religion is Christianity, which explains that life originated from the events that took place in the book of Genesis.

In Genesis 1, the chapter discusses how God created the Earth and the living creatures within a span of six days (Carson et al., 2011). In the beginning, God created heaven and Earth, which was a formless and empty, watery void (**Figure 4.2**). On the first day God created light, which he then called Day, from the darkness, which he then called Night (Carson et al., 2011). On the second day, God created a vault to separate the water; he called the vault the Sky. On the third day, God created land by gathering the water under the Sky to one place (Carson et al., 2011). He then made the land produce vegetation. On the fourth day, God created two great lights under the Sky: the greater light, which governed the Day; and the lesser light, which governed the Night (Carson et al., 2011). This served as time, specifically the days and years present today. On the fifth day, God created creatures that lived in the water. In addition, he also created creatures that flew across the Sky (Carson et al., 2011).

On the sixth day, God made the land produce living creatures according to their kind: the livestock, the creatures that moved along the ground, and the wild animals. Thereafter, God finally made mankind, who would rule over the fish in the sea, the birds in the Sky, the livestock, all the wild animals, and the creatures who roamed along the ground (Carson et al., 2011).

With the uprising of scientific thought, the religious viewpoint on the origin of life began to be questioned. There was no method of proving the Theory of Special Creation, as it was entirely based on faith (Raven and Johnson, 2002). Thus, people began to make scientific theories associated with the origin of life, which will be discussed later in the chapter.

The Theory of Spontaneous Generation

For centuries, the Theory of Spontaneous Generation was a widely accepted explanation for the origin of life. This theory essentially states that life originated from nonliving matter.

The Greek philosopher Aristotle was one of the first to propose this theory. He accumulated past ideas that supported Spontaneous Generation to explain his views on the origin of life. An example is Anaximander (610-546 BCE), who believed that sea slime was the source in which the first animals on Earth arose from (Ponnamperuma, 1972). Aristotle used such works to then explain the biological origin of animals. He stated that animals arose on Earth from nonliving matter (Oparin, 1957). This is seen in his example on how fireflies formed from the morning dew of decaying dung and mud. Aristotle's work influenced the minds of many thinkers for nearly 2000 years (Oparin, 1957). This is evident in many historical documents that refer to the beliefs of Spontaneous Generation, including: the Georgics, in which Virgil (70-19 BCE) describes how a swarm of bees arose from the carcass of a calf; and in Antony and Cleopatra, in which Lepidus (88-12 BCE) explains how the snakes and crocodiles in Egypt were formed by mud (Ponnamperuma, 1972).

It was not until the 17th century that the Theory of Spontaneous Generation was actually questioned, as such speculations could not be explained by the ongoing growth of scientific method. Francesco Redi (1626-1697) was the first to reject the Theory of Spontaneous Generation (Ponnamperuma, 1972). Many believed that worms spontaneously developed from meat; however, Redi demonstrated that they were actually larvae from the eggs of flies. He proved this by placing meat under a screen of muslin, which resulted in no maggot development in the meat (Ponnamperuma, 1972). This was because muslin ensured that flies were incapable of laying their eggs.

Despite these results, there was still constant debate on the origin of life. This was very evident when Antony van Leeuwenhoek (1632-1723) invented the microscope, for it was about the time when humans finally discovered the world of microorganisms (Ponnamperuma, 1972). However, because they could not discern anything about the sexual generative processes involved with these "creatures", those who looked under the microscope began to question their origin. This caused many people believe that microorganisms formed from the nonliving materials in the mixture (Ponnamperuma, 1972).

Poor experimental attempts were made in illustrating concepts associated with Spontaneous Generation. This was especially evident in a time in which the French Academy wanted to decisively put an end to the theory, as it was problematic in the scientific world (Ponnamperuma, 1972). Thus, they offered a prize to anyone who would accomplish this feat, and Louis Pasteur was the one to do so. Pasteur tested whether sterile nutrient broth could spontaneously generate life in 1862 (Oparin, 1957). Thus, he added the broth to his swan-necked flasks, and after doing so, he then boiled the broth to kill any existing microbes. After the broth was sterilized, Pasteur set his experiment into two conditions: the first having the broth be exposed to air, while the second was having the broth remain in the flask (Oparin, 1957). He performed the former by breaking the swan neck of the flask, and found that the broth exposed to air turned murky in colour. In addition, he also discovered that the broth that remained in the flask was still clear (Oparin, 1957). This was because the dips and curves of the flask trapped any incoming microbes from making contact with the broth. Thus, Pasteur refuted the notion of Spontaneous Generation, as he illustrated that the solution itself could not generate life, and could only do so when microorganisms entered the flask (Oparin, 1957). For more information on Spontaneous Generation and Pasteur's experiments, see page 122.

Eternity of Life and Panspermia

The underlying principle behind the Eternity of Life belief saw living organisms as fundamentally different than nonliving matter. Many believed that life existed forever and could not freshly arise. Therefore, the birth and death of living organisms was simply a change in bodily material (Oparin, 1957). This belief dated back to ancient Greek philosophers who took on an idealistic perspective and believed that a "life force" from a divine source entered nonliving matter to give rise to life, and this force was transferred upon death. This was in accordance with the Theory of Spontaneous Generation.

Pasteur's experiment in 1862 that conclusively disproved Spontaneous Generation mostly led to the abandonment of the "life force" belief, but the Eternity of Life concept remained strong in the late 19th and early 20th centuries. Many simply accepted the additional fact that nonliving matter needed to be in contact with living organisms to spawn life. Even Charles Darwin's (1809-1882) work on evolution in 1859 (see page 134) supported the notion that life must originate from other forms of life (Haldane, 1929). The Eternity of Life belief continued on, with most taking on a materialistic perspective: perhaps there was a physical element or property that was unique to living organisms, which could explain why organisms had to be present for life to form (Oparin, 1957). Russian geochemist Vladimir Vernadskii (1863-1945) proposed that living organisms had different chemical "orientations" (isomers) than nonliving matter. He also proposed that living organisms had uniquely high isotopic proportions. However, both propositions ran into issues when chemists were able to synthesize these chemical "orientations" from nonliving matter and when high isotopic proportions were found in volcanic rocks (Oparin, 1957).

Figure 4.3: *Photograph of Alexander Oparin*

The materialistic Eternity of Life belief ran into issues when theories on the origin of Earth became well established. This posed serious questions on how life on Earth could be eternal if Earth itself formed around 4.5 Ga. In 1938, Swedish astronomer Erik Holmberg (1908-2000) mathematically deduced the existence of planets orbiting distant stars, indicating that the Solar System was not unique (Oparin, 1957). Taken together, the Theory of Panspermia became popular, which suggests that microorganisms and spores attached to celestial bodies could inhabit new planets and develop into complex organic creatures if conditions are suitable. The idea of Panspermia dates back to Greek philosopher Anaxagoras (500-428 BCE), but the scientific theory was first established by Hermann Richter (1808-1876) in 1865 (Orgel, 1973). However, many rightfully questioned whether microbes and spores could survive the journey in space as they faced strong UV radiation and temperatures of -200°C. The largest caveat of the theory is the ability for microorganisms to survive the journey through Earth's atmosphere. The resulting heat of friction between the meteorite and atmosphere sterilizes the surface of the meteorite. Furthermore, no extraterrestrial microorganisms were ever found within meteorites (Oparin, 1957).

Overall, the Theory of Panspermia is plausible but goes against most objective facts. Work on Panspermia today focuses on the transport of organic molecules and possibly extremophiles. However, to those rejecting the eternal life belief, Panspermia is not a satisfactory explanation as it simply pushes back the date for the genesis of life.

Oparin and Chemical Evolution

Alexander Oparin was a Soviet biochemist whose publication *Proiskhzhdenie zhizny (The Origin of Life)* marked the start of the scientific field on the origin of life (**Figure 4.3**). The purpose of his publication set to clarify that there was no fundamental difference between living and nonliving matter (Oparin, 1924).

During the 19th century, many chemists still believed that organic material was unique and could only be formed from living organisms through a "vital force". The chemist Friedrich Wöhler (1800-1882) disproved this in 1828, as he was able to synthesize organic substances from inorganic material (Oparin, 1924). It was eventually understood that organic substances follow the same physical and chemical laws as all matter. However, the unique characteristics of life, especially its ability to metabolize, reproduce, and respond to stimuli, remained mysterious. Oparin maintained that these processes were not unique from a chemistry perspective. For instance, he claimed that the decomposition of hydrogen peroxide using a platinum catalyst was analogous to metabolism. Both of these processes absorbed substances and broke them down, giving off products. He also argued that replication was analogous to breaking a crystal in half, placing the pieces into its mother liquor, and watching the crystals reform (Oparin, 1924).

In summary, Oparin showed that the fundamental mechanisms that govern life are not unique to processes occurring on Earth. He then proposed that life resulted from the conglomeration of organic material that slowly transformed and became more efficient. However, Pasteur's experiment that disproved Spontaneous Generation made it hard for people to accept that in the remote past, life on Earth originated from nonliving matter due to natural processes.

Early Earth Environment and Origin of Life

When devising theories for the chemical origin of life, it is important to consider the early Earth environment and how these conditions may be suitable for such processes. The atmospheric composition of early Earth was subject to much debate in the early 20th century. Some believed that it was similar to the present, being chemically oxidizing (oxygen rich; Urey, 1952). This type of environment would degrade organic substances as they formed. However, Oparin and John Haldane independently concluded that the early atmosphere was chemically reducing (hydrogen rich) in 1924 and 1929 respectively, consisting of ammonia, methane, carbon dioxide, and water (Oparin, 1924; Haldane, 1929). Oparin's reasoning was that hydrogen was abundant in the solar nebula through which Earth formed and that oxidizing atmospheric conditions were rarely observed in the cosmos.

Today, current evidence suggests that the early atmosphere was not as chemically reducing as Oparin suggested but did have low traces of free oxygen (Orgel, 1973). Although Oparin's reasoning for the atmospheric composition is outdated, evidence supporting a reducing or non-oxidizing environment was found by analyzing Pre-Cambrian rocks and observing that iron was mostly in the ferrous rather than the ferric state. Oparin and Haldane proposed that reactions in oceans and lakes involving these atmospheric compounds and ultraviolet light could form organic substances.

The chemist Harold Urey developed Oparin's arguments in his 1952 publication (Urey, 1952). By accepting that the early atmosphere was chemically reducing, he was able to justify the synthesis of organic compounds from atmospheric compounds using a chemistry perspective. He attributed the source of energy for these reactions to ultraviolet light and lightning sparks. This was likely to be the scenario, as ultraviolet light was not shielded by ozone due to the lack of oxygen. The reducing atmosphere would also cause more lightning. In 1953, his graduate student Stanley Miller tested the hypothesis by setting up a flask filled with boiling water, methane, hydrogen, and ammonia and applying electrical charges to simulate the early Earth conditions that Oparin described (**Figure 4.4**; Orgel, 1973). After a week, he discovered that this produced several amino acids including glycine, alanine, and glutamic acid. This was a remarkable and revolutionary discovery, as organic molecules can take on a myriad of structures, so this result could not have occurred by chance.

Although Oparin was not entirely correct about the atmospheric composition, the results sparked a lot of scientific excitement and soon, more studies showed that different mixtures of reducing gases could also produce similar organic substances. Of particular importance was Joan Oró (1923-2004), who was the first to synthesize adenine, a component of deoxyribonucleic

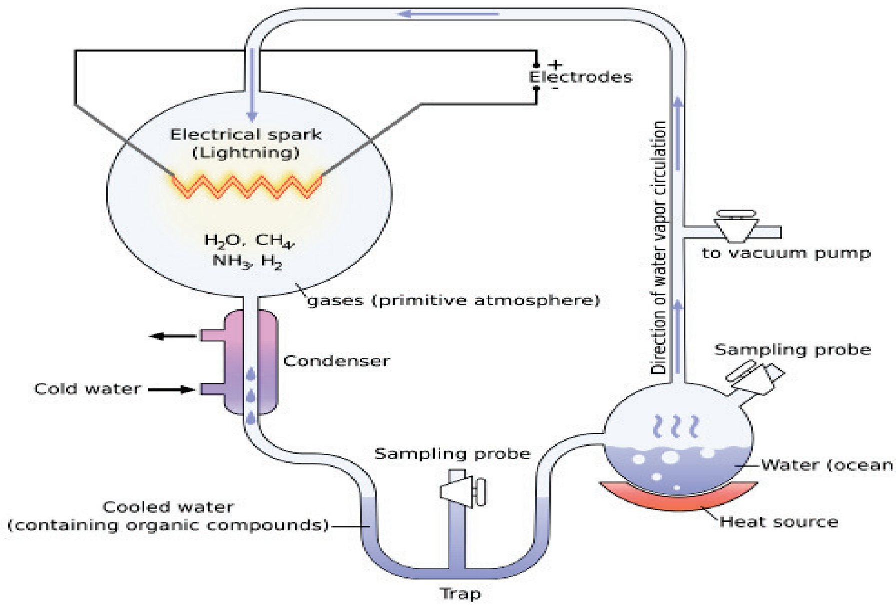


Figure 4.4: *Miller-Urey experimental setup*

acid (DNA) and adenosine triphosphate (ATP), using prebiotic conditions in 1962 (Orgel, 1973). Soon enough, more biologically relevant chemicals including cysteine, uracil, deoxyribose, and more amino acids were synthesized. The overwhelming evidence indicates that early Earth had a chemically reducing atmosphere that was conducive to the generation of organic substances that formed the basis of life. Organisms today have evolved but retained similar chemical compositions.

Modern Theories: Origin of Life

With exciting results from the Miller-Urey experiment in 1953, it seemed as if the mystery of life's origins was soon to be solved. Many theories have been proposed and developed since then, but no experimental work has been able to replicate or confidently explain the transition from organic substances to life. The two most important properties of life are metabolism and replication. This has generated much debate regarding metabolism or replication as the first process to evolve.

RNA World Hypothesis

The Replication-First Hypothesis suggests that replicative properties were the first to be generated in life. This ties in with the RNA World Hypothesis that was first proposed by Walter Gilbert (1932-) in 1986. Today, DNA and protein function as the fundamental macromolecules that sustain life. This is because DNA is responsible for containing, transmitting, and duplicating genetic information, while proteins serve as the major metabolic catalysts and structural component for cells (Alberts, 2002). For many years, scientists have believed that life originated from DNA and protein; however, there was and still is a great debate regarding which macromolecule came first (Bernhardt, 2012). It was highly unlikely that both macromolecules appeared simultaneously. Since DNA is a modified RNA molecule (**Figure 4.5**), the debate is essentially between RNA and protein (Bernhardt, 2012).

The RNA World Hypothesis suggests that in during the early stages of the Earth, RNA molecules were the only molecules present in cells (Alberts, 2002). It suggests that these macromolecules were able to both store genetic information and catalyze reactions (Robertson and Joyce, 2010). Thus, the hypothesis states that life originated from RNA, and was also a precursor to DNA and protein (Alberts, 2002). This was hypothesized because RNA molecules catalyze reactions in modern-day cells and in ribosomes (Alberts, 2002). This hypothesis also explains the evolutionary timeline in which DNA and protein arose. The RNA molecules could synthesize proteins by developing RNA adapter molecules which would then bind to amino acids (Gilbert, 1986). Thereafter, they would arrange them according to an RNA template, using RNA catalyst molecules as an example. DNA would form simply by reverse transcription on the genetic RNA molecules (Gilbert, 1986).

Deep-Sea Hydrothermal Vent Hypothesis

In contrast, the Metabolism-First Hypothesis suggests that the formation of ordered chemical reactions was the first property of early life. One of the largest issues with this hypothesis is the mystery surrounding the process that allowed large enough concentrations of organic substances floating in the Hadean ocean to come together in an organized manner and form the chemistry of life (Martin and Russell, 2003). Some suggested that inorganic catalytic surfaces captured these substances and allowed them to react, but this did not solve the issue, as the products were likely to diffuse away. There was the need for a system to capture reactants and store products. Hence, there is strong support for the idea that deep-sea hydrothermal vents were the location for the origin of life. This was first proposed by Günter Wächtershäuser (1938-), who suggested that iron(II) sulphide (FeS) formed from deep-sea vents could act as metal catalysts to generate organic substances (Martin and Russell, 2003). FeS forms a three-dimensional structure (**Figure 4.6**), so it is able to capture chemically reduced compounds provided by the vents that serve as sources of energy. The FeS uses this energy to capture and catalyze the reduction of compounds such as carbon dioxide and carbon

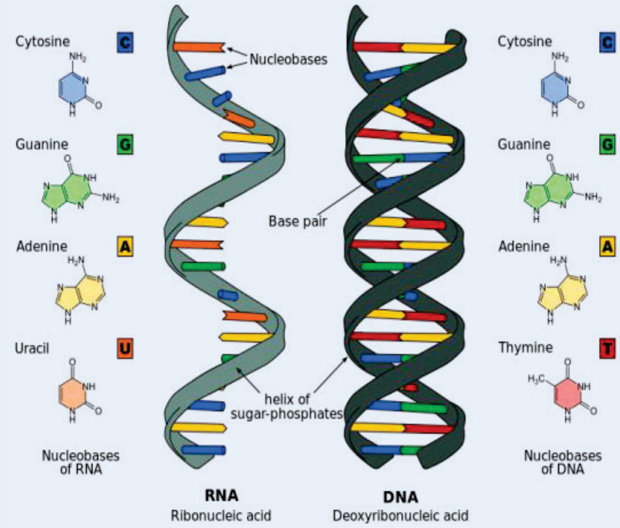


Figure 4.5: *The comparison between an RNA and DNA molecule*

monoxide to form more complex organic molecules. These reactions are sustainable, as the hydrothermal vents provide continuous geochemical input. This leads to the accumulation of organic substances in an enclosed area, forming the basis of cells. Some suggest that these FeS structures formed the encasing material for the first cells, and over time, the accumulation of lipid molecules formed membranes that allow the cells to mobilize (Martin and Russell, 2003).

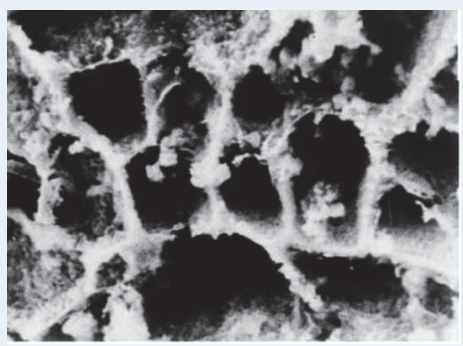


Figure 4.6: *FeS structure under electron microscopy*

Many modern theories on the origin of life continue to be probed and developed. However, these theories are not necessarily mutually exclusive. For instance, Panspermia may have provided the original source of organic monomers. The Deep-Sea Hydrothermal Vent Hypothesis proposes a solution that allows these monomers to gather and form the first RNA. It is apparent that current progress on elucidating the origin of life leaves much to be desired and requires an integrated approach.

Spontaneous Generation

As demonstrated in the previous section, several theories regarding the origin of life throughout history have caused turmoil amongst academics and religious institutions. The Theory of Spontaneous Generation is no exception. Originating in the 3rd century BCE, Spontaneous Generation is an outdated body of thought developed by Aristotle whose theology relied on the assumption that living organisms could spontaneous develop from nonliving matter (**Figure 4.7**). The Theory of Spontaneous Generation prevailed for over two millennia until French microbiologist Louis Pasteur (1822-95) ultimately disproved it. During this period, the theory was heavily supported by the Catholic church. The disproval of the theory, which was originally based on imperfect observations and philosophy, gave rise to the modern understanding of the scientific method. From Aristotle to Pasteur, this section will take a deeper look into a long accepted doctrine and the scientist who eventually caused its demise.

Figure 4.7: *A Boromet growing from the Earth like a plant.*

Origin of Life in Ancient Greek Mythology

Aristotle's proposition of the origination of life from the environment was not unique, as this concept was incorporated into the cultural myths and mindset of the time period. Concurrent Greek myths presented the origination of man from nonhuman objects, such as an oak tree or a stone (McCartney, 1920). Embedded within these myths was the concept that the creation of life required both a vitalizing force and an appropriate material. For instance, prominent Greek myths depicted the wind impregnating horses, and claimed the blood of Medusa which dripped on the sands of Africa gave rise to serpents (McCartney, 1920).

Aristotle's Theory

Despite the presence of this concept in the collective understanding, Aristotle's description of his Theory of Spontaneous Generation was based upon observations taken from the physical world and followed a similar rigorous analysis as his other schools of thought which were discussed in previous chapters. Aristotle divided life into two categories: that originating from pre existing parents of similar form, and that from the coincidental combination of inorganic material (Dunster, 1876). He hypothesized that while some organisms originate from "kindred stock", others are a product of putrefying earth or vegetable matter (Aristotle and Cresswell, 1862). The philosophical reasoning used by Aristotle in his explanation mirrors that of his interpretation of sexual generation. The explanation appears to be an attempt to reconcile within the mind the existence of sexual generation as well as a second method for the creation of organisms for whom sexual reproduction seemed impossible.

The Theory of Spontaneous Generation attempted to address the same three questions presented at the introduction of *On the Generation of Animal*: from what material, through what forms, and into what forms are animals created (Aristotle., 1963; Zwier, n.d.). In sexual generation, the female body was to provide the material for the new life, while the semen gave direction for the formation (Lennox, 1982). In contrast, a mix of earth and water which will undergo purification was deemed the materials required for Spontaneous Generation (Aristotle, 1963). The life source of these spontaneously generated organisms was a portion of the *pneuma* which had been sectioned off into the environment; this soul-principle is the same force which was theorized to be contained in semen (Aristotle, 1963). This life source, in both the semen and the decaying matter, was considered to be the guide of the developmental process (Lennox, 1982). The life source could generate different organisms based upon the exact organic materials and climate conditions present (Zwier, n.d.).

The situations Aristotle used as examples of the unmistakable evidence of the necessity of Spontaneous Generation had similar characteristics. These situations presented perplexing conditions in which the generation of the organism in question from parents appeared impossible. For instance, he cites the spontaneous appearance of small fish in previously dry ponds after a rainfall (Aristotle and Cresswell, 1862). Additionally, the exemplar organisms display a lack of proof for the existence of a generative substance, such as eggs or semen. Eels are used to display this property, as it is suggested they possess neither the required substances nor a passageway to release these substances; consequently, they cannot be born of an egg (Aristotle and Cresswell, 1862). Furthermore, many insects were attributed to arise out of the material in which they were commonly found; for example, the cabbageworm was said to originate from the cabbage, while others originate in animal wastes, the dew on decaying leaves, and the flesh of living animals (Aristotle and Cresswell, 1862).

Although this reasoning was based in a foundation of philosophy and observations, the limitation of the human senses consequently influenced the theory. For example, further evidence for the Theory of Spontaneous Generation was found in non-apparent breeding patterns; specifically, hidden locations of egg deposits and long migrations associated with quick departures gave the appearance of organism appearing without similar progenitors (Dunster, 1876). A great disparity between the forms of juveniles and adults of many species also created a barrier from a comprehensive understanding of life cycles, and consequently origins (Dunster, 1876). Relationships not apparent to the eye could not be perceived and therefore interpreted; conclusions were an imperfect analysis of the visible world.

Adaptation in the Church

The Theory of Spontaneous Generation was widely accepted at the time of Aristotle, and remained in scientific thought for centuries into the future. Early Christian Fathers accepted and spread the notion of Spontaneous Generation; the theory gave them a means by which to explain the possibility of the virgin birth to pagan converts (McCartney, 1920). These missionaries would recall concepts from mythology such as the birth of Aphrodite from the sea, or the impregnation of horses by the wind, in order to help ease the transition from a pagan mindset to that of an early Christian (McCartney, 1920). The Church continued to accept the Theory of Spontaneous Generation, as can be seen in the writings of Thomas Aquinas (1225-74). In *Summa Theologica*, he suggests organism can originate from the dead matter of simpler creatures, suggesting organisms can rise from dissimilar organisms (Behr and Cunningham, 2015).

Recognition of Error

One of the first scientific based challenges to the Theory of Spontaneous Generation was put forward by Francesco Redi (1626-97) in 1688 (Keezer, 1965). The Florentine, through a systematic experiment, displayed maggots do not originate from decaying meat but rather from similar progenitors. Redi created two experimental set ups by placing meat in jars and sealing only half of the samples with gauze, leaving the other portion open to the air. Maggots were recorded to have only appeared on the meat in the uncovered jars (Redi and Bigelow, 1909). To provide further evidence for his discovery, Redi repeated the study multiple times, and recorded the presence of eggs on the gauze on the covered jars (Keezer, 1965). By displaying this, Redi proved the maggots were not a result of an intrinsic property of the meat, but rather were the product of eggs laid by flies; the maggots were simply consuming the meat as a source of energy, and eventually matured into the flies of a similar form to the ones which he had observed around the meat initially. Although Redi was able to gain an appreciation for the true source of the maggots he routinely saw on the decaying meat, he still attributed the source of the flies to Spontaneous Generation. Redi's conclusions were never accepted by the masses due to the nature of scientific communication at the time, but his experimentation laid the ground work for the eventual refutation of the theory by the end of the 17th century.

Refutation By Pasteur

The Theory of Spontaneous Generation thrived for many years after Aristotle, intermittently receiving the heavily weighted support of both natural philosophers and the Catholic church. This doctrine reached the pinnacle of its popularity in the late 1860s when renowned French microbiologist Louis Pasteur (**Figure 4.8**) famously challenged its theology (Farley & Geison, 2001). Pasteur was considered to be a prophet among his colleagues with an equally reputable and controversial career. His many accomplishments include the development of the vaccination, germ theory, microbial fermentation, pasteurization and of course the rejection of the Theory of Spontaneous Generation (Conn, 1895). Although Pasteur was a devout catholic, he was strongly against blending religion with science. He had a flare for the dramatics but it was ultimately his philosophy and experimental ingenious that would play crucial roles in his success (Lignon, 2002).

Religious & Social Context

In the early 1800s, the Theory of Spontaneous Generation was publicly associated with transmutation and subsequently perceived as a threat to the Church (Corsi, 2005). When Pasteur began conducting his experiments, France was under the authoritarian reign of Napoleon Bonaparte's nephew, Louis Napoleon. He developed many laws that embedded religion into France's political and educational fabric during his reign as president and self-declared emperor (Roll-Hanson, 1974). These brash actions initiated a liberal undercurrent that caused the French government and Catholic church to become even more authoritarian and reactionary. As a result, scientists whose work went against biblical beliefs received much outside pressure that arguably impacted the motivation behind 19th century science. Luckily for Pasteur, the Theory of Spontaneous Generation had fallen out of favor with the church providing the perfect opportunity to disprove it (Roll-Hanson, 1974).

Pasteur-Pouchet Debate

The controversy over the Theory of Spontaneous Generation was brought to the forefront of the scientific community in 1859 when Felix Archimede Pouchet (1800-70) reported that he had created experiments, which had indefinitely proven Aristotle's ancient theory. Pasteur doubted this proclamation and publicly challenged him in what was arguably one of the most well known feuds in the history of medicine. Pouchet was a distinguished microbiologist and director of the Museum of Natural History in Rouen, France (Horowitz, 2001). He was also much older than Pasteur and carried greater respect within scientific community. At this time, Pasteur had recently been immersed in controversy over his theories on fermentation leading Pouchet to have the upper hand (Strict, 2009).

The Experiments

Pouchet's experiments used hermetically sealed flasks and pure oxygen gases to prove that "animals and plants could be generated in a flask by a medium

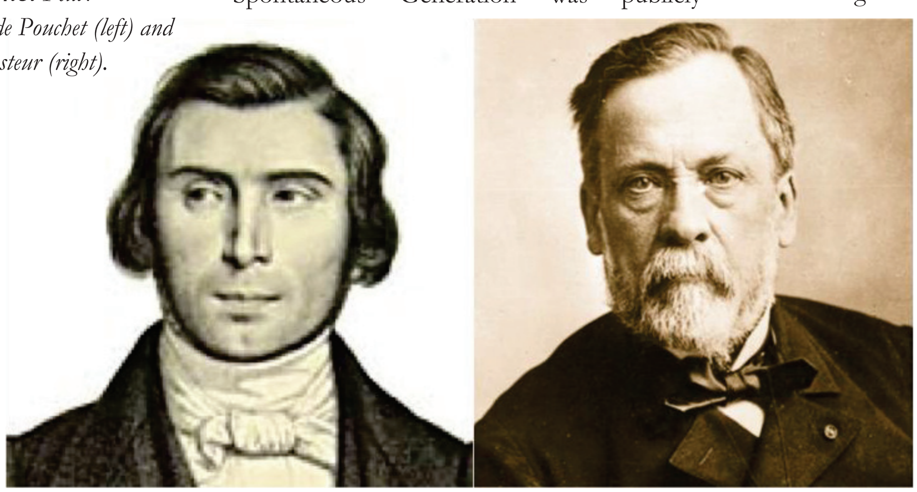


Figure 4.8: *Felix Archimede Pouchet (left) and Louis Pasteur (right).*

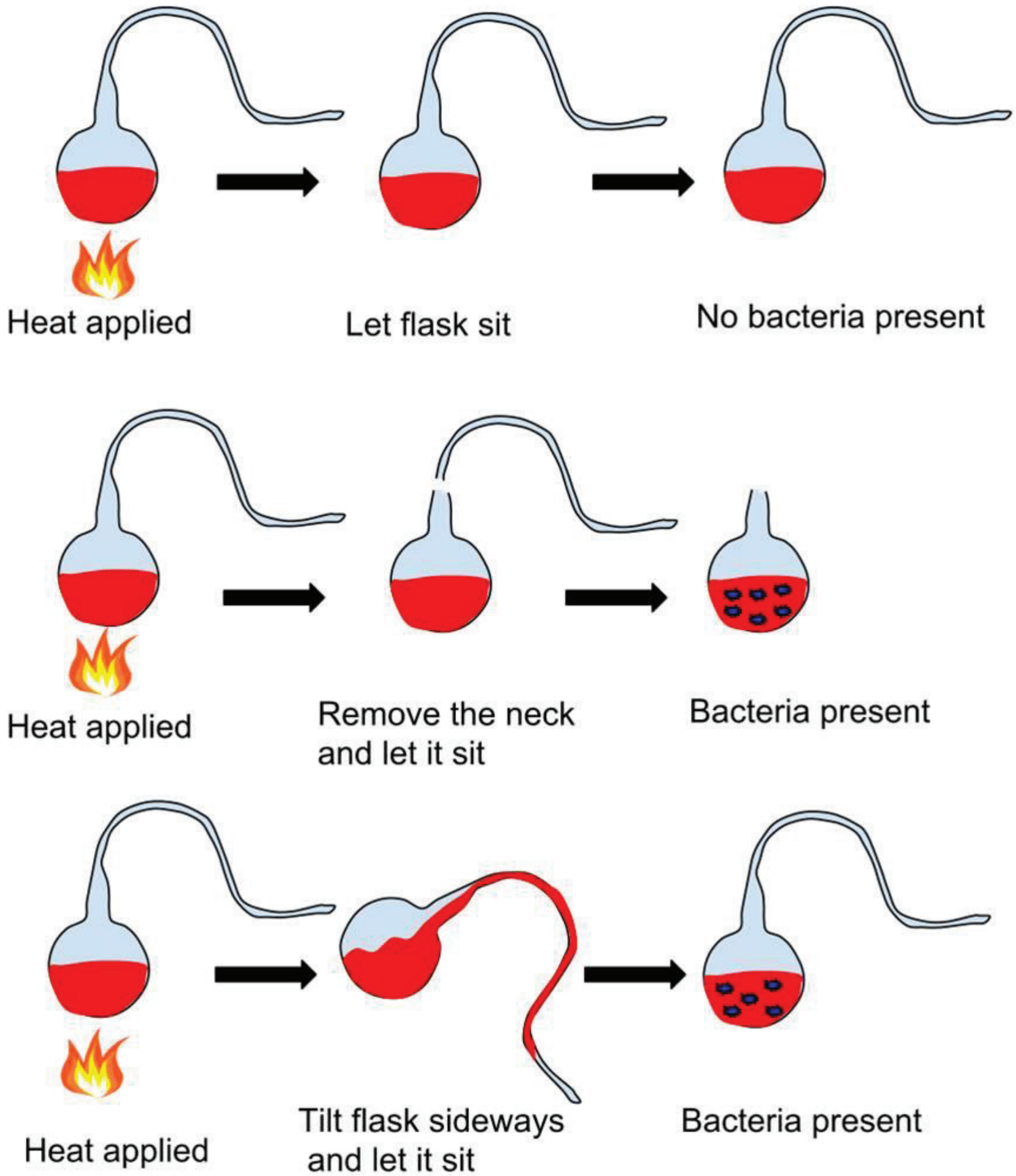


Figure. 4.9: *Louis Pasteur's experiments disproving the theory of spontaneous generation.*

absolutely free from atmospheric air and in which therefore no germ of organic bodies could have been brought by air" (Farley & Geison, 2001). This would theoretically confirm that life could arise spontaneously from non-life. Upon reviewing Pouchet's critically acclaimed results, Pasteur suggested that Pouchet had unwittingly introduced contaminated air with the potential for presence of microorganisms. As a result, Pasteur developed three simple but ingenious experiments that undoubtedly disproved the Theory of Spontaneous Generation (Farley & Geison, 2001).

The first experiment demonstrated that air could contain microorganisms. He did so through microscopic observation concluding that species seen in air were indistinguishable from microorganisms found in liquid culture. For his second experiment, Pasteur hypothesized that the microbes found in dust were causing contamination in Pouchet's sterilized broths and not the 'vital forces'. He investigated this by carrying sealed sterile flasks to a multitude of locations in France. At specific sites, he broke the seal and allowed air to enter the flask. After multiple repetitions and analysis, he concluded that all flasks that contained air from regions with excessive dust became contaminated whereas flasks remained sterile in clear mountainous regions (**Figure 4.9**). Pasteur used this data as a base to develop his third and final experiment. In this experiment, Pasteur used specifically developed Swan-neck flasks to prevent the entry of any external air and thus contamination. Each Swan-neck flask contained a sterile liquid medium that was heated to kill any living organisms present (**Figure 4.9**). Pasteur completed three trials of the experiment: one where the swan neck was broken off, one where it stayed upright and one where the flask was tipped. As seen in Figure 1, in order for bacterial growth the flask had to be exposed to air (Farley & Geison, 2001). From these controlled experiments, Pasteur concluded that the microorganisms in atmospheric air were necessary for bacterial growth (Pasteur 1877). Although these findings produced arguably indisputable evidence against the Theory Spontaneous Generation, the debate was far from over.

Over the next few years, Pouchet continued to publish work, which corroborated his initial experiment. This baffled the scientific community. Pasteur concluded that Pouchet was lying or his experimental design was faulty so he challenged Pouchet to a competition where each opponent would repeat their experiments in front of their colleagues at the Academy of Science to settle this centuries old debate (Latour, 1995). Pouchet graciously accepted the challenge stating "If a single one of our flasks remains unaltered, we shall loyally acknowledge our defeat". On the day of the event, scientists from all over Europe gathered at the media-infested Museum of Natural History in Paris. Everyone was left disappointed when Pouchet did not show and Pasteur won by default (Roll-Hanson, 1974).

Although Pasteur had the support of the church, the science spoke for itself. His methodically designed experiments had a reproducibility and controlled nature that Pouchet's did not; consequently, it was his use of the scientific method that allowed for the acceptance of his findings. The rejection of the Theory of Spontaneous Generation was crucial for the development of biology as a field and more specifically for the theories on the origin of life concluding that:

"Never will the doctrine of spontaneous generation recover from the mortal blow of this simple experiment. There is no known circumstance in which it can be confirmed that microscopic beings came into the world without germs, without parents similar to themselves" (Roll-Hanson, 1974).

Application in Phylogenetic trees

The disproval of the Theory of Spontaneous Generation created many ripples in the scientific community. Not only did it discredit two millennia of research, but it was pertinent for many scientists to successfully pursue their preexisting theories from a novel perspective. Pasteur's experiment confirmed that there is no known circumstance in which life is generated spontaneously and thus all life must come from previous life (Tyndal, 1868). Although it did not solve the ongoing mystery of the origin of life, it was clear from Pasteur's conclusions that establishing a lineage from the first organism to those extant today is theoretically possible. In modern society, these lineages are constructed and communicated via phylogenetic trees.

Phylogenetic trees are branched diagrams that convey evolutionary relationships among extinct and extant species based upon their morphologic and genetic compatibility. In evolutionary biology, phylogenetic trees can be either rooted or unrooted (Hall, 2004). A rooted tree is a directed tree with a unique node corresponding to the most common ancestor of all the leaves originating from that node (Figure **4.10**). In contrast, unrooted trees do not make any inference on ancestry and as such there are no nodes (Hall, 2004).

As one might imagine, constructing a phylogenetic tree is quite a daunting task. It requires mass amounts of data and complex analyses. Fortunately, computer-based algorithm technology has advanced dramatically in the past few decades. Modern phylogenetic trees are constructed using computational phylogenetics (Felsenstein, 2004). Computational phylogenetics uses complex computational algorithms in conjunction with phylogenetic analyses to assemble a phylogenetic tree that accurately represents hypothesized evolutionary ancestry. Characters that define the algorithm include both morphological and molecular analyses. Morphological characteristics such as average body size, length, physical features and behavioural manifestations can be distinguished using a matrix. The biggest challenge associated with morphological-based construction is the high probability of inter-taxon overlap concerning the distribution of phenotype variation. Additionally, the inclusion of data from extinct species is difficult due to incomplete fossil records. Data regarding molecular analyses is gathered through deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) sequencing as well as distinct amino acids in protein sequences. Distance-matrix methods such as neighbor joining use molecular sequencing alignment and morphological characteristics to calculate estimated genetic distances of related species (Lutenic, 2007).

It is important to note the various limitations in modeling phylogenetic trees. Most phylogenetic trees are solely based on multiple sequencing alignments. This poses issues as molecular analysis can be confounded by several genetic processes such as genetic recombination, horizontal gene transfer and hybridisation between species that are not direct neighbors. As a result, evolutionary biologist use morphological, fossil and molecular data to obtain the most accurate lineage. Additionally, evolution is unpredictable (Losos, 2011). The rate, direction and mode of evolution varies with time and external factors such as climate and niche space. In the past few decades, phylogenetic models have tried controlled this by using statistical analysis within their algorithms to determine the most probable lineage (Losos 2011).

In conclusion, Pasteur's indisputable evidence that all life comes from preexisting life allowed evolutionary biologists to form the "tree of life" by using molecular and morphological data in conjunction with complex computational algorithms. Phylogenetic trees are powerful but not omnipotent to evolutionary biology (Losos, 2011). They are tools to understanding the history of life on earth, but like any tool, they have their limitations. Recognition of its strengths and limitations will be essential in creating the most accurate "tree of life".

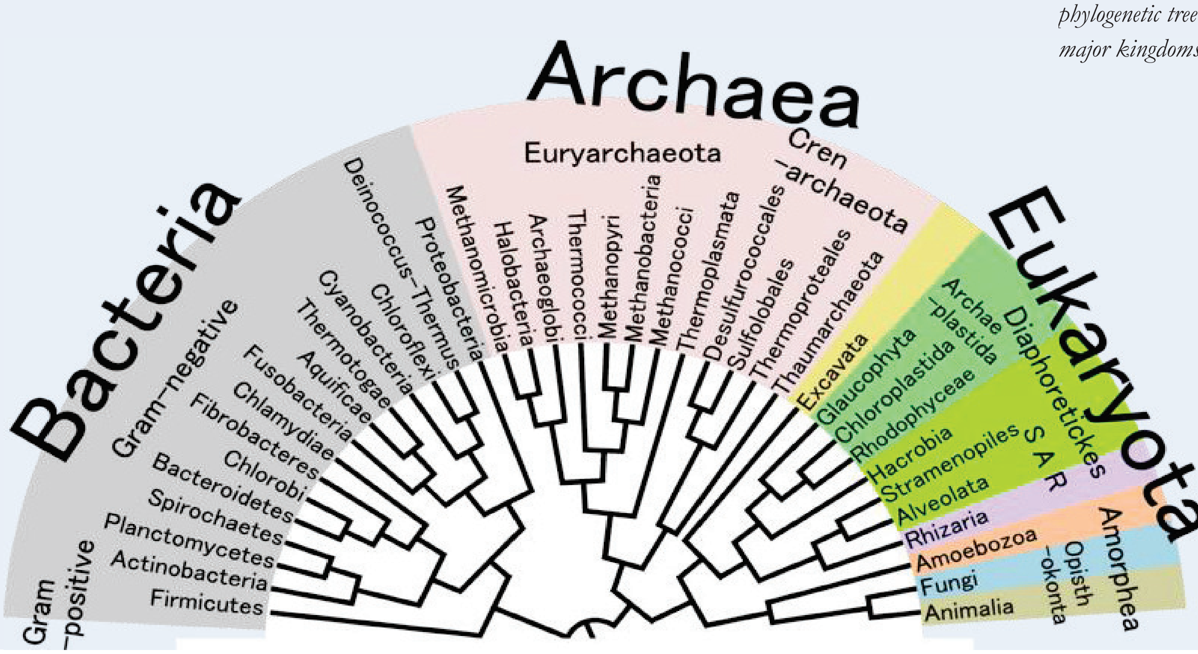


Figure. 4.10: *Modern phylogenetic tree depicting the major kingdoms*

The Birth of Biology

Modern science, and all of the complex theories it entails, largely explains many aspects of the human race, from human anatomy to the biological and physiological processes occurring within the body. However, dating back several centuries to the periods of Empedocles (495-430 BCE), Vesalius, and through to the seventeenth century, very little was known about the aspects of the body that appear trivial to modern scientists. For instance, modern scientific theories can coherently describe the function of every internal human organ, as well as the various organ systems that compose the human body. However, throughout the Middle Ages, philosophers did not know of the existence of blood , let alone that it is a substance that sustains human life. Therefore, in order to gain a comprehensive understanding of how the modern doctrines of anatomy and biology evolved, it is essential to examine the development of the many ancient theories that laid the foundation for modern science, beginning in the 7th century BCE.

Thales, Anaximander, and Anaximenes

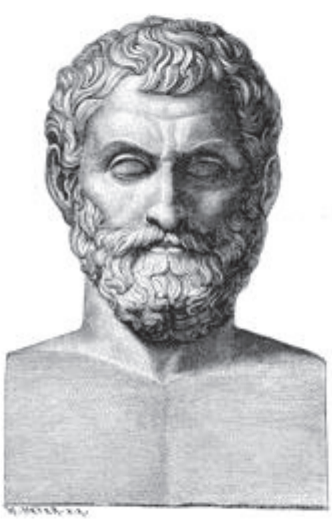


Figure 4.11: *Statue of Thales of Miletus (624-546 BCE).*

As introduced in the first chapter, Thales of Miletus (624-546 BCE) was regarded as the first philosopher in Greek tradition (Smith, 1867). His statue is depicted in **Figure 4.11**. Thales hypothesized that the principles of nature and all of its derivations originated from a single material source: water (Allen, 1991). Thales' view postulated that the Earth was a solid mass floating on a vast, unbounded body of water. An ancient symbol of life, the primordial water was thought to be alive and its life to be the source of motion (Allen, 1991). Thales' standpoint invited numerous objections, criticisms, and conflicting viewpoints from other natural philosophers.

As a student of Thales, the natural philosopher Anaximander (610-546 BCE) asserted that the Earth floated in the centre of the universe, unsupported by any material source (Couprie, 2005). Anaximander identified the principle of life as "the Boundless", or "the Unlimited," as the origin of the universe. It was believed that life resulted from the work of natural processes, and the action of the hot and dry on the cold and wet (Couprie et al., 2003).

Akin to Thales, Anaximenes (585-528 BCE), a Greek pre-Socratic philosopher, believed that all derivations of life originated from one underlying source: primordial air (Allen, 1991). Anaximenes believed that natural forces and physical processes acted on air to transform it into various materials that compose the world (Graham, 2009). Two contrary processes of rarefaction and condensation were used to explain sequences by which air changed and transformed (Graham, 2009). Rarefaction, or thinning of air, resulted in fire, whereas the condensation of air became wind, then cloud, then water, then earth, and, finally, stone (Allen, 1991).

Alcmaeon

In the 5th century BCE, Alcmaeon (540-500 BCE), a medical theorist from Crotona, was the first reported historical figure to practice dissection (Beare, 1906). His ultimate aim was to locate the regions of the body responsible for forming human intelligence. Furthermore, he held the belief that reason was controlled in the head, as concussions, which directly harm the head, resulted in an affected mind. However, through his research, Alcmaeon made many significant discoveries regarding optic nerves and ocular anatomy. His findings suggested that a singular vein spanned from the membrane of the brain to each eye, thereby connecting the brain to the eyes. From this observation, Alcmaeon theorized that viscous fluid from the brain entered the eyes through this vein, forming the lens of the eye. As light reflected from the lens, humans were supposedly given the ability to see (Beare, 1906). Through Alcmaeon's discoveries, light was shed on the human sense of sight, which had not previously been understood.

Empedocles

Referenced in the third chapter, Empedocles (495-430 BCE) was a Greek pre-Socratic philosopher, and is renowned for his contribution to Greek medicine (see **Figure**

4.12). He postulated a theory of health and, in doing so, accounted for many biological phenomena (Longrigg, 1993). His most significant contribution to scientific thought was his cosmogenic theory regarding the four classical elements, which functioned as the foundation of ancient biological sciences. In his four element theory, Empedocles postulated that the elements earth, water, air, and fire reflected the minimal requirements for life to exist. These elements are also referred to as "states of matter."

***Figure 4.12**: An illustration of Empedocles (495-430 BCE).*

In creating this theory, Empedocles suggested that human beings were composed of particles of each of the four elements in nearly equal quantities. However, if an imbalance existed in the distribution of these elements, Empedocles believed a divergence from ideal health, wisdom, or sanity would occur. Moreover, the distribution of each element varied depending on the part of the body. For example, he theorized bone was comprised of 25 per cent water, 50 per cent fire, and 25 per cent earth. However, although all four elements were believed to compose the entirety of the body, not all elements were necessarily present in each substance of the body. On the other hand, he believed all four elements were responsible for forming the eye, with fire and water being the dominant components. The pupil was believed to be composed of fire, while the tissue surrounding the pupil was a collection of water particles that aimed to control the "fire" (Longrigg, 1993).

The four element theory was simultaneously used by Empedocles to aid in his explanation of physiological processes, primarily regarding digestion and nutrition (Longrigg, 1993). He postulated that food was first degraded by teeth before passing into the stomach, where it proceeded to be degraded further into its compositional elements. Following digestion, the nutrients released were transported to the liver, where they were used to form blood. Blood, according to Empedocles, was a substance composed of all four elements in relatively equal proportions. Following transport through vessels, the blood could then be distributed throughout the body in a "like-to-like" manner, in which the elements forming blood would each be distributed to parts of the body containing higher concentrations of the specific element (Longrigg, 1993).

Aristotle

As introduced in the first chapter, Aristotle (384-322 BCE), a renowned Greek philosopher (**Figure 4.13**), focused on both the *philosophy* behind biology, as well as on the *science* of biology itself, thereby establishing a connection between his philosophy of science and his physical scientific practice. His biological practices focused on explaining why animals contained specific organs, and how animals were able to behave and develop in the manner he observed them to. Thus, Aristotle's philosophy of biology emphasized his desire to theoretically explain parts of animals, and how they aided in their development and behaviour (Lennox, 2001).

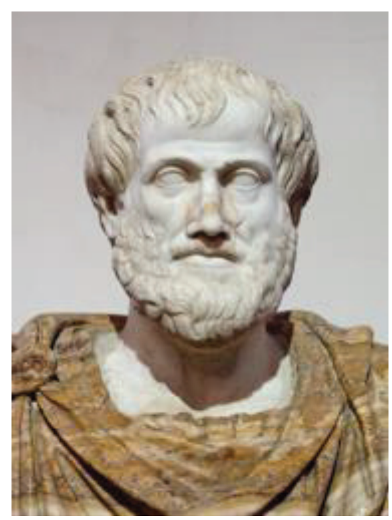


***Figure 4.13:** Statue of Aristotle (384-322 BCE), renowned Greek philosopher.*

In *Posterior Analytics,* a text from his famous work *Organon,* Aristotle discussed the various complexities involved with understanding animal anatomy. He pondered whether animals should be understood by examining the processes of their development in chronological order until obtaining the final product, or vice versa. Additionally, he examined whether only visible characteristics of animals should be studied, or if the structure and function of their internal organs were also relevant (Lennox, 2001). Such questions set the foundation for the anatomical discoveries of future philosophers in their attempt to find concrete answers.

Galen of Pergamon

Galen of Pergamon (129-216 CE) was a renowned Greek physician and philosopher in the Roman Empire around the period of the 2nd century CE (Sarton, 1954). He was appointed the chief physician of the Roman gladiators in 158 CE. As a physician, Galen was constantly given the opportunity to study wounds, and was particularly knowledgeable of muscles. In his attempt to gain a comprehensive understanding of the internal organs of the human body, he dissected apes and pigs. In doing so, he was able to disprove several Hippocratic and Alexandrian theories. His greatest scientific triumph was establishing that arteries, contrary to popular belief, were not responsible for the transport of air throughout the body. The reason this belief was so widely held until this time was due to the fact that blood was not observed in the arteries of dead animals. Instead, it was assumed that air was contained within the arteries and, therefore, could not be distinguished within the arteries of carcasses. Thus, through his dissection of living animals, Galen postulated that blood was found within arteries. However, he believed blood traveled in a random ebb-and-flow motion to and from the heart, which would later be deemed inaccurate (Sarton, 1954).

Figure 4.14: *An illustration of shoulder muscle movement, by Leonardo da Vinci.*

Leonardo da Vinci

Following the "Scientific Siesta," a period dominated by Christian beliefs spanning from the 8th to the 15th century, Leonardo da Vinci (1452-1519) rose to prominence with his revival of scientific thought (Nuland, 2000). Between 1485 and 1515, da Vinci produced a series of anatomical sketches based on the observations obtained from his dissection of human corpses, as in **Figure 4.14**. He is the first recorded historical figure to create illustrations of the human body, as all previous data regarding human anatomy had only been collected in writing. From this period forward, all anatomical observations could be preserved as illustrations, which present a more accurate depiction of the human body than written observations ever could (Nuland, 2000).

The artist's illustrations are categorized into two main periods, the first spanning from approximately 1487 to 1493. During this time, da Vinci's dissections focused on the nervous system, with a particular emphasis on visual processes and the anatomy of the skull, as he endeavoured to discover where each of the five senses were controlled within the skull (da Vinci et al., 1983). Following a twenty-year hiatus from anatomical illustrations, da Vinci continued his illustrations, with his new focus being the mechanisms of movement within the body, including maternal and fetal circulations, as well as bone and muscle movement (**Figure 4.14**). Unfortunately, da Vinci had been on the verge of discovering the mechanism of blood circulation, but he could not gain further knowledge into this subject matter following the orders of Pope Leo X, who demanded that da Vinci ceased his dissection practices.

Scientific thought continued to be revived throughout the Renaissance of the 16th century. The invention of printing occurred during this period, enabling scientific philosophers to produce woodcut illustrations to supplement their written texts. From this point forward, the accuracy of anatomical observations was significantly improved through both da Vinci's precise three-dimensional depictions of the human body, as well as the invention of printing (da Vinci et al., 1983).

Vesalius

During the period between 1533 and 1543, Andreas Vesalius (1514-1564), a medical student from Brussels, rose to prominence (Richardson and Carman, 1998). At the University of Paris, he specialized in anatomical studies, and was thereby influenced to begin dissecting corpses himself. Through his dissections, Vesalius learned a great deal about the structure and anatomy of the human body, which enabled him to publicly denounce Galen's anatomical theories as being false in the year 1540. The reason for the falsity surrounding Galen's discoveries was largely due to the fact that his dissections were conducted strictly on apes, leading him to assume their anatomy very closely resembled that of humans.

However, Vesalius clearly demonstrated this was not the case through his examination of both human and ape anatomies, thereby allowing him to form accurate comparisons between the two. His greatest work was his publication *De Humani Corporis Fabrica Libri Septem, (On the Fabric of the Human Body*) in Switzerland in 1543. This publication contained several woodcut illustrations of his drawings and dissections of humans and apes, thus providing accurate images of the human body. Nevertheless, Vesalius' theories enraged traditionalists who were loyal to Galen's postulates, although these new theories were far more accurate than traditionally-held schools of scientific thought (Richardson and Carman, 1998).

Vesalius' famous publication is divided into seven books. The first book focuses on analyzing the function and differentiation of bones, the names and locations of bones, as well as the function and differentiation of cartilage. Vesalius identified and examined the functions of very specific body parts, including the upper and lower jaws, the hyoid bone, the sacrum, the coccyx, the scapula, the fibula, the femur, the patella, and several more. In doing so, he provided a very descriptive overview of the human skeletal system, as illustrated in **Figure 4.15**, which had never been completed before. Furthermore, Vesalius described the shapes of various bones by likening them to recognizable objects (Richardson and Carman, 1998).

Figure 4.15: *An illustration of the human skeleton, by Vesalius.*

Vesalius' second book clearly depicts the differentiation and function of various ligaments and muscles in the body (Richardson and Carman, 1999). Throughout the book, Vesalius examined the cuticle, as well as the muscles and ligaments of the forehead, the eyelids, the lips, the arms, the head, the abdomen, the thorax, and several additional body parts. Through the publication of this book, Vesalius endeavoured to establish how the mind used the muscular system to initiate movements of the body. Additionally, his discussion of ligaments, which are responsible for joining muscles, teaches the reader how they enable the performance of specific motions (Richardson and Carman, 1999).

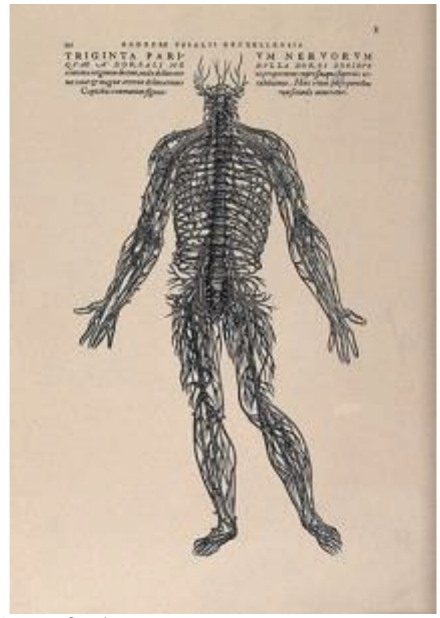


Figure 4.16: *An illustration of the nerves in the human body, by Vesalius.*

The third and fourth books are generally associated together due to the similarities in their content (Vesalius, 1543). Vesalius' third book discusses arteries and veins, while his fourth book, as shown in **Figure 4.16**, focuses on the concept of nerves, thereby shedding light on the structure and function of both the circulatory and nervous systems. Throughout these writings, Vesalius found similarities and differences between the veins and arteries of the circulatory system, and the nerves of the nervous system. He stated they were similar in the sense that all three structures function as vessels. However, he also noted the distinct differences between them. The most significant observation was that veins and arteries resemble the structure of hollow tunnels, while nerves do not contain such empty channels within them. Furthermore, Vesalius identified the portal vein, the venae cavae, the pulmonary vein, and the umbilical vein, which are known to be the four categories of veins in modern anatomy. In addition, he also discussed the pulmonary artery and the aorta, which are known in modern science as the two types of arteries in the human body. However, Vesalius did not identify the capillaries as being distinct vessels of their own, thereby leaving his discussion of the circulatory system incomplete (Vesalius, 1543).

In his fifth book, Vesalius examined the structure and function of the digestive system (Richardson and Carman, 2007). He analyzed such organs as the peritoneum, the stomach, the intestines, the liver, and the kidney, in addition to male and female reproductive organs. Moreover, although he was less knowledgeable of the anatomy of pregnancy, he attempted to discuss and illustrate the fetal membrane and placenta, though these drawings were based on his observation of canine pregnancy and reproductive organs. As a result, his discussion of pregnancy was not thoroughly accurate (Richardson and Carman, 2007).

Lastly, Vesalius' sixth and seventh books are generally coupled together due to the connections Vesalius drew between their contents (Vesalius, 1543). His sixth book emphasizes the structure and function of the heart and its associated organs, while the seventh book focuses entirely on the brain. Specifically, Vesalius discussed the heart and its associated respiratory organs, the membranes of the brain, the organs involved in sensation, and the nerves extending throughout the limbs. As well, Vesalius detailed how certain organs were structurally attached to each other, such as the diaphragm and pericardium, and closely examined the particular shapes of the ventricles. Moreover, at the conclusion of each book, Vesalius included the techniques and chronological order necessary to dissect each organ discussed in his books, thereby enabling future scientific philosophers to further study human anatomy (Vesalius, 1543). Therefore, through his careful analysis and illustrations of the skeletal system, muscles and ligaments, the circulatory system, the nervous system, and the digestive system, Vesalius provided an exceptional foundation for the structure and function of the human body, thus providing valuable resources for future students of anatomy to use in their anatomical research.

Figure 4.17: *An illustration that demonstrates the process of blood circulation in the arm.*

William Harvey

In 1628, William Harvey (1578-1657), an English physician, theorized that blood, contrary to popular belief, did not undergo random ebb-and-flow motion, but was, rather, pumped continually throughout a distinct circuit (Harvey, 1889). He discussed this theory in his Latin text *Exercitatio anatomica de motu cordis et sanguinis in animalibus (The Anatomical Function of the Movement of the Heart and the Blood in Animals)*.

At this time, the traditionally held view was that arteries and veins contained different types of blood due to their differences in colouration; however, in modern science, it is known that oxygenation accounts for the discrepancies in colour, though oxygen had not yet been discovered in Harvey's time. Through his dissection of dogs, pigs, slugs, and oysters, Harvey concluded that only a single supply of blood existed within the body, while the heart functioned as the muscle continually pumping this blood throughout its established circuit (Harvey, 1889).

Harvey established the correct movement of blood through the body, and this theory remains accepted by modern scientists (Wright, 2013). His practices for determining the correct direction of flow are illustrated in **Figure 4.17**. He postulated that blood from the veins flowed into the right ventricle before being transported to the lungs. Afterward, the blood entered the left ventricle before being distributed by the arteries throughout the entire body once again. Nevertheless, Harvey did not identify the capillaries, resulting in a lack of knowledge of how the arterial and venous systems were connected (Wright, 2013).

However, in 1661, Marcello Malpighi (1628-1694), a lecturer in theoretical medicine at the University of Bologna, identified capillaries, thereby filling the missing link in Harvey's theory (Takeda, 2011). To do so, Malpighi used the sun as a light source and shined it into a lens to observe a section of a frog's lung. Through his microscope, he could observe the tiny connections joining the arteries to the veins, which are now known as capillaries (Takeda, 2011).

Seeing the Body through Modern Technology

With a vast knowledge of human anatomy at the fingertips of modern scientists, coupled with the significant advances in medical technology since the 17th century, the human body, and all of the complex organs composing it, can continue to be analyzed to a far greater degree. Such accurate and precise observations could not be made of the body several centuries ago, when the only tools available to scientific philosophers were paper and ink. However, with the evolution of such technologies as magnetic resonance imaging (MRI), computed tomography (CT) scans, and x-rays, the scientific world is far better equipped to observe and examine anatomical structures and their functions, as well as how damage to these structures affects physiological processes in the body.

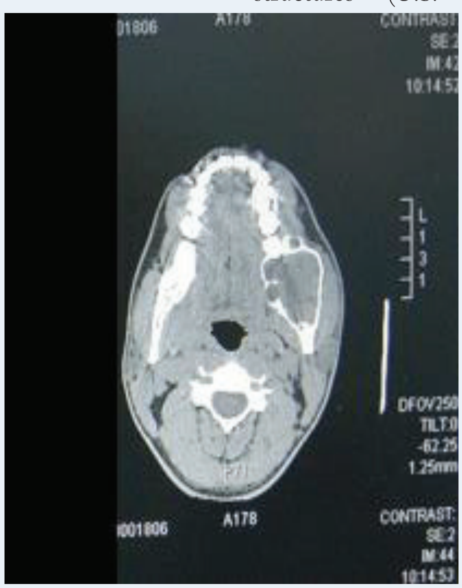


Figure 4.18: *An image of a patient with an ameloblastoma initiated at the left mandibular third molar, created using a CT scan.*

MRI scanning generates three-dimensional images of soft tissues and bones through the use of radio-frequency waves and a source of magnetism (Canadian Cancer Society, 2015). The three-dimensional images formed provide a significantly more accurate depiction of internal organs than the sketches produced by early philosophers. This procedure is most commonly used for the diagnosis of cancerous tumours, particularly in the brain, spinal cord, breasts, and muscles. Furthermore, MRI images indicate changes in the structure, shape, and size of organs, lesions within tissues, as well as the location of tumours. Such advanced observations of internal structures could not be made with the lack of technology available centuries ago (Canadian Cancer Society, 2015).

An x-ray machine uses x-rays, which are a type of electromagnetic radiation (National Library of Medicine, 2015). Individual x-ray particles are sent through the body, and images of tissues and structures inside the body are recorded on a computer or film (National Library of Medicine, 2015; National Institute of Biomedical Imaging and Bioengineering, 2015). Different tissues inside the body absorb different amounts of x-ray particles, and produce high contrast on the x-ray detector (National Institute of Biomedical Imaging and Bioengineering, 2015). Bones readily absorb x-ray particles, and provide a distinct image of the skeleton and tissues. X-ray technology may be used in medical examinations and procedures as a diagnostic or therapeutic tool (National Institute of Biomedical Imaging and Bioengineering, 2015). Additionally, CT scans (**Figure 4.18**) utilize x-rays to generate cross-sectional images of internal body structures (U.S. National Library of Medicine, 2015). CT scans are most useful for the diagnosis of broken bones, blood clots, internal bleeding, and certain forms of cancer. Contrast dyes are often administered to patients to allow their organs to appear more clearly in the images produced (U.S. National Library of Medicine, 2015).

Therefore, since the 6th century, the anatomy of the human body, as well as the elements required to sustain life, has been relentlessly observed and analyzed. From Empedocles' four element theory, to the evolution of anatomical sketches and woodcut illustrations, to the advancement of medical technology, the anatomy of the human body is a mystery that continues to be unravelled by modern science.

History of Evolutionary Thought

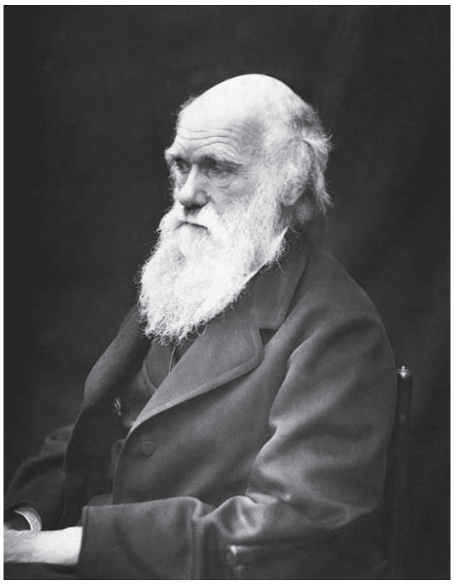
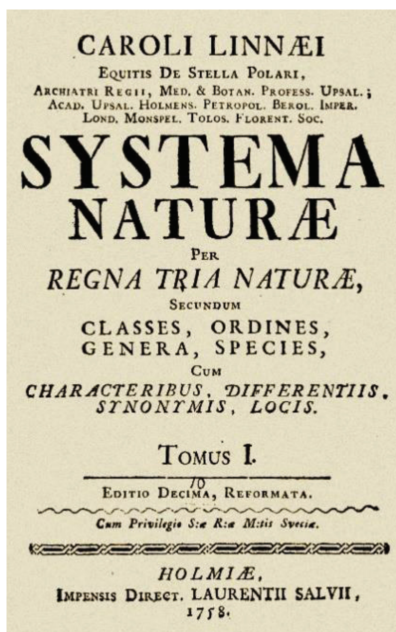


Figure 4.19: *Portrait of Charles Darwin taken by Julia Margaret Cameron during a family holiday in 1868.*

The origin of life as it is today has been a topic of controversy and curiosity among scientists, philosophers, and naturalists for as long as such individuals have held these titles. So far, this chapter has discussed several theories of the origin of life, and many of these were well accepted in their time. Few of them, however, were as groundbreaking as Charles Darwin's Theory of Evolution by Natural Selection. As the predominant theory for over 200 years, Charles Darwin (1809-1882) (**Figure 4.19**) built on a culmination of centuries of work to finally put together a single, unifying theory of evolution. From Aristotle to the naturalists mere decades before his work, Darwin truly stood on the shoulders of giants to make this leap forward in biology. His work was not only the first to recognize natural selection, but the first to be free of influences from religion and politics, assuring that his theories were free of bias and truly based in science. Though his work was not without its controversy, and still needed to be built upon before it became the principles we seen today, Darwin's work set in motion the acceptance of evolution over creation, and ushered in the dawn of a new era of ecology.

The Early Contributors

The scientific discoveries that preceded Darwin's revolutionary theory predate his birth by centuries. The birth of biology itself, as discussed earlier in this chapter, can in part be credited to the ancient Greek philosopher Aristotle (384-322BCE). His momentous influence can be seen in virtually all fields of science, and evolution is no exception. Aristotle's *History of Animals* is one of the oldest texts in existence to suggest several methods to attempt to classify life into distinct categories. Additionally, this text was among the first to make distinct and detailed observations about anatomy (Locy, 1930). Aristotle's writing laid the fundamental groundwork for some of the largest scientific fields, such as anatomy, physiology, and biology, possibly in its entirety. This work, however, was far from complete. As important as this initial attempt to classify species was to science, Aristotle's writings were just that – an attempt. His suggested methods of classifications were solely based on the primitive physiological knowledge of the time, and were not at all definitive (Caswell, 1862). Though Aristotle made very detailed observations about physiological differences, a hierarchal classification of species, similar to modern systems, would not be developed for another 700 years (Caswell, 1862).



CAROLI LINNÆI
EQUITIS DE STELLA POLARI,
ARCHIATRI REGII, MED. & BOTAN. PROFESS. UPSAL.;
ACAD. UPSAL. HOLMENS. PETROPOL. BEROL. IMPER.
LOND. MONSPEL. TOLOS. FLORENT. SOC.
SYSTEMA
NATURÆ
PER
REGNA TRIA NATURÆ,
SECUNDUM
CLASSES, ORDINES,
GENERA, SPECIES,
CUM
CHARACTERIBUS, DIFFERENTIIS,
SYNONYMIS, LOCIS.
TOMUS I.
EDITIO DECIMA, REFORMATA.
Cum Privilegio S:æ R:æ M:tis Sveciæ.
HOLMIÆ,
IMPENSIS DIRECT. LAURENTII SALVII,
1758.

Figure 4.20: *Title page of the 10^{th} (1758) edition of Carl Linnaeus' Systema Naturae, his most well-recognized publication.*

Carl Linnaeus (1707-1777), a Swedish botanist, physician, and zoologist, took Aristotle's work a monumental step forward. Linnaeus' most famous publication, *Systema Naturae* in 1735, symbolised the birth of modern taxonomy by classifying species into a distinct, hierarchical naming system, similar to the one used today (**Figure 4.20**). It also used a dual name system to identify an organism's genus and species, almost identical to modern classifications (Locy, 1930). Though the original *Systema Naturae* was a mere twelve pages, its popularity helped Linnaeus grow its contents exponentially, and by the tenth edition published in 1758, it classified over 4,400 animals and 7,700 plants (de Beer, 1955). The tenth edition in particular was so influential, that it is now considered the starting point for the entire field of zoological taxonomy (International Commission on Zoological Nomenclature, n.d.). As a result, Linnaeus is often considered the father of zoological taxonomy and ecology. His work jumpstarted the field of ecology and physiology, as naturalists everywhere were now able to operate under the same system. The exact method of classification however, was based purely on observational physiology, and did not consider function nor shared ancestors, as the idea of evolution, in any form, had yet to be formally introduced.

Lamarck – The Evolutionary Spark

The next leap forward towards understanding evolution was made by a French naturalist by the name of Jean-Baptiste de Lamarck (1744-1829). Lamarck's contributions to science are plentiful; he is even credited with inventing the term "biology". His most famous work, *Philosophie Zoologique* (*Zoological Philosophy*), was among the first to refute the idea that organisms were created the way they are seen them today. Lamarck revolutionized zoology by suggesting that organisms changed based on their environment, making him one of the first to propose a main component of the idea of evolution. In *Philosophie Zoologique*, Lamarck suggests that the simplest of organisms were created via spontaneous generation, a theory discussed earlier in this chapter. These organisms were created with an intrinsic tendency to change based on their environment, and to become more complex (Lamarck, 1809). He suggested that these changes, or traits, were passed down through generations of organisms, a principle that would come to be known as "heritability of traits". This concept is still accepted today, and is considered one of Lamarck's greatest contributions to science (Locy, 1930).

Lamarck's suggestion that organisms tended to become more complex gave rise to his theory that all known species could be linearly ordered in history, with each species in the line having only miniscule changes from its neighbours. He proposed that this theory could be used to trace natural history from man (the most complex organism) all the way back to the simplest forms of life. The large gaps between organisms, he hypothesized, were occupied by undiscovered organisms. Notably, he did not suggest that they were filled with extinct species, as Lamarck did not believe in total extinction. Instead, he suggested that these organisms existed in unexplored regions, such as on the seafloor. He did not believe that nature would be so imperfect that it allowed for an entire species could be wiped out, and that these species eventually evolved into the organisms seen today (Lamarck, 1809).

Lamarck theorized that this linear history of organisms was governed by environmental pressures. Based on his theory, organisms could never remain constant unless their environment was unchanging. As natural selection was not yet a concept, the idea of mutation was not a component of Lamarck's theories. He believed that changes were gradual and constant throughout generations, and that organisms adapted perfectly as their environment changed. There was no room for useless traits in Lamarck's theories, as he believed that if a trait was not used, it would disappear with the passage of time (Lamarck, 1809).

Though these hypotheses are logical, and made sense at the time, Lamarck failed to fill many holes in this theory. The primary issue was that of mechanism, as Lamarck hypothesised why the change occurred (i.e. in response to the environment) yet there was no mention of how. The mechanism of evolution would not come until Darwin's *Origin of Species*, and Lamarck's theories would forever lack this crucial piece of information. Lamarck failed to see many of the shortcoming of his theories, yet he had an unwavering confidence in them (Locy, 1930).

Cuvier vs. Geoffroy

In the decades preceding Darwin, zoology, classification of organisms, and what is now known as evolution had become a very high profile topic for debate. Many academics took opposing stances, and debates raged for years. Few, however, were quite as high profile and influential as the debate between Georges Cuvier (1769-1832) (**Figure 4.21**) and Etienne Geoffroy Saint-Hilaire (1772-1884) (**Figure 4.22**). The debate between these two was, in many ways, a direct result of Lamarck's controversial work on evolution, with Cuvier opposing the idea of evolution entirely, and Geoffroy suggesting an entirely different method of looking at morphology. The rivalry, however, was based on much more than just evolution; it was a debate between the fundamental approach to zoology and physiology (Appel, 1987).

Figure 4.21: *Portrait of Georges Cuvier taken by François-André Vincent in 1795. His debate with Etienne Geoffroy set the stage for Darwin's 1959 publication of his theory of evolution*

Geoffroy's philosophy was that all animals were formed by a single plan, and the organic materials from which they are made could be traced through to the simplest of animals (Appel, 1987). His approach to anatomy eventually became known as "philosophical anatomy", the core tenant of which was that an animal's physiology determined its function, and in turn the role it plays in nature. Geoffroy was also responsible for popularizing the idea of homology, another central idea of philosophical anatomy. Though defined in different terms today, homology in Geoffroy's time arose when trying to compare different animals. Homologous parts were any physiological characters that were nearly the same, but existed in different animals, though many of these parts served vastly different purposes. The comparisons between these parts were not what made this field of thought unique, as identifying similar structures in animals had been done by philosophers as early as Aristotle (Caswell, 1862). Rather, Geoffroy's ideas as to why these similarities exist is part of what sparked controversy. He suggested that these homologous parts were evidence of the Creator's ideal plan for nature, and that one could use homologues to trace connections between all forms of vertebrates, from fish, to mammals, to insects. He staunchly opposed Lamarck's ideas that organisms evolve based of environmental change, and one of his most famous works, *Philosophie Anatomique* (*Anatomical Philosophie*), was titled as such in direct mockery of Lamarck's work. Geoffroy's work in developing philosophical anatomy laid the foundation for the great debate with Cuvier (Appel, 1987).

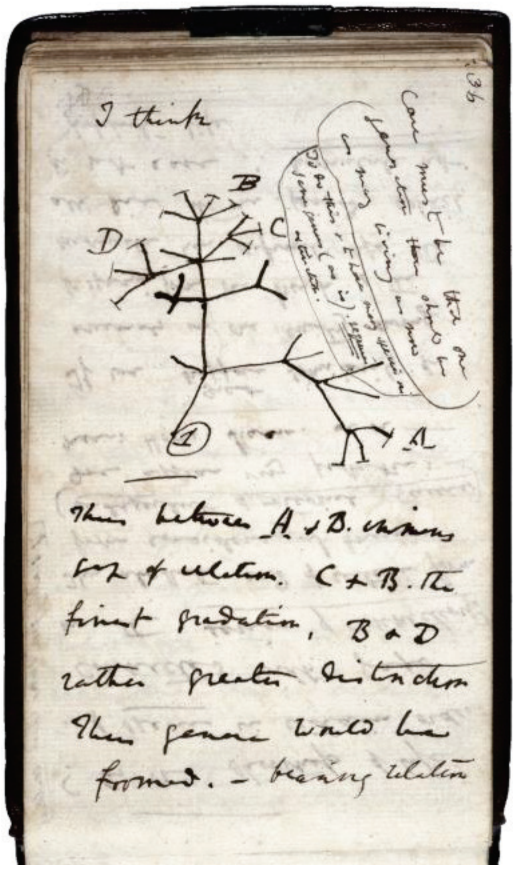
Figure 4.22: *Sketched portrait of Etienne Geoffroy Saint-Hilaire. His debate with Georges Cuvier set the stage for Darwin's 1959 publication of his theory of evolution.*

Geoffroy's beliefs were a very stark contrast compared to his colleague Cuvier's. Rather than basing anatomy on morphology alone, Cuvier was the father of a school of thought known as functional anatomy. He believed that the Creator gave rise to the "conditions of existence", which were the conditions necessary for an animal to thrive in a given environment, and as a result, there was no room for useless features (Appel, 1987). Every organ served a purpose, and the laws that govern what organs could coexist were as definite to Cuvier as the laws of physics or mathematics. Cuvier wasn't opposed to Lamarck's idea of evolution, but instead built upon the idea with his functionalist approach. As Lamarck suggested the progression of organisms in response to their environment, Cuvier expanded that to the functional necessities of the environment in question (Griffith, 1835).

Cuvier stood steadfast in his beliefs, and thus was in direct opposition to Geoffroy's morphological approach to zoology. In one of his works, he stated that supporters of Geoffroy's theory were "more poets than observers" (Appel, 1987). Geoffroy took that as a personal insult, and the heated debate rose to a fever pitch. The two scientific powerhouses published multiple papers attempting to refute one another, and defend their own theories. For example, Geoffroy embarked on a voyage to Egypt, and brought back mummified animals whose physiology was identical to the species that were extant at the time of the discovery. He used this as evidence against Lamarck's theory of adaptive change in *Philosophie Zoologique*, and Cuvier (in support of Lamarck) was quick to refute the accusation, stating that if the animals did not change, one could conclude that their environment did not change. This pattern of accusations and rebuttals lasted for decades, eventually expanding beyond academia and into the public eye (Appel 1987). Though neither side's ideals were close the modern theory, the debate gathered enough attention on the matter of evolution that many scholars believe it set the tone for *The Origin of Species* to be published some years later.

The Origin of Species

Ever since naturalists in the 17th century realized that fossils were actually the remains of once-living plants or animals, there had been a debate about the precise nature of the creation and continuance of life on Earth. On November 12th, 1800, Cuvier declared the existence of 23 now extinct species at a meeting of the *Academie des Sciences*, and reignited the debate about the fixity of species (Cuvier, 1800). Although Cuvier was unfalteringly anti-evolution, his findings drew attention to questions about the origin and progression of life on Earth that would lead to the formation of the single most unifying concept in present day life sciences: Had all species been created at the same time? In what form had species been created? Did all species look the same now, as they did originally? If there was change, how had this been caused?



Over half a century later, on November 24th, 1859, the publication of Charles Darwin's *On the Origin of Species by Means of Natural Selection*, or *The Preservation of Favored Races in the Struggle for Life*, henceforth referred to as *The Origin of Species*, ushered in a new era in thinking about speciation (Darwin, 1859). *The Origin of Species* was finally able to deliver the scientific theory and evidence required to answer the questions generated by Cuvier.

Via *The Origin of Species*, Charles Darwin brought evidence demonstrating that populations evolve over the course of generations through a process of natural selection (Pickering, 1988). This text, and subsequent follow-up publications, presented a body of evidence from various scientific disciplines, such as biology and geology, which argue that the diversity of life arose by common descent through branching and observable patterns of evolution. Darwin also included evidence gathered from his previous expedition aboard the *H.M.S. Beagle* in the 1830s (**Figure 4.23**) and his subsequent findings from his research, correspondence and experimentation (Darwin, 1859).

Darwin was interested not only in the truth of his theory, but also in its acceptance by the scientific community; the eventual widespread acceptance of Darwin's *Origin of Species* reflected the changing social world around him; the movement supporting the emancipation of science from philosophy and religion (Hull, 1973). The book was written for non-specialist readers, making his theory comprehensible to the layperson. The effect of this increased accessibility was seen immediately – the first edition was sold out on the day of publication, and a second printing was issued a month later due to high demand. In its first year, the work sold 3,800 copies and in Darwin's lifetime the British printings alone sold more than 27,000 copies (Hull, 1973). As Darwin was already a celebrated scientist, his findings were taken seriously and the evidence he presented generated scientific, philosophical, social and religious discussion about the faults and merits of *The Origin of Species*.

Controversy Before Acceptance

The publication of *The Origin of Species* aroused

Figure 4.23: *Image taken page 36 of Darwin's "B" Transmutation of Species notebook, started in mid-July 1837. Displayed is Darwin's first sketch-concept of an "Evolutionary Tree" and immediately above the words "I think".*

international attention and invoked a widespread debate, with no sharp line between scientific issues and ideological, social and religious implications. It was expected with such a novel theory that theologians, laypeople and even scientists who were strongly religious would object violently to his theory of evolution. Ideas about the transmutation of species were controversial as they conflicted with the "scientific" beliefs that species were unchanging parts of a designed hierarchy, and that humans were unique, unrelated to other animals – such ideas were not widely accepted in the scientific community (Hull, 1973). Darwin also anticipated the skepticism of his fellow scientists about the theory of evolution. In the early 1800s, the conflict between science and religion was largely settled; scientists could concern themselves with the workings of the material world, once created, but the first creation, life, mind, and soul were the province of the theologian. Instead of abiding by this fragile arrangement, Darwin instead stopped it dead in its tracks with the publication of *The Origin of Species*, leading to large segments of the scientific, religious, and intellectual community to turn their allegiance (Darwin, 1859).

What Darwin had not anticipated, however, was the vehemence with which even the most respected scientists and philosophers would denounce his efforts as not being properly scientific in methodology. To be scientific in the nineteenth century meant to follow the process of induction, and to indiscriminately collect data without preconceived ideas. Darwin however, rejects the notion that observations can be made without a preconceived notion of what to look for – saying "I have therefore, only to verify and extend my views by careful examination" (Darwin, 1958). Darwin's own experiences as a scientist forced him to recognize that the order in which hypotheses were formed and the relevant data gathered could not be rigidly set; his theory of evolution by natural selection was formulated over several years of observation as a naturalist, followed by two decades of additional, selective investigation (Pickering, 1988).

Darwin was thus caught in the middle of a great debate over some of the most fundamental issues in the philosophy of science – the difference between deduction and induction, and the roles of each in science. Before philosophers were able to determine the solution to this debate, they were presented with an original and highly problematic scientific theory to evaluate (Bowler, 2003). The fact that they rejected evolutionary theory, a theory which has outlasted many of the theories judged to be empirically "scientific" at the time, says something about the views of science held by these philosophers and scientists at the time.

The Origin of Species, as a book with wide general interest, became associated with ideas of social reform and so despite the initial controversy and ridicule Darwin received for its publication, by the mid 1870's evolution reigned as the prevailing theory about the history of life on Earth (Bowler, 2003). Darwin's book legitimized scientific discussion of evolutionary mechanisms, and set the precedent for our modern-day understanding of nature and the place of humanity within it.

Modern Ecological Principles via Darwin

The word 'ecology' did not exist until late in Charles Darwin's career, and was not used in a scientific publication until 1876 (Bowler, 2003). Although Darwin himself never used it, it was his work on the complex interactions of organisms and habitats that inspired the word's creation in 1867. It is nonetheless believed that the roots of the scientific study of ecology can be traced back to Darwin and the publication of *The Origin of Species*. In fact, this publication contains numerous observations and proposed mechanisms that clearly fit within the boundaries of modern ecology: trophic cascade, the relationship between physiology and function, and competition all are principles drawn directly from *The Origin of Species* (Darwin, 1859).

The concept of trophic cascade can be tied directly to speculative remarks made by Darwin in *The Origin of Species*. He wondered about the interconnectedness between several species, namely that red clover and heartsease (Viola tricolor), pollinated only by bumblebees, are harmed by field mice which destroy bees' nests, and benefitted by cats which catch the mice (Darwin, 1859). This is essentially what is understood in modern ecological terms to be a trophic cascade, (**Figure 4.24**) which occurs when predators in a food web suppress the abundance or alter the behavior of their prey, thereby releasing the next lower trophic level from predation or herbivory (Kennedy, 2012). Although Darwin was actually incorrect about the mechanism of this particular cascade, the concept of indirect interactions across and within food webs is still a fundamental concept in modern ecological principles, owing its inception to Charles Darwin's astute observations.

Another modern ecological principle is indirectly attributed to Darwin's early work aboard the *H.M.S. Beagle* is the understanding of the complex interactions between abiotic and biotic factors in an environment. It is often understood that Darwin worked only with the environment as a selective pressure, however he also saw the environment as a determinant of species interactions (Darwin, 1859). According to Darwin, lush places support a lot of species and the control of populations is due to competitive interactions, whereas in harsh places, populations are controlled by "injurious action" of the environment (Darwin, 1859). Thus there is the shift from biotic to abiotic controls on ecological processes, which is understood today to be part of a network of complex interactions between living and nonliving environmental pressures.

Finally, and possibly the most noteworthy contribution of Darwin to the field of modern ecology is the understanding of competition as the driving force behind speciation. A large section of the discussion in the Struggle for Existence chapter of *The Origin of Species* is concerned with ecological interactions and the severity of negative interactions, which stems from the fact that populations, if unchecked, will increase exponentially (Darwin, 1859). Although he was correct, in that competition between and within species does influence speciation and evolution, he failed to realize that it was not the sole driving force. In modern ecology, it is well understood that other factors such as resource availability, gene flow, and environmental factors can and do influence the struggle for existence and in turn the divergence and creation of new species (Morjan and Rieseberg, 2004).

Darwin is often attributed with creating and progressing the discipline of ecology more than anyone else in its young history. Although Darwin's work was pivotal – and in more ways than one – in establishing the modern understanding of ecology, the assumptions and frameworks that he worked within were very different, and sometimes incorrect, from the perspective that are taken for granted today. It is now common knowledge that evolution directly informs our expectations and predictions of ecological patterns and processes, and in this respect, Darwin can rightfully be proclaimed one of the fathers of modern ecology.

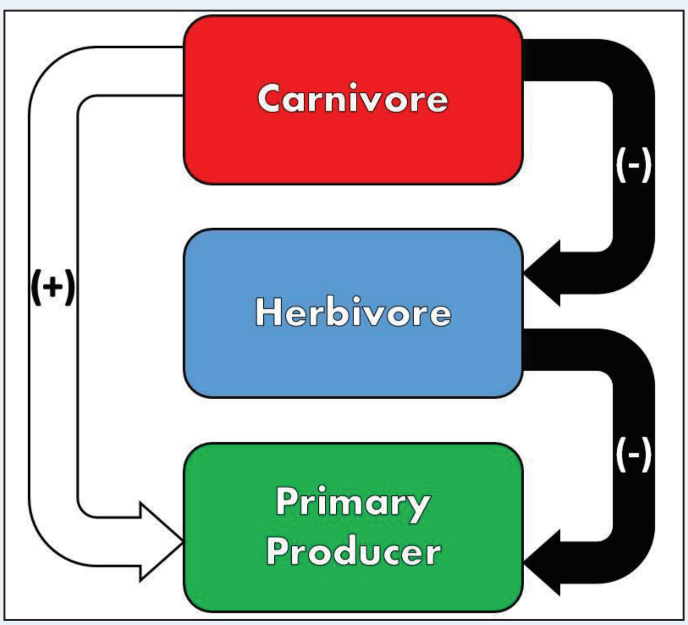


Figure 4.24: *Diagram of a simple trophic cascade. Carnivores, indicated in red, have a positive effect on the species two trophic levels below them, Primary Producers. Trophic levels immediately adjacent (ex. Carnivores and Herbivores) have negative effects on each other.*

Paleobiology Through the Ages

In the preceding sections of this chapter it has been shown how life in our world has evolved over millions and even billions of years. It has also been shown how our understanding of the biosphere on Earth has grown as we look at our world with new perspectives. However, there has been a critical perspective which has not been addressed when looking at biological perspectives on Earth. Throughout history, the development of the biosphere has been intimately linked to geographical phenomenon. The fact that life is observed as it is today is the result of a series of geographical processes occurring over billions of years. Because of this, as the understanding of Earth's geographic history grows, so too does the understanding of Earth's biology.

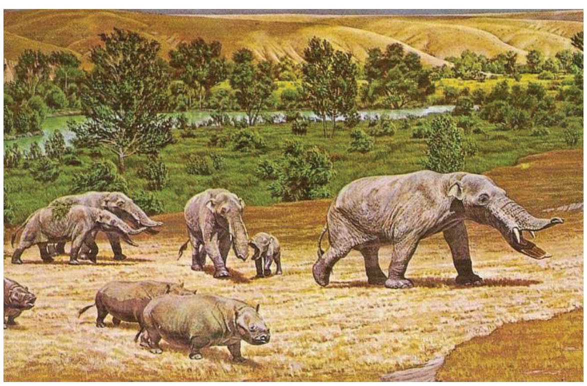


***Figure 4.26**. The study of paleobiology can help us determine the geographic context in which animals may have historically lived.*

The integration of biology and geology is a relatively recent field of study. This broad field of study is known as paleobiology. Generally, paleobiology – also known as geobiology – is concerned with the interactions of the biosphere and the lithosphere (**Figure 4.26**). More specifically, a paleobiologist will look at how various geographical processes and phenomenon have affected the nature of our biological world (Jablonski, Flessa and Valentine, 1985). Existing theories and assumed knowledge in the field of biology may be shown to be false through discoveries in the field of geography. This can be done in many different ways through subsections of paleobiology. Fossil records which are used to gain insight into ancient biology are a core component of a field of study known as paleoichnology. Our understanding of evolutionary patterns as influenced by geological process is known as evolutionary developmental paleobiology (Plotnick and Baumiller, 2000). This is a subsection of paleobiology of particular concern within this section. More specifically, this section will be looking at how our understanding of geography has affected evolutionary thought.

The Father of Paleobiology

The history of paleobiology as a rigorous scientific discipline begins with a man named Franz Nopcsa von Felső-Szilvás (1877-1933). Nopcsa is widely regarded as the father of paleobiology as his contributions to the scientific world were some of the first to integrate both geology and biology to a thorough extent (Dyke, 2011). Much of his work was carried out in the Balkans in the early 20th century. His work was intensely focused on the abundance of Transylvanian dinosaur fossils that were being discovered in the area at the time. In a time when scientists were concerned almost entirely with assembling the bones of the new found beasts which had once roamed the earth, Nopcsa was interested in their evolutionary behaviour as well as looking at the geographical world that these animals once lived in (Grigorescu, 2003).

Nopcsa's deductions regarding the geographical world that the dinosaurs once lived in proved to be invaluable to the study of their evolution as well as the evolution of animals as a whole (Jablonski, 2000). One of the most important principles brought forward by him was the evolutionary principle of insular dwarfism. Much of Nopcsa's observations on fossils were made in the Hateg area in Romania. While studying fossils within this area, he noticed that the fossils were considerably smaller than the fossils of the same animal found in different parts of the world. In his studies of the local geography, Nopcsa proposed that the area in which the fossils were found was once a large island in the Tethys ocean known as Hateg island. Nopcsa theorised that the seemingly stunted size of the fossils found in this area was a result of this geographic profile. The nature of being confined to an island meant that the inhabitants were limited in their resources and as a result, there was a "downsizing" of the organisms in the area over an evolutionary time scale (Lomolino, 2005). These observations were key in Nopcsa's development of the theory of insular dwarfism which would be widely used in evolutionary biology.

Paleobiology Before Nopcsa – Georges Cuvier

Prior to the establishment of paleobiology as a rigorous scientific discipline, many prominent scientific figures had made observational connections between geography and biology. However these connections were often superficial and lacked the depth necessary to form detailed theories and principles which could be consistently applied throughout studies. More often, scientists were predominantly concerned with the consequences of their observations from a narrow perspective and only applied alternate perspectives as means to further substantiate their established beliefs (Plotnick and Baumiller, 2000). These observations were very important none the less as they would influence the thinking of countless scientists in the years to come.

In the year 1769, a scientist was born whose work in the fields of earth science would have critical effects on our understanding of historical biology. This scientist was Georges Cuvier (1769 – 1832) who was born In Montbéliard, France. Cuvier (**Figure 4.27**) is often regarded as the "father of paleontology" as his works concerning the comparison and analysis of vertebrate fossils was unprecedented in their rigour (McClellan, 2001). Cuvier was also a naturalist meaning that he was concerned with the natural world and the process by which nature took its course. Within his naturalist studies, Cuvier was particularly interested in the school of thought known as catastrophism. He proposed that the history of life on Earth was a direct consequence of a series geological catastrophes which had occurred throughout history. In other words, it was not the evolution of animals which propagated change, but rather the selective destruction and rebuilding of species through geologic disasters (Appel, 1987). Although it seems silly to the contemporary thinker to discredit evolution entirely, the works of Cuvier would prove to be valuable when studying the succession of animals groups as the dominant species on this Earth. More specifically, Cuvier's theories were used as a fundamental basis to study the succession of mammals following the extinction of the reptilian dinosaurs due to the Cretaceous–Paleogene extinction event (Jablonski, 2000).

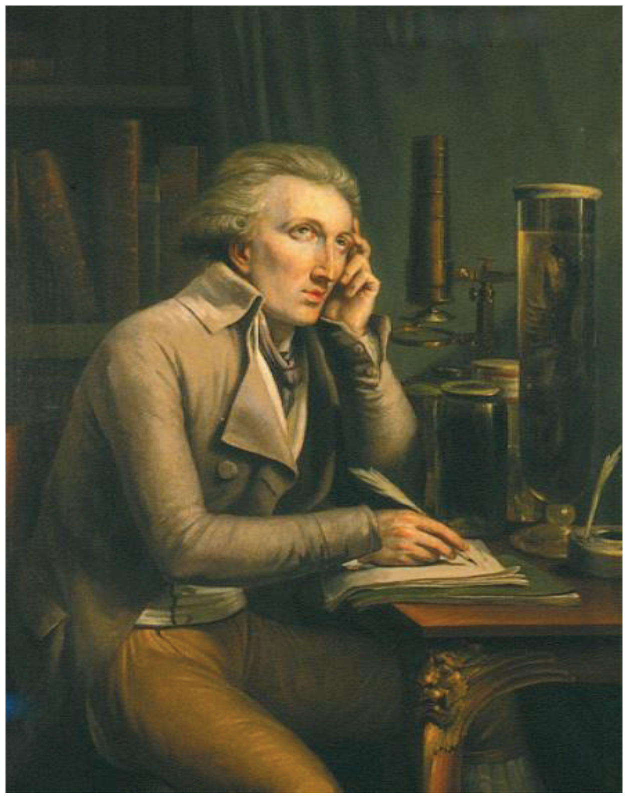


***Figure 4.27**. Although he was not a supporter of evolution, Georges Cuvier's works regarding extinction and catastrophism helped shape evolutionary knowledge in future studies.*

Cuvier had suggested that mammals were not always the dominant species on this earth and that reptiles were at some point the dominant species (Cuvier, 1831). Cuvier's use of geologic catastrophes to explain observed biological phenomena represents some of the first links between the earth and biological sciences.

The Link to Evolution – Alexander von Humboldt

Born in the same year as Georges Cuvier, Alexander von Humboldt (1769 – 1859) was one of the most prominent holistic scientists in history. Humboldt sought to integrate aspects of multiple scientific disciplines in his work as he believed that his was the only way by which one could truly obtain an understanding of the universe (Botting, 1973). In addition, perhaps one of the most prominent postulations made by Humboldt in all his studies was the notion that South America and Africa were once connected – a notion which would gain widespread support in future years. Furthermore, this notion would have profound impacts on the study of the radiation of species throughout the world.

Although he indulged in nearly all the scientific disciplines, Humboldt (**Figure 4.28**) was a fiercely passionate botanist. In 1799, he requested leave from King Carlos IV (1788 – 1819) of Spain to explore the flora of the Spanish colonies in the Americas. Humboldt was interested in looking at the geographical distribution of various tropical and temperate plants (Dolan, 1959). In a series of essays known as *Ansichten der Natur* (Views of Nature), Humboldt wrote, "But although life is everywhere diffused, and although the organic forces are incessantly at work in combining into new forms those elements which have been liberated by death, this fullness of life and its renovation differ according to differences of climate" (Bohn, Humboldt and Otté, 1850). This idea was very much at core of Humboldt's research.

The results of Humboldt's expedition yielded an extensive exposition of plant diversity gradients throughout the "new world". Humboldt theorised that his gradient was a direct result of temperature and climate differences which were found at varying latitudes (Norris, 2000). Although concerned primarily with an ecological perspective, these postulations provided valuable insight when the same locations were looked at from an evolutionary perspective shortly after. Humboldt's integration of climate geography profiles and ecological diversity presented an essential stepping stone for future evolutionary scientists to effectively integrate geographical phenomena intro their studies.

Among the important characteristics for any scientists is a yearning for knowledge and an observant mind. Humboldt personified these qualities to an unprecedented degree. So much so that he was revered across the world – especially by one Thomas Jefferson (1743 - 1826) who eagerly sought a meeting with him throughout his life. Humboldt's primary scientific expedition was his journey to the Americas which were documented by him in an extensive collection of observations and documents published as *Le voyage aux régions equinoxiales du Nouveau Continent* (The Voyage to Equatorial Regions of the New Continent). Even perhaps more significant to Humboldt's legacy was Charles Darwin's adoration for Humboldt's scientific work which significantly influenced his own expedition to the Americas.

***Figure 4.28**. Humboldt's holistic and integrated approach to scientific study was yielded many fascinating links between various fields of study. Unlike many brilliant minds who are often appreciated post-mortem, Humboldt's popularity was extremely high during his life.*

From Humboldt to Darwin

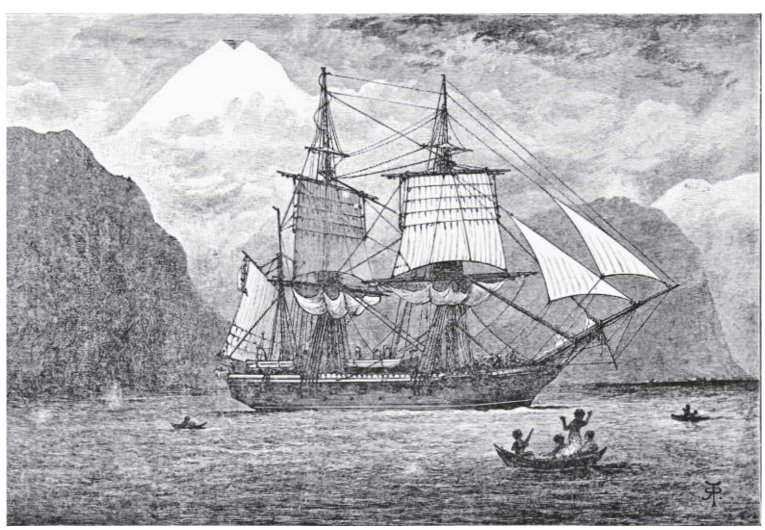
The study of evolution is intertwined with the study of geology as geology holds the buried remains of past animal and plant life, thus allowing for the discovery and examination of the events of the past (Nelson, 1925). The geological record encompassing information about both environmental conditions and biological life forms provides matter for delving into the issue that was why changes occurred in the structure of life forms. The classification of rocks and being able to date rocks allowed the study of evolution to be put on a time scale. As the age of the rocks in the geologic scale decrease, the complexity of life forms increase and this time scale was necessary because without it trends could not be put together (Nelson, 1925).

Charles Darwin (1806-1882) is known as the father of evolution (Appleby, 2013). Darwin's ideas and studies were largely influenced by the works of Humboldt. Growing up, Darwin was always fascinated by the natural world but at this point in time science did not provide much of a career path though it was being taught in universities. His father did not approve of his interests and sent him off to multiple universities to be educated in a disciple that he thought was respectable, but Darwin found no interest in medicine or other mainstream suggestions by his father. Darwin was more fascinated by what he learned about from his peers concerning Jean-Baptiste Lamarck (1744-1829) and other naturalists' views on the world (Appleby, 2013).

Among all other naturalists, Darwin adored Humboldt and his works (Appleby, 2013). At the age of twenty-two Darwin set off to explore the New World just as Humboldt had (**Figure 4.29**). Darwin called Humboldt the parent of "a grand progeny of scientific travellers" and mentioned him over four hundred times in the compilation of his works (Appleby, 2013). On Darwin's voyage to the New World he took with him Charles Lyell's (1797-1875) book "The Principles of Geology". This book outlined the gradual transformation of the surface of the Earth, which is a key subject matter that aided in Darwin's explanation of the transmutation of species. The specific component that helped the most was the discovery of Lyell's that organisms could be transported to oceanic islands by means of geological processes (Manier, 1978). Darwin thought very fondly of Lyell, and Lyell's cosmogonical theories about the tipping of the Earth's axis and the cooling of molten Earth linked geological processes with climate change that could explain extinction of certain species found in the fossil record. Lyell's work in this area set a foundation for Darwin in that changing geology causes climate change and this affects species over time (Manier, 1978). Darwin himself noticed on his exploration in the New World that island species that were separated spatially had varying characteristics and features, and after his voyage he studied geology for two whole years to gain a better understanding of the geological processes involved in separation events such as islands (Appleby, 2013).

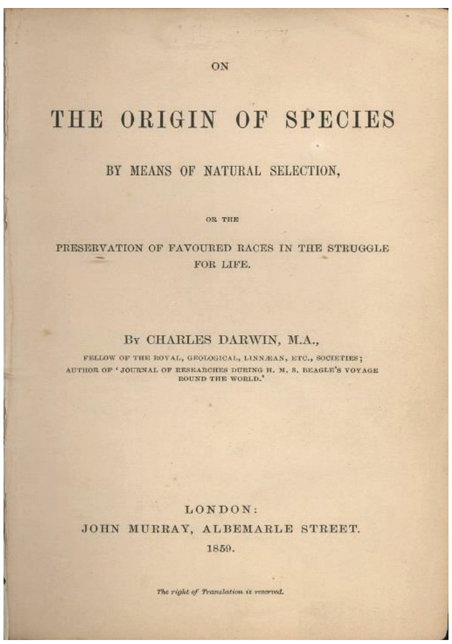
Humboldt made an attempt at the theory of evolution in saying that the perspective of human life is affected by climate and vegetation, where climate and soil conditions had the largest influence on survival (Appleby, 2013). Humboldt theorized that diversity had to do with adapting to different environments and he focused specifically on mountain ranges and the relationship between earthquakes and the Earth's crust. These ideas about how geology plays a large part in evolution began the unravelling of Darwin's own theory. The study of biogeography was invented by Humboldt and used by Darwin to understand the distribution of species. Humboldt used fossils to date strata and Darwin was fascinated with fossils as they are a constant reminder that certain species have gone extinct (Appleby, 2013).

Figure 4.29. Charles Darwin's voyage to the new world on the HMS Beagle (shown below) was inspired by Humboldt's own voyage. Furthermore, Darwin's postulations regarding evolution were built on the foundations laid by Humboldt's geographical studies.



Paleobiology in Darwin's Theory of Evolution

During the time period of Darwin's life there was a general desire to find an explanation for the origin of new species. After Darwin's life, evolution was forever seen as the survival of the fittest (Appleby, 2013). He had answered the unanswerable question during his lifetime—how to place humans in nature. His publication of "The Origin of Species" (**Figure 4.30**) was criticized for not citing enough fossil sequences of species that showed changing characteristics (Appleby, 2013), but during his lifetime the breaks in the geologic record was known to present huge problems for understanding all that is evolution and geology (Manier, 1978). Fifteen years after the publication of "The Origin of Species", a palaeontologist named Othniel Marsh (1831-1899) discovered and provided evidence in the geologic record to prove that animals of the same species do change over time (Appleby, 2013).



ON

THE ORIGIN OF SPECIES

BY MEANS OF NATURAL SELECTION,

OR THE

PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE.

BY CHARLES DARWIN, M.A.,

FELLOW OF THE ROYAL, GEOLOGICAL, LINNÆAN, ETC., SOCIETIES;
AUTHOR OF 'JOURNAL OF RESEARCHES DURING H. M. S. BEAGLE'S VOYAGE ROUND THE WORLD.'

LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.

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***Figure 4.30**. The title page of the 1859 edition of "The Origin of Species" by Charles Darwin. This was one of Darwin's most famous works and it is a revolutionary text for the field of evolution.*

Darwin played a key role in the overthrow of the church's control on scientific studies and endeavour (Appleby, 2013). During this time period religion had acted as a temporary roadblock in scientific discoveries as it attempted to disallow research into areas that would suggest anything that goes against the belief of the church (Nelson, 1925). When writing "On the Origin of Species" Darwin was very careful so as to lessen any offense to the church and he even moved many times so that he was in an area that he felt would alienate him the least after he published his works. This is because Darwin's theory went against the idea that God created everything and thus cut the bond between man and God. Only by the 19th century did most naturalists agree that inferior life forms could go extinct, but many still had trouble believing species could be created by other means than a God (Appleby, 2013).

Darwin's discoveries used natural selection to explain both macroscopic and microscopic jumps in the geologic record, and then in the 20th century molecular biologists made impeccable advancements in the study of genes (Clark, 1948). These discoveries in gene's provided a mechanism by which evolution can be explained. Molecular biology ruled as the science of the late 20th century and once the composition of Deoxyribonucleic acid (DNA) had been understood, so with it followed the understanding of inheritance. Thus, beyond these historical discoveries evolution became something less studied by geological processes but rather instead by microbiological processes (Clark, 1984).

Advanced Evolution

As time goes on humans become more and more resourceful and are able to manipulate almost anything they would like. Nothing is out of reach and natural selection does not get in the way of designing evolution. Artificial selection allows humans to create what would otherwise not appear in the geologic record on its own. In addition, advancements in molecular biology allow humans to manipulate genomes: the main determining factor that passes down traits to offspring and allows evolution to occur. By being able to select what proliferates and what does not, and by being able to create life that would otherwise not exist if it had to survive with the geological changes of the Earth, humans have changed the game of evolution.

Genetic Engineering

Genetic engineering involves the transferring of parts of the genes of one cell into another cell of selected species (British Medical Journal, 1981). The plausibility of genetic engineering came about in the late 20th century, and its purpose was to give certain cells additional functions or different functions. Using these techniques humans have achieved the production of insulin by bacteria cells amongst other things (**Figure 4.31**). Foreign DNA can either be manually inserted into the DNA of the selected organism, or it can alternatively be inserted into the DNA of the selected organism via a virus (British Medical Journal, 1981). Genetic engineering of plants has allowed the insertion of herbicide resistance, insect resistance, drought tolerance and even nitrogen fixation abilities. This allows plants to flourish and survive in environments that would otherwise be deemed unsuitable. By genetically engineering certain plants, humans have been able to produce sufficient quantities even in areas where certain crops would likely die off (Colwell, et al., 1985).

Traditionally it was believed that plants could only survive and thrive in environments that were suitable for their genetic makeup (Bennett, 1995). Engineering plants to be drought-tolerant and efficient at preventing water-loss is a large benefit for having consistent crop yields even if environmental conditions are unfavourable. Weather is unpredictable, and so manipulating crops to be able to thrive even if rain is scarce one season limits unpredictable outcomes. Rice is one of many crops used for conventional breeding where parts of the genome of wild rice is inserted into the genome for cultivated rice producing a viable plant. This mutated plant will gain traits in places like the roots to enable it to avoid drought (Bennett, 1995).

Impacts on Evolution

Artificial selection involves only manipulating genomes of one species and it also involves sexual reproduction so that the new gene combinations are integrated into one another to create one final output (Flint and Woolliams, 2008). A common use of selective breeding by humans is in the manipulation of canine species. Humans selectively breed dogs for many reasons including to optimize them to be service dogs, for medical or scientific research, for aesthetic purposes, or for pets. With genetic engineering and technology humans are able to be precise when breeding. This is done through having a thorough understanding of the biological processes that happen inside each species and manipulating this to achieve what is needed (Flint and Woolliams, 2008). Previous knowledge would state that existing species were naturally selected to exist in their environments, and if you took them out of their environment or introduced a different species into a non-native environment the species would suffer. Selective selection thus offers a loophole in previous knowledge by being able to selectively choose traits that will be sustainable in the current environment, but would otherwise not exist on its own (Bellon, 2002).

Humans have broken the barriers that biological processes developed over long periods of time. Through knowledge of the processes inherent in evolution humans are able to craft and manipulate species over very short periods of time. From deciding how dogs should act and look, to making sure food is always secure, humans have turned evolution into a tool that can be manipulated to benefit the race. Geology no longer plays a key role in limiting this new advanced evolution, and in the future the fossils created by our engineered dogs and plants may cause much speculation into the nonsensical evolution that occurred.

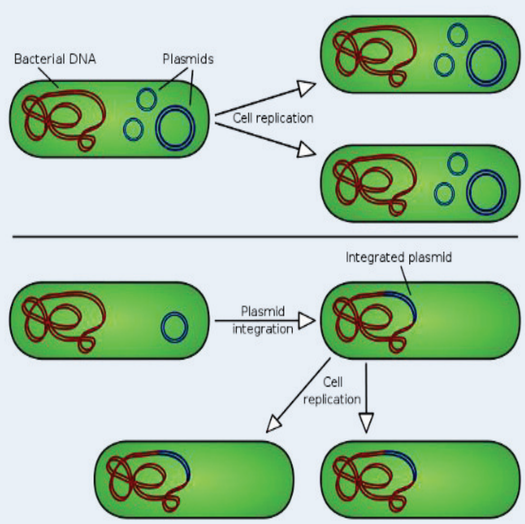

Figure 4.31*. The mechanism by which genetic engineering uses plasmids to transfer pieces of a genome of one cell into a bacterium so as to make human insulin when the bacteria replicates.*

Figure 5.1: *Fighting Stegorsaurus and Allosaurus recreation at the Denver Museum of Nature and Science.*

Chapter 5: Ancient Lifeforms

Time is perhaps the most difficult thing to survive. The life that exists today represents a tiny fraction of genes that against all odds, managed to slip through the turmoil of infection, competition, and a series of ever-changing geological events. The majority of biodiversity was not so lucky, pushed to extinction and compressed into the soil like the pages of a book glued shut, now opened to the present chapter of life. However, these remnants were not meant to be forgotten. Life occurs in a number of successions that evolve from one another, and the current is no more important than those of the past. Thus, paleontology is important not simply because of the marvels of knowing what exists, but because it is the only way to understand the slow development of how our species came to be. From a microscopic cell floating in an infinite sea, to an age of photosynthesizing producers, to a time where the world was dominated by enormous reptiles, the genetic code of our ancestors have progressed, as shown by the traces buried in the lithosphere. These traces also indicate the kind of impactful events the world has undergone; floods, meteorite impacts, volcanism, all pushing life to the limit of how much adaption is possible.

The following pages will explore some of the individuals who have uncovered the vestiges of ancient species, buried deep below the Earth's surface. They will describe the problems and triumphs encountered by the brave souls who endeavored to wonder what had come before them. The species that are described will be difficult to interpret but will bring some insight into the world before humans existed.

One section of this chapter will go through the discovery of dinosaurs, and the early years of paleontology with respect to dinosaurs. It will start with the confusion civilizations faced when unearthing bones that were bigger than those they had ever seen, and then proceed to the times when dinosaurs were known, but facts around them were hotly contested. This section will serve as an overview of the history behind our discovery and interactions with the fossils of the huge beasts that roamed the Earth before humans existed.

With the discovery of the dinosaurs came new questions surrounding their demise. When did these powerful beasts die out and what caused their extinction? The concluding section of this chapter will work through a chronology of extinction theory from the time of Ancient Greece to the present. Throughout the ages various theories of life and by extension, various theories of extinction have existed. The concluding section of this chapter will explore the ideologies underlying some of the main theories as well as some of the commonalities that exist between theories. Finally, the most recent development in extinction theory, the Alvarez Hypothesis, will be outlined in great detail as a revitalised spin on classical catastrophism.

People of Paleobotany

Paleobotany is a field of study concerning the evolutionary history of plants through the analysis of geological evidence, or fossils. Prior to the 17th century, the study of fossils was merely considered a "sport of nature" (Batten, 1887). They served an aesthetic interest, but served a limited academic purpose and gained virtually no scholarly attention. Attention to the field started to take place in the 18th century, with true interest in paleobotany peaking in 19th century. The publication of Darwin's *On the Origin of Species* in 1859 was the catalyst for the growth of interest in evolutionary studies, simultaneously creating interest in paleobotany (Seward, 1898). The 19th century was also a period of advancement in microscopy analysis. William Nicol (1810-1879) developed the calcite prism to polarize light, which he used to analyze thin sections of petrified wood. Henry Clifton Sorby (1826-1909) was the pioneer in microscopy analysis of rocks, a field which was refined by Ferdinand Zirkel (1838-1912) and Karl Heinrich Rosenbusch (1836-1914) (Wilding, 2005).

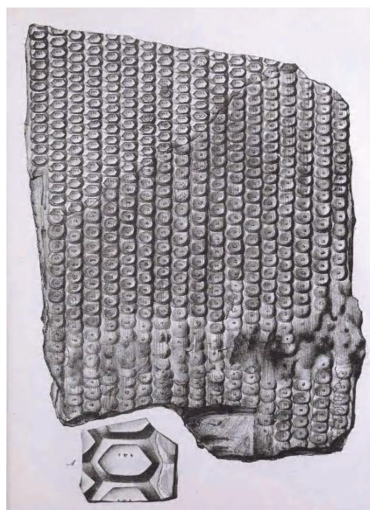

***Figure 5.2**: Illustration of* Sigillaria hexagona *fossil by Adolphe Brongniart. The illustration consists of a general sketch (top) and a section with specific detail (bottom). Brongniart's greatest criticism of his predecessor's illustrations was the lack of detail*

Major contributions to paleobotany came from many nations. The French and Germans created the early illustrations of plant fossils. Canadian geologists used different methods to create more detailed and accurate images of fossils, while British paleobotanists made some of the greatest findings in the field and reconfirmed the discoveries of others.

Illustrators of the 19th Century

Science relies heavily on communication; with scholars dispersed around the world, books and journals provided a method for the spread of ideas and thoughts (Von Sivers, 2014). The ideas of many sciences can be communicated with empirical evidence. Evidence in paleontology, however lies in the physical evidence, the fossils. Prior to the invention of photography, paleontological evidence was documented using detailed illustrations; the quality of these images relied on the skill of the illustrator. Ernst von Schlotheim (1764-1832), Kaspar von Sternberg (1761-1837) and Adolphe Brongniart (1801-1876) created images that laid the foundation in the field of paleobotany (Cleal, Lazarus and Townsend, 2005).

In addition to being a student of Abraham Werner (1749-1817), one of the fathers of geology, Schlotheim was mentored by many botanists and zoologists. This allowed him to progress into the relatively new field of paleobotany (Torrens, 1990). During his career, Schlotheim wrote two key paleobotanical publications–*Flora of the Ancient World* in 1804 and *History of Petrification's* in 1820. Most of his observations were made on fossils of Carboniferous and Lower Permian origin, from the Thuringia and Saarland regions of modern Germany. Schlotheim's 1804 analysis compared fossils with living plants, identifying similarities with tropical flora. This publication contained detailed descriptions but no formal names. The 1820 publication compared fossils with other fossils, allowing Schlotheim to develop a binomial nomenclature, but none of these names remained in the field. Schlotheim's published illustrations were copper-plate etchings created by Johann Capieux (1748-1813). It is unknown whether they were based off of original drawing from Schlotheim or if they were drawn under Schlotheim's supervision (Cleal, Lazarus and Townsend, 2005).

Sternberg was born to a wealthy family, and was expected to follow a career in the clergy like most aristocratic boys. When the French Revolution started in 1789, Sternberg's older brothers entered the military service; Sternberg's parents enrolled him in a holy order, which cause him to travel around Europe (Andrews, 1980). During these travels, he encountered Schlotheim's *Flora of the Ancient World*, influencing him to study paleobotany. His work formed a two volume publication in 1820 and 1838, titled *Flora der Vorwelt* (Ancient Flora). Since Sternberg funded his own work, he employed over 15 illustrators to complete his sketches. Sternberg's work mainly examined the stem structure of *Calamites* and *Lepidodendron*. However, his work was one of the first to establish the genus of ancient plants based on similar characteristics (Cleal, Lazarus and Townsend, 2005).

Brongniart, the son of a distinguished geologist, became a doctor of medicine at the age of 25. At that point, he was already immersed in the field of paleobotany. Brongniart's early work is a criticism of his predecessors' research. Schlotheim's 1804 illustrations lacked detail–they only showed images of the whole organism without a detailed close-up. They also lacked geological or biological classifications. His 1820 work creates analogies between fossils that are too uncertain to be true. Sternberg's work only examined a small portion of plant species, but he did associate samples with genera (Brongniart, 1822). Brongniart's most prominent work came in the form of a 15-part series titled *Histoire des vegetaux fossiles*. This series contained nearly 200 images that showed extremely fine detail such as veining and vasculature (Cleal, Lazarus and Townsend, 2005; **Figure 5.2**). In addition to his critiques, Brongniart drew inferences about evolution and continental drift well before the published theories of Darwin (1859) and Wegener (1924). He noted that newer rocks have fossils that had a closer relation to extant plants. He also noted that the vegetation found in European fossils does not match Europe's current environment and that they could have potentially been transferred from other locations (Brongniart, 1822).

Canadian Contributions

The early years of paleobotany are highlighted by the illustrations of people like Schlotheim, Sternberg and Brongniart. As mentioned earlier, Brongniart was very critical of previous artwork due to lack of detail (Brongniart, 1822). The detailed analysis of plant structure commenced with the invention and the advancement of microscope technology (Sorby, 1858). Canadian geologist John William Dawson (1820-1899) was at the forefront of this paleobotanical revolution.

Dawson was born and raised in Nova Scotia, where he began collecting plant fossils at the age of 12. He studied locally at Pictou College and in overseas in Edinburgh, before returning to Canada in 1842. Within seven years, he was named the Superintendent of Education for Nova Scotia, a position which allowed him to travel the province to collect data for his monumental geological publication, *Acadian Geology* (Andrews, 1980).

Figure 5.3: *Fossilized root imprints on a cliff near Joggins, Nova Scotia, Canada. John William Dawson discovered one of the finest specimens of a lycopsid on these cliffs.*

Studies in paleobotany began with carboniferous plants, transitioned to coal plants during the industrial revolution and moved to the tertiary soon after. However, the earliest land plants (of the Lower Paleozoic) were ignored until Dawson began to study them (Wilding, 2005). Dawson had a keen interest in anatomically preserved plants in permineralized fossils. These fossils are formed when plant tissue mineralizes at an early stage in fossilization, but require the time-consuming process of preparing petrographic thin sections for analysis. In 1846, Dawson discovered axes of lycopsids (earliest extant vascular plants) and cordaitales (early conifers). In the latter part of his career, Dawson began examining fossils of the Joggins Cliffs in Nova Scotia (**Figure 5.3**). There, he discovered one of the finest specimens of a lycopsid tree, with its full axis intact and showing structure. In a different petrographic section from Joggins, Dawson also discovered hexagonal disks similar to araucarians (a sister group to the cordaitales) (Falcon-Lang and Calder, 2006). Recent research indicated the trees in these samples grew in coastal habitats (Falcon-Lang, 2005).

In addition to his studies on permineralized fossils, Dawson undertook charcoal analyses and whole-plant reconstructions to understand the forest communities of the Lower Paleozoic, specifically the Pennsylvanian subperiod of the carboniferous period (Falcon-Lang, 2005). Dawson culminated his career with the publication of *The Geological History of Plants* in 1889

(Andrews, 1980).

The British Influence

While Dawson was conducting his studies on Carboniferous plants in Canada, William Crawford Williamson (1816-1895) was carrying out his own research at Manchester University in Great Britain. Williamson was introduced to Jurassic fossils at an early age by his father; he later completed medical school at the age of 16. However, during an apprenticeship with an apothecary, Williamson regained interest in geology and botany, joining Manchester Museum as a curator at the age of 19. Williamson's most significant work in paleobotany was the discovery of *Stigmaria* fossils (lycopsid tree root) in a quarry at Clayton near Bradford, Yorkshire. His monograph on the *Stigmaria* fossil determined that it was a pteridophyte rather than a gymnosperm, a debate that Brongniart and his successors clashed over for the 50 years prior. In addition to his scientific contributions to paleobotany, Williamson is well known for directly influencing many great paleobotanists including Albert Charles Seward (1863-1941) (Watson, 2005).

Not much is known on the earlier parts of Seward's life. He graduated from St. John's College, Cambridge in 1886 with highest honours in natural sciences and began to study paleobotany under Williamson that same year. During this time, he was given the opportunity to travel to many museums to study fossil plant collections (Wilding, 2005). Throughout the course of his career, Seward analyzed a wide variety of fossil plants–this is evident through his comprehensive four-volume work *Fossils Plants*. This series starts with a general volume on fossilization, describes lycopods and pteridophytes in two volumes, and ends with a volume on conifers (Andrews, 1980). In addition to his publications, Seward is known for his early inferences on continental drift. In the early 1900s Seward studied the *Glossopteris* fossil in detail, noting that it originating in Antarctica and is present in Argentina, South Africa, and Australia (Seward, 1931). Over 30 years later, South African geologist Alex du Toit, an early supporter of the continental drift theory, analyzed the species distribution in further detail. The *Glossopteris* spanned across nearly four-fifths of Gondwana, spreading from south to Russia and potentially Persia, and completely contrasted the vegetation of Laurasia (Du Toit, 1937; **Figure 5.4**). Like Brongniart, Seward's first mention of continental drift was before Wegener's publication of the theory. Seward mentioned it in 1903, over 20 years before Wegener.

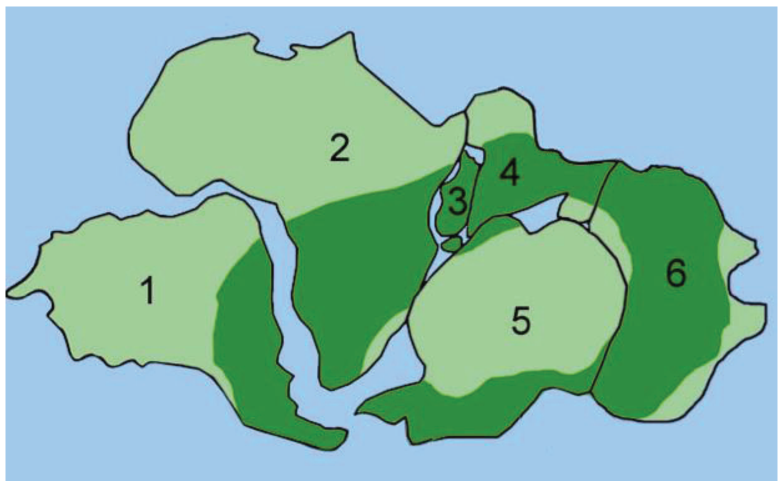

Figure 5.4: *Distribution of* Glossopteris *(dark green) on Gondwana, based on paleobotanical evidence. The continents on the map are: South America (1), Africa (2), Madagascar (3), India (4), Antarctica (5) and Australia (6).*

From "a sport of nature" to early evidence of continental drift, the study of plant fossils, paleobotany, changed a fair bit over thin 19th and 20th centuries. Previously a western-dominated field, paleobotany demonstrated an increase in popularity in Asian countries. Indian Birbal Sahni (1891-1949), who was trained by Seward, investigated fossils of Gondwana (specifically *Glossopteris*). His legacy resulted in the opening of Birbal Sahni Institute of Paleobotany in Lucknow, India (Andrews, 1980). Scientists such as Sze Hsing-Chien (1901-1964) and Hu Hsen-Hu (1894-1968) increased the popularity of paleobotany in China (Sun, 2005). With increasing technologies that allow for greater analysis of fossils and spread of information, the field has infinite potential for growth.

3D Printing of Fossils

In the early 1800s paleontological publications included artist-interpreted drawings like Sternberg's and Brongniart's, which lacked fine detail. Invention of mainstream cameras in the 20th century allowed for photography of fossils. All these depictions are 2D (two-dimensional) images of 3D (three-dimensional) artifacts which eliminates a dimension of structure and detail. The recent affordability of 3D printers has permitted the creation of 3D replications of fossils (**Figure 5.5**).

Figure 5.5: *3D printed replicas of* Spinosaurus *skulls at the National Geographic Museum in Washington, DC. The posterior skull is a to-scale replica in foam, while the anterior skull is a plastic replica 17% of actual size.*

The creation of a 3D reconstruction is a three step process. The fossil is first scanned using computed tomography (CT) scanning. CT is an X-ray based diagnostic technology commonly used in hospitals for detecting internal ailments and injuries. In a CT scan, X-rays are sent through the fossil as it rotates 360º. The level of absorption or scattering by the fossil is inputted into a computer algorithm as 2D tomographic slices (Rahman, Adcock and Garwood, 2012). The second step in reconstruction involves computer visualization. This step takes the 2D tomographic slices and projects virtual beams of light through them to create 3D images. These images can be altered in their orientation, colour and transparency (Sutton, 2008). The final step is printing the 3D computer image. Prints are most commonly created using spools of plastic, coloured polymers. These plastics are melted at temperatures greater than 200ºC and dropped layer by layer (bottom-up or top-down, depending on the printer) to create a 3D image (Rosen, 2014).

The 3D reconstruction of fossils gives many advantages. Small specimens can be enlarged so that micrometer details can be viewed by the naked eye. The most delicate fossils can be scanned, since CT is a non-invasive technology. Reconstructed models of these fossils can therefore be analyzed by anyone, not just experts (Teshima et al., 2010). Certain plastics allow for flexibility, allowing models to be like toy bricks–they can easily be separated and put back together. Franciszek Hasiuk of Iowa State University created a flexible Tyrannosaurus head whose jaw can be separated and put back together without damage (Rosen, 2014). Finally, 3D replications of fossils allow for a rare or popular specimen to be analyzed by many people at once (Rahman, Adcock and Garwood, 2012).

Despite the great advantages to 3D, the technology has some downfalls. While it is very effective in basic 3D geometries, it struggles with more complex interiors, such as porous rocks. The printing of solid models takes most time and has an increased cost, since materials come at a price per kilogram. A size limitation also exists for 3D printing–the largest, readily available 3D printer (BigRep ONE) can print a volume of $1m^3$. For reference, Sue, the largest intact *Tyrannosaurus Rex* specimen in the world, has a skull 1.5m in length (Rosen, 2014). Hence, 3D printing of very large fossils will be a challenge until the technology is further developed.

The Discovery of Dinosaurs

Introduction

It is interesting to think that an entire era of gigantic creatures were not always known to exist. For millions of years, they lay far underground, silently existing as a forgotten variety of extinct organisms concealed in rock. Now, these great marvels of evolution have become integrated into the global conscience, appearing everywhere from geological societies to references in the media. How then, did humans make the transition from having no knowledge about any of these creatures, to a time when a complete taxonomic understanding of these ancient megafauna is slowly being realized. This is the story of how it began, and how lives of the first paleontologists provided the foundation for the science of clade: *Dinosauriformes*.

The First Developments

Around 300 BCE, something very peculiar was exposed from a rock outcrop in southern China. It appeared to be an ancient bone structure, having the shape of a lizard and a size that rivaled the modern elephant. The discoverer, likely a farmer from a small village, had no means to interpret it, so scholars were brought in from the nearby metropolis, who believed they had found the remains of a dragon. This was a reasonable answer for the time, after all, dragons flourished in Chinese literature, stories, and religion (Gould, 1886). So, for the following odd occasions that these enormous bones were discovered, the public accepted them as dragons, and scholars would catalogue them by place of discovery, gender or even age. For example, in an ancient text called the *Kwoh-shi-pu*, Li-chao explains many 'dragon bones' that can be found buried near the east end of an unnamed river. Unfortunately, most of this documentation was eventually lost or destroyed, leaving humans without any knowledge of the discovery of such impressive bones for many thousands of years (Gould, 1886).

Figure 5.6: *Richard Brooke's illustration of the femur discovered by Robert Plot in 1677, named Scrotum Humanum, a name would eventually be dropped in favour of Megalosaurus, the species to which the bone belongs.*

The strange bones did not appear in the literature again until the 17th century, when an English professor named Robert Plot (1640-1696) came across an enormous petrified femur near his hometown in Oxford. Upon careful observation, he assumed it to be the thigh bone of a giant man, which may sound nonsensical today, but would have been fairly accepted by the religious convention during this time. 'Augmentation' as it was known could occur in organisms or rock fossils for a variety of reasons, and this was a popular theory for the huge size in "real bones, now petrified" (Plot, 1677). In his book *The Natural History of Oxfordshire*, written in 1677, Plot also explains that other discoveries of large fossils near Cornwall "might be the bones of man or woman" (Plot, 1677) during a time when humans were structurally taller. During this time, a student of Dr. Plot named John Woodward (1665-1728) delved into the reason these bones existed in the first place; specifically, what caused these megafauna to phase out of the living biosphere. Incorporating his beliefs like Plot, Woodward hypothesized that the biblical flood was responsible for the death of fossilized organisms, a theory that seemed to fit well with the other geological findings by creationists during this time (Woodward, 1723). Later on, Plot's fossil discoveries were revisited by a geologist named Richard Brookes (1721-1763), who in 1763 included a drawing of Plot's petrified femur (**Figure 5.6**), which he then named *Scrotum Humanum* after what he thought it resembled (Brookes, 1763). This would become the first published name and illustration of a dinosaur bone in history. In the following decades, a number of small discoveries were made, including a notable stratigraphic observation by Alexander von Humboldt (1769-1859) who coined the time period 'Jurassic' (Jurakalkstein) for the limestone deposits in Jura Mountains of the Alps (Humboldt, 1799). This, along with the Cretaceous period and the Triassic period would eventually become the time periods in which most species of dinosaurs would be found (Benton, 1990).

Megalosaurus, Iguanodon and an Emerging Fossil Collection

The next major player in the discovery of dinosaurs would be a figure known for his idea of catastrophism; Georges Cuvier (1769-1832). He was one of the first to suggest that Earth was once dominant species of large reptiles roaming its surface which were eventually wiped out by some form of catastrophic event. During his relatively long life, Cuvier discovered and examined a great number of 'crocodile' fossils as he first named them, cataloging them according to Linnaeus taxonomy (Cuvier, 1830).

One such specimen he examined was the *Megalosaurus*, named and discovered by the Englishman William Buckland (**Figure 5.8**) (1784-1856) who first described it as "a lizard of great size" (Buckland, 1836). Buckland also realized a number of things based on the layout of the skeletal structure; its large, strong bone cavities meant it had adapted to roam on land, and its teeth indicated that it likely fed on reptiles of smaller proportional size (Buckland, 1893). Cuvier was fascinated by the size of the animal, predicting that it was likely 55 feet or so across from tail to head, and probably stood upright on its hind legs (Cuvier, 1830). As it turns out, Plot's *Scrotum Humanum* fossil turned out to be the same species as Buckland's fossil, making it a *Megalosaurus*, however this would not be realized until much later (Moore, 2014). A few years later in 1841, Richard Owen a British paleontologists coined the term 'dinosaur' as a word to describe the great fossil lizards being found, and specified that the *Megalosaurus* would be considered a type of dinosaur (Owen, 1841). During this time, the prevalent hypothesis for why these species were no longer extant, is the biblical flood theory originally proposed by Woodward, however the understanding and taxonomy of dinosaurs was on the rise (Moore, 2014).

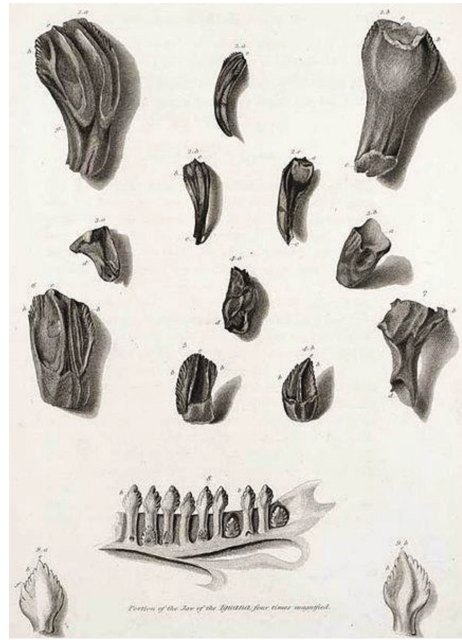

Figure 5.7: An illustration of the Iguanodon teeth fossils discovered by Gideon Mantell (1790-1852) in 1822. These teeth were first rejected as being reptilian by Cuvier and Buckland, but they eventually realized its similarities with the skeletal remains of modern iguanas.

In addition to the *Megalosaurus* another famous discovery took place in the 19th century by a man named Gideon Mantell (1790-1852), who discovered a collection of fossilized teeth and a femur (**Figure 5.7**) in 1822 "that have evidently belonged to the same kind of animal" (Mantell, 1822). Mantell sent his teeth specimens to Cuvier and Buckland, who believe they were "teeth of no particular interest" (Mantell, 1851), and probably originated from kind of fish species, not a reptile. Other specimens Mantell sent to Buckland from the same discovery site (such as metacarpal bones) were dismissed by Buckland as "to belong to a species of Hippopotamus" (Mantell, 1851). However, after a long period of no real academic support, Mantell compared his specimens to that of a modern iguana skeleton, showing off its obvious similarities in respect to the fossilized teeth, an observation that great paleontologists of the time took seriously. Eventually the specimen was named '*Iguanodon*', and even Buckland admitted that the teeth "are so precisely similar, in the principles of their construction, to the teeth of the modern iguana" (Buckland, 1836) that

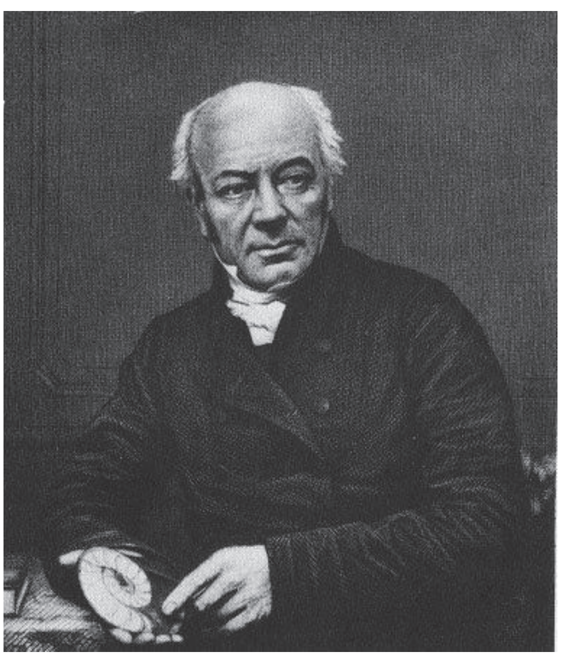

Figure 5.8: William Buckland (1784-1856), pictured here, was the discoverer of Megalosaurus in 1836.

there must be some kind of relation (designed by God). He also respectfully suggests that this Iguanodon would have been a "reptile much more gigantic than the *Megalosaurus*" (Buckland, 1836). Mantell's fossils of the *Iguanodon* and the *Hylaeosaurus* (another dinosaur recognized for its hard, defensive exterior shell) soon became relatively famous in the science community. A report in 1851 explained how Mantell's collection of "gigantic saurians" (Mantell, 1851) in Brighton and the British Museum were visited by thousands (Mantel 1851).

The North American Dinosaur Rush

In the 1870s, there was a large rush for fossil discovery in North America – particularly the fossils of ancient vertebrates in the western United States. This rush was largely due to two reasons. Firstly, Charles Darwin's (1809-1882) *Origin of Species* (1859) made fossils valuable as they were seen to have the potential to answer questions surrounding vertebrate evolution. Secondly, unearthing fossils in the United States became a lot more feasible once the Civil War ended (Wheeler, 1960).

This rush to unearth and analyze fossils discovered in North America lead to a large amount of competition in the field of paleontology (Lanham, 1973). Perhaps the best example of this comes from the two famous feuding paleontologists Edward Drinker Cope (1840-1897) (**Figure 5.10**) and Othniel Charles Marsh (1831-1899) (**Figure 5.11**) (Moore, 2014). The seemingly petty feud between these two figures, and the sheer amount of capital they were willing to invest essentially drove Joseph Leidy (1823-1891) – a naturalist viewed as the founder of paleontology in North America – out of the field (Conn, 2000). However, Leidy is still recognized today for identifying the first dinosaur fossil in the United States, a *Hadrosaur*, who was inspired by Mantell to suggest how the close the jaw bone appeared to the bones of a modern iguana (Leidy, 1864).

Cope had already experienced scientific strife – leading to his famous naming of a Miocene mammal as *Aninchonus cophater*; on this mammal he wrote "I have named it in honour of the number of Cope-haters who surround me" (Moore, 2014). However, his feud with Marsh brought this scientific animosity to new heights. One of the main sources of contention among scientists at the time stemmed from what is termed 'the law of priority". This rule regarding the naming of animals, held that the name first proposed in literature, is the name that should be accepted by the scientific community when referencing that animal in the future (Lanham, 1973). In 1872, the professional feud between Cope and Marsh was brought to light when collecting fossils in the Eocene beds of the Bridger basin of Wyoming (Wheeler, 1960). Due to both scientists performing excavations at the Bridger Basin, multiple instances arose in which there was conflict regarding the initial naming of the unearthed remains of an organism (Lanham, 1973).

Although the feud later extended to mostly cover dinosaur bones (**Figure 5.9**) (Debus,

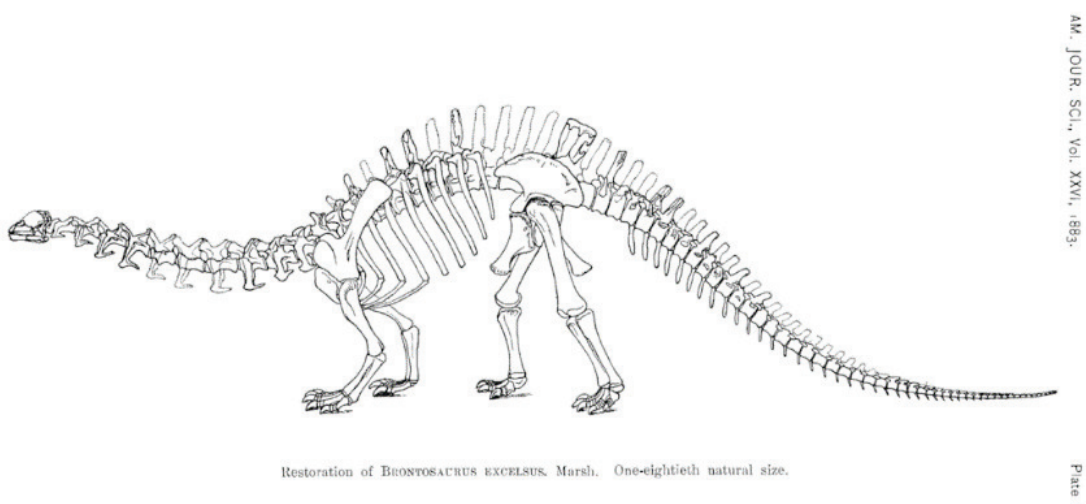

Figure 5.9: *A restoration of a Brontosaurus Excelus by Othniel Marsh in 1883. It was later shown that this dinosaur had the head of a Camarasaurus, and was the same species as earlier named Apatosaurus.*

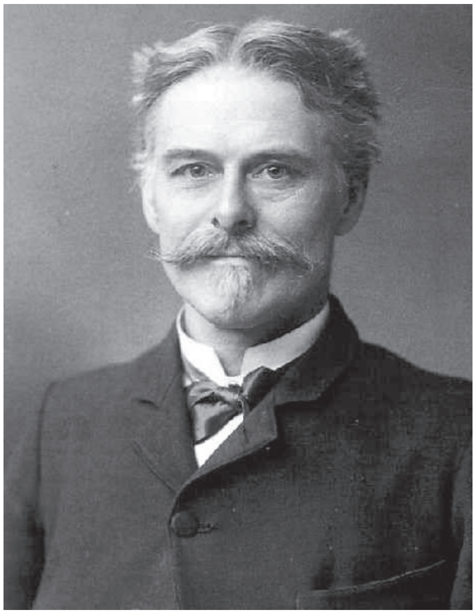

Figure 5.10: *Edward Drinker Cope (1840-1897), a paleontologist who feuded with Othniel Charles Marsh over dinosaur bones in North America.*

2002), it started on August 7th 1872, when both Cope and Marsh published papers regarding the same historical lemur specimen. Due to the fact that the time of publication was uncertain, Cope's term *Tomitherium rostratum* was accepted over Marsh's *Limnotherium affine* due to a more descriptive article that accompanied the coining of the name (Lanham, 1973). Although it was contended that this was the same organism that Marsh had published on in 1871, Cope later stated that it had accompanied "a description in which the characters of species and genus were not distinguished, nor were the grounds of separation from other genera previously described, set forth" (Cope, 1884).

The feud grew tremendously, and turned to dinosaur fossils in 1877; the subsequent rush ensued for dinosaur fossils and discoveries in North America. In this year, a clergyman by the name of Arthur Lakes (1844-1917) discovered a fossil vertebra in the Morrison formation. Lakes collected more dinosaur specimens from the area, and sent some to Cope and some to Marsh. Marsh published a description of the dinosaur; due to payments from Marsh to Lakes, Cope was told not to publish. In July of that year, Marsh published an account of "an enormous Dinosaur, which surpassed in magnitude any land animal hithero discovered" (Marsh, 1877). The dinosaur described by Marsh was originally called *Titanosaurus montanus* to mean 'giant mountain reptile', but was renamed after Cope pointed out the name had been used

a different discovery in India; the published dinosaur is what we now call *Atlantosaurus*. This title of largest land animal ever discovered pushed the competition to new lengths; in subsequent years, Marsh and Cope would uncover numerous dinosaur bones (Lanham, 1973).

The effect of competition on the field lead to great strides in paleontology, but also facilitated some issues. In addition to personal issues in which Cope and Marsh spied on each other, and financially ruined each other, the quality and accuracy of science also came to a test. Actions such as smashing bones upon leaving a site, so the other could not glean any information and publish greatly hinder the breadth of scientific information (Davidson, 1997).

In order to quickly get published work into the general scientific community due to his competition with Cope, Marsh proposed a new species of dinosaur with two notable flaws. When he first proposed the *Brontosaurus excelsus* (the largest dinosaur discovered at that time) in 1879, no image accompanied it. However, given that no head was found for it, Marsh (perhaps mistakenly) attached the head of another sauropod from the area of Como Bluff called a *Camarasaurus*; a reconstruction including this was published in 1883 (Moore,

Figure 5.11: *Othniel Charles Marsh (1831-1899), a renowned paleontologist in North America during the 19th century. He had many professional disputes with Edward Drinker Cope.*

2014). In this publication, he described a specimen where "nearly all the bones […] belonged to a single individual […] nearly or quite fifty feet in length" (Marsh, 1883). Secondly, Marsh had mistakenly counted this new specimen as an entirely new species. In 1903, it was noted by Elmer Riggs that the Brontosaurus appeared to be of the same species as the *Apatosaurus* that Marsh had described in 1877. Thus, the name was to be dropped in favour of *Apatosaurus* (Choi, 2015). However, by the end of their feud in 1900, Marsh and Cope had collectively named 144 dinosaurs; this equated to approximately 40% of the 359 species named at the time. Among these discoveries include famous dinosaurs such as the *Triceratops* (**Figure 5.12**), *Stegosaurus*, and *Camarasaurus* (Moore, 2014). More generally to the field of paleontology as a whole, they also contributed hugely. Before Leidy, Cope and Marsh began their work, only approximately 100 genera and species in North America had been uncovered. This number grew immensely with Leidy contributing 375, Marsh adding 536, and Cope discovering 1282 North American genera and species (Conn, 2000).

In addition to their own astounding achievements, the Cope and Marsh era inspired paleontologists who were key players in their own ages. One of these figures was Robert Bakker (1945-) who first proposed that dinosaurs were warm-blooded creatures in 1971. Bakker worked to overturn the view of the early 1900s that dinosaurs were slow and stupid creatures, and ushered in an age known as the 'Dinosaur Renaissance' (Parsons, 2001). In addition, Bakker added on to the work of Huxley who suggested that dinosaurs were linked to birds, and proposed that a new class Dinosauria should include two reptilian orders and all of the Aves order. This theory would be reinforced throughout the Dinosaur Renaissance when it was found that dinosaur bone was more similar to bird bones than usual reptile bones (Horner, 2009). This age of paleontology which had huge increases in discoveries of new dinosaurs, also saw new fields of exploration such as social behaviour and reproduction; it also opened up a more widespread renewed analysis of prehistoric life in general (Debus, Morales and Debus, 2013). Bakker saw his proposals at this time as an attempt to restore the lively view of dinosaurs indicative of the Cope and Marsh 'Bone Wars' era (Parsons, 2001).

Paleontology as a Growing Science

The progress of dinosaur paleontology has been gradual, slowly adapting to the scientific ideas of the present era, but its investigation has been entirely rewarding. Human society now has a fairly in depth understanding of dinosaur biodiversity, which continues to be discussed and incorporated into all-encompassing theories such as natural selection and ecology. It is truly amazing to think of how far the collective understanding of ancient megafauna has developed from Plot's apparent 'giant human' femur, to Marsh and Cope's questionable taxonomic namings, to the current phylogeny of clade Dinosauria. Only time will tell how precise the estimates of recreating the life of a Dinosaur will become.

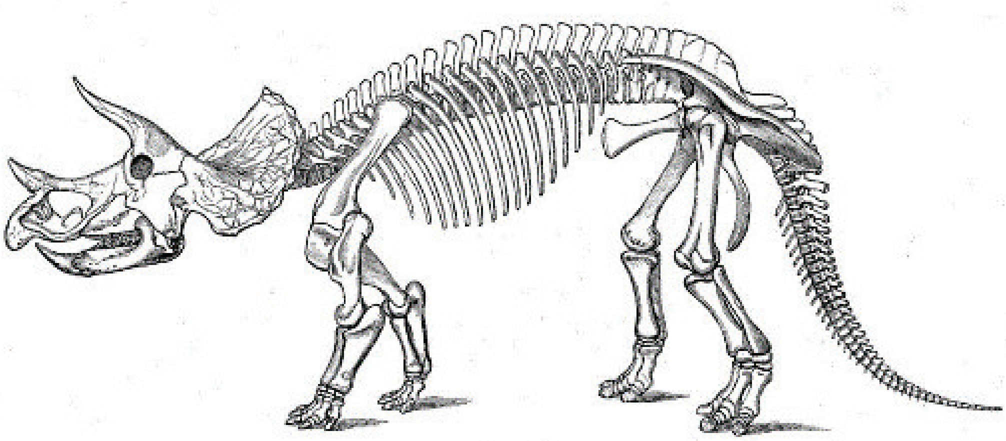

Figure 5.12: *A restoration of a Triceratops by Othniel Marsh in 1896. This was one of the many famous dinosaur discoveries that came as a result of the feud between Cope and Marsh.*

Modern Classifications of Dinosaurs

Clearly, the way we catalogue and classify dinosaurs has changed dramatically over the centuries. During the 18th and 19th century, giant fossilized reptiles were classified under the genus of crocodiles and lizards, until they eventually got their own heading: dinosaurian. Today, dinosaur classification has become a confusing web of characteristic categories, based on misrepresented fossil specimens and a number of still unknown species. However, there is a general rulebook that all paleontologists can follow to some extent.

To begin, dinosaurs can be split into two different divisional clades, *Saurischia* and *Ornithischia* based on the pelvic bone structures of the fossils found. *Saurischia* are known for having 'lizard-hips', in which the dinosaur's pubis bone is extended away from the ischium and *Ornithischia* are recognized for the 'bird-hip', in which the pubis bone is back near the ischium (**Figure 5.13**). Within the *Saurischia* are two main basal taxa groups, the first being the *Theropoda*, known for *Tyrannosaurus* among other giant carnivores like the *Ceratosaurus*, recognized for its nasal horn. The second of these groups is the herbivorous *Sauropods*, which includes the *Diplodocus* family, recognized for being some of the largest terrestrial creatures to ever live on Earth (Benton). Due to a number of inaccurate historical publications, many species have been named falsely or even altered, such the *Brontosaurus*, an ordeal which began in 1879, and still resonates in popular culture today.

The modern way to determine a dinosaur species now requires more rigorous analysis. In particular, paleontologists look for clues such as allometry (the size of an organism in relation the size of one of its parts) as developed by Julian Huxley (1887-1975) in 1932 (Huxley, 1932). Other various means of in-depth morphometric analysis became prominent in the 1980s for the study of living reptiles and were subsequently applied to the study of dinosaur bones which can be digitized for accuracy. This is especially important for distinguishing sexual dimorphism from species separation, since a male and female dinosaur may look near-identical or completely different depending on their reproductive behaviour (Carpenter and Currie, 1992). Statistical methods have also become widely used to make predictions of species types based upon a large number of dinosaur specimens, which has grown considerably since the mid 19th century. In addition, the understanding of evolution has become a huge tool in such analysis, since the evolutionary lineage of dinosaurs can be determined to identify common ancestors. However, perhaps the most important modern technique used for cataloging species of dinosaurs is radiometric dating which allows the exact age of the dinosaur to be determined. Standard C-14 dating, the method generally used to date recent organic samples cannot be used for bones millions of years in age, so instead scientists have to consider the age of the rock the bone was found in (Fastovsky and Weishampel, 2012). Unstable radioactive elements that occur in a lava or volcanic ash associated with the bone can be measured to get a window of time that the organism must have existed in. Similarly, from knowing the time period that other organisms buried within the same sediment layer as the dinosaur lived, paleontologists can make a fair assumption that this new specimen was coeval (Fastovsky and Weishampel, 2012). In summary, the development of revolutionary ideas and technical analysis has transformed the process of dinosaur bone cataloguing.

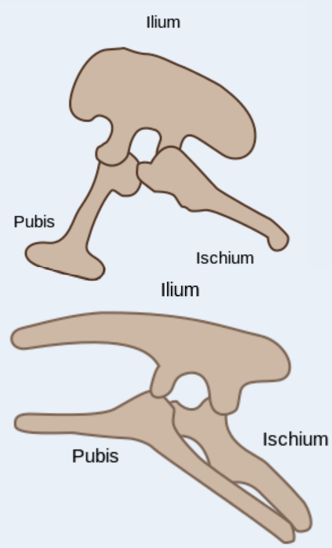

Figure 5.13: *The general bone structure for Saurischia (top) and Ornithischia (bottom) divides the Dinosaur clade into two groups.*

The Extinction of the Dinosaurs

The extinction of the dinosaurs is a profound topic which has intrigued palaeontologists from the 19th century to the present. These theories have ranged wildly throughout the years with consensus shifting from one view to another almost generationally. In order to understand the nature of these scientific, or sometimes unscientific, theories for the extinction of dinosaurs, it is necessary to realise the fundamental ideas that have gone into their formulation.

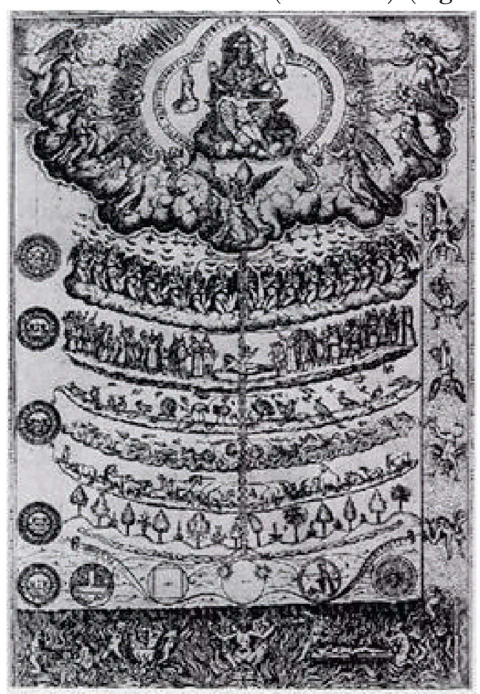

Figure 5.14: *A drawing of the great chain of being taken from Didacus Valades, Rhetorica Christiana. This drawing shows a hierarchy of beings from God to the simplest lifeforms.*

Interestingly enough, extinction as a natural phenomenon was not even considered until the late 18th century. To understand the historical context for this seemingly delayed realisation, as is usually the case, one must begin with the ancient Greek philosophers. Aristotle (384BCE-322BCE), despite his philosophical leanings, also had a very keen interest in biology. He correctly recognized plants as living things while he sought to classify life from its simplest forms to its most complex (Hantz, 1939). Plants, he stated, had nutrition, which is fundamental to all living things. From there, species become more and more complex as they gain varying degrees of motility, sensation, and self-awareness. In this sense, Aristotle believed that all life existed on a spectrum (*scala naturae*). Aristotle's curiosity also extended to how life passed on from generation to generation. He viewed all life as containing an *energeia,* or life-force, which was transmitted from parents to offspring (Preus, 1975). In truth, Aristotle did not give much consideration to the idea of extinction. Most importantly, his thoughts on biology, along with concepts from Platonism, laid the foundation for the doctrine of the great chain of being (Lovejoy, 1936).

The Great Chain of Being

For many Christian philosophers the idea of a natural order of species, ranked from simplest to most complex, fit well with their view of God's institution of a natural order in the Universe (Lovejoy, 1939). The most popularised interpretation of the great chain of being was held by St. Thomas Aquinas (1225-1274) (**Figure 5.14**) (Feser, 2009). In his view, the chain could be extended to divine beings such as cherubim, seraphim, and even God Himself. His interpretation, which was largely transmitted to Renaissance thinkers and beyond, was that humans formed the middle link in the chain between the simplest elements and God. It was this position in the chain, he argued, that gave man the ability to hold dominion over the animals and at the same time be humbled in their knowledge of divine beings.

Aquinas' order of beings, along with his revitalisation of Aristotle's view on the classification of life, was taken up by many 17th and 18th century thinkers including Gottfried Wilhelm Leibniz (1646-1716), Alexander Pope (1688-1744), and Immanuel Kant (1724-1804). They, along with many of their contemporaries, spoke of the great chain of being as an essential fabric of nature (Lovejoy, 1936). This affirmation by many of history's great philosophers was enough to cause many 18th century scientists to presuppose their hypotheses around the validity of the chain. It is for this reason, in part, that extinction as a natural phenomenon was not considered before the late 18th century; for extinction to be true, there would have to be missing links in the chain, and missing links would lead to chaos and disorder in the Universe (Lovejoy, 1936). For this reason, the discovery of unknown species was often written-off as a consequence of the fact that there remained unexplored sections of the globe (Donovan, 1989). Scientists of the time logically proposed that these species could simply be 'hiding' in yet unexplored regions of the Earth.

Development of Extinction Theory

Perspectives began to change towards the end of the 18th century when more and more unknown fossils began to appear. At this point in history, the probability that all these species were hidden in isolated corners of the globe seemed highly unlikely. It was at this time that the French naturalist and zoologist Georges Cuvier (1769-1832) (**Figure 5.15**) correctly stated that some of these species must no longer be living on the planet. Cuvier came to his conclusion by studying the fossilized remains of megafauna such as *Mammuthus primigenius* (woolly mammoth) and *Coelodontata antiquitatis* (woolly rhinoceros) (Rudwick, 1997). He correctly recognized that these fossilized species that had been found in Europe, were in fact different species than their extant African relatives. His findings were in direct opposition with many influential scientists of the time, including the Comte de Buffon (1707-1788), who thought that the fossils were identical to those of African elephants and rhinoceroses (Rudwick, 1997). Buffon argued that these species had simply migrated to warmer climates as Earth's climate cooled. However, the convincing evidence that Cuvier provided, particularly the anatomical differences in the dentition of mammoths and elephants, was enough to convince many that the megafauna found in Europe had in fact gone extinct.

Cuvier believed that the explanation of these *espèces perdus*, or lost species, was found in periodic catastrophes that had occurred throughout Earth's history (Rudwick, 1997; Kolbert, 2014). In his view, global deluges were a sufficient explanation for these extinctions, as the disappearance of species from the stratigraphic layers appeared instantaneous. It is now known that this instantaneous 'disappearance' of species is actually quite deceptive due to the poor resolution of ancient geological events in Earth's history (Fastovsky and Weishampel, 2005). In fact, an extinction which appears instantaneous in the fossil record could actually have occurred over a period of a few million years, which is still nearly instantaneous in geological terms. From Cuvier's perspective, however, it seemed reasonable that these species had gone extinct in a drastic fashion. Subsequent errors, or possibly omissions, in translation of his original French works into English have led many in the English-speaking world to believe that Cuvier's catastrophic view of extinction was a literal explanation of the biblical Flood (Rudwick, 1997). Although Cuvier was most likely a pious man in his private life, the extent to which his work was touted as an affirmation of the Flood was greatly exaggerated by Anglophone translators.

Cuvier's theory of extinction, which would later become known as 'catastrophism', was widely respected and accepted by his contemporaries. In hindsight, individuals have questioned what influence the Church had in promoting Cuvier's ideas, which were at the time well-aligned with Church doctrine (Ardouin, 1970). As an extension to this, Cuvier held a hard stance against *transformisme,* which would later come to be known as evolution. His views on the subject are often cited as a contributing factor to the resistance that Charles Darwin's (1809-1882) theory of descent with modification received from many of his contemporaries (Zittel, 1901). Despite the drawbacks of Cuvier's work, he was nonetheless a great scientist and is viewed by many as the father of modern palaeontology.

***Figure 5.15**: Portrait of French naturalist and zoologist Georges Cuvier.*

Uniformitarianism and Extinction

Around the mid-19th century, the tide began to shift again, this time away from Cuvier's catastrophism and towards a new ideology. In 1830, a British geologist named Charles Lyell (1797-1875) published the first edition of his *Principles of Geology* in ground-breaking fashion (Kolbert, 2014). To this day, his tenet of 'uniformitarianism' remains a central geologic principle. Lyell recognized that the processes that were being observed on the surface of the Earth, if given enough time, were sufficient to explain the enormous geologic diversity that is found on the planet (Zittel, 2001). Unlike his predecessors, Lyell saw no need for biblical deluges or revolutions of catastrophe to explain the fossil record. He noted that the processes that exist on Earth today are the same processes that have been working in the past (Kolbert, 2014). The belief that a series of chance catastrophes had led species to go extinct, seemed to Lyell a gross understatement of the Earth's inherent power.

Lyell's Principle of Uniformitarianism ushered in the complete rejection of the great chain of being as an explanation for the organization of life on Earth; not only could life become extinct, it could also become extinct as a result of natural processes that were apart from divine retribution. Lyell's Principle of Uniformitarianism can be concisely summarised as follows: the present is the key to the past (Kolbert, 2014).

Uniformitarianism was well-received by scientists of the time and was soon regarded as an essential principle to the field of geology. At the same time, many palaeontologists began proposing new theories for the extinction of dinosaurs. It is not surprising to note that many of these early theories were grounded in Lyell's Principle of Uniformitarianism (Donovan, 1989; Kolbert, 2014). For example, many of the early theories were centred on gradual climate change as a leading factor towards the demise of the dinosaurs. The Volcanism Theory, as it would come to be known, was the most popular of these theories and was in fact well-supported by the knowledge of the time. For example, the Deccan traps of India, which constitute a large igneous province, were formed around the same time as the Cretaceous-Tertiary Boundary Extinction (K-T extinction) (Parsons, 2004). By the late 19th century, the effect that volcanism could have on Earth's climate was well-documented. With the eruption of Mt. Krakatoa in 1883 came a short-term cooling of the planet (Simkin and Fiske, 1983). Palaeontologists believed that an increase in volcanism in the Late Cretaceous, as evidenced by the Deccan traps, could have similarly cooled the planet, albeit to a much greater extent.

Early Hypotheses

After scientists agreed upon the existence of a mass extinction at the K-T boundary the real controversy began: what was the cause of the mass of extinction of the dinosaurs? Many theories began to be hypothesized in the 20th century, based upon ideas asserted in the 19th century. The two proposed mechanism of mass extinction were either based on a catastrophic event, occurring over months to years, or a series of gradual events, occurring over several thousand to millions of years (Donovan, 1989). Some early gradual theories of extinction were based on Darwin's (1859) theory that extinctions were caused gradually by interspecific competition, physical factors and regional environmental catastrophes. Orthodox Darwinians followed this theory and blamed the abrupt changes in species on the imperfect fossil record (Donovan, 1989). Followers of Giovanni Battista Brocchi (1772-1826), who proposed each species is created with a specific predetermined life span, believed species extinction was independent of environmental influences. Followers of Brocchi believed that extinction occurred because animals had reached the end of their lifespan (Donovan, 1989). Brocchi's theory was later rejected by modern evolutionary biology. The fossil record around the K-T boundary was not well understood until improvement of stratigraphic interpretation in the 20th century (Officer and Page, 1996). Paleontologists discovered that the mass extinction was operating across the Earth and not geographically confined, which had been the general understanding prior to this discovery.

Throughout the first three quarters of the 20th century a broad range of explanations for the K-T mass extinction were proposed by geologists and paleontologists across the Earth. Explanations were based on different pieces of evidence that weren't always correct, this led to great variety in the proposed theories. Some scientists strongly favored catastrophism and some leaned towards gradualism, others switched between the two sides to gain a better understanding of what occurred. Many of these theories were proposed just to satisfy the seeming unanswerable question: what caused the disappearance of the dinosaurs 65 million years ago? The lack of hard evidence behind either perspective led to some imaginative hypotheses, as one scientist, Otto Heinrich Schindewolf (1896-1971), put it, he wrote his hypothesis as a 'desperate move' to explain what happened at the K-T boundary (Donovan, 1989). The proposed theories follow no real progression as far as catastrophism or gradualism, but tend to shift back and forth based on the popular evidence at the time.

Early 20th Century Theories

The best data for understanding the K-T extinction started to be uncovered in the 1920s as scientists began to use marine invertebrates, such as ammonites, to date the extinction event and gain an understanding of what was occurring on the Earth 65 Ma (Officer and Page, 1996). Marine invertebrates left an abundant record to be studied. Their decline began earlier in the Cretaceous, around 100 Ma, leading early scientists to believe gradual changes led to the K-T extinction (Officer and Page, 1996). In 1924 and 1928 scientists hypothesized that extinction occurred gradually over millions of years through processes such as geographic, climatic and biotic effects (Donovan, 1989). Around the same time catastrophists in 1928 and 1932, rejected this theory, and proposed that the K-T extinction was caused by a global catastrophe caused by a sudden wave of cosmic radiation (Donovan, 1989). The hypothesis that the K-T extinction was caused by a catastrophe rather than gradual events became popularized among prominent paleontologists and geologists. Scientists such as Schindewolf (1954) switched to studying from a catastrophic perspective, finding it odd that many species 'lifespans' all ended at the same time (Donovan, 1989). They hypothesized that the causal factors were a mix of terrestrial and extraterrestrial forces. A popular catastrophic explanation for the K–T extinction was cosmic radiation from a nearby planetary system's supernovae explosions, this was proposed by Schindewolf (1954), and other scientists of the era (Donovon, 1989). A gradual proposal was made in 1960 that intense volcanism in the late Cretaceous increased Earthly radioactivity to lethal levels, thus causing mass extinctions. Another extraterrestrial, catastrophic theory proposed, which ended up being surprisingly accurate that a bolide impact occurred at the K-T boundary (Donovan, 1989). Without enough solid evidence, this theory was not widely accepted until proposed again by the Alvarezes in 1980, which will be discussed in greater detail. In 1978, scientists proposed that a spillover of cold, brackish water from the Arctic entered the ocean, because of shifting plate tectonics, caused the mass extinction of pelagic plankton (Donovan, 1989). The effects of this gradual event on the rest of Earths biota was further explained that, the death of pelagic plankton would lead to a greenhouse Earth because of a dramatic build-up of CO_2 in the atmosphere. This build-up of CO_2 would have led to dramatic climate change, wiping out species that could not adapt to the changing conditions. All these hypotheses did their best to explain the mysterious disappearance of the dinosaurs, but none had enough evidence to become fact, until the Alvarez hypothesis in 1980.

The Alvarez Hypothesis

In the 1970s geologist Walter Alvarez (1940-present) made a discovery that changed the way the K-T boundary was studied, with the examination of a thin layer of clay in Gubbio, Italy (Kolbert, 2014). Alvarez examined an exposed piece of rock in Gubbio, with layers from before, during and after the K-T extinction. Local Italian geologist, Isabella Premoli Silva (c.1940-present) pointed out to Alvarez the abundance of forams, a marine species used to date rocks based on where they settled, in one clay layer, the complete absence of them in the next clay layer directly above, and a decrease of size and abundance of them in the next layer (Kolbert, 2014). This anomaly in the fossil record confused Alvarez who believed in uniformitarianism, and he noticed that the disappearance of the forams occurred at the same time as the extinction of the dinosaurs. This revelation lead Alvarez to wonder, what happened in the half inch of clay between these two fossil records. In order to determine what had led to such a dramatic change in fauna, he consulted his father, Nobel Prize winning physicist, Luis

***Figure 5.16**: An artist's rendition of the asteroid that struck the Earth at the end of the Cretaceous.*

Alvarez (1911-1988) (Kolbert, 2014). In 1977 L. Alvarez came up with the idea to date the clay using the element iridium, what he discovered in 1978 was there were shocking amounts of iridium in the mysterious clay layer. After taking multiple samples from deep-sea limestones in Italy, Denmark and New Zealand he found the iridium levels had spiked to 30, 160 and 20 times that of the background level at the end of the Cretaceous period 65Ma (Alvarez et al., 1980). The pair determined this anomaly was not due to a nearby supernova as previously hypothesized, but instead due to a large asteroid impact, which ejected 60 times its mass into the atmosphere (**Figure 5.16**) (Alvarez et al., 1980). This ejected matter would stay up in the stratosphere for some time and slowly settle across the Earth, causing the layer of clay to have increased levels of iridium (**Figure 5.17**) from the asteroid. It took the Alvarez's a year to come up with this theory after discovering the increased level of iridium, they based the theory of the fact that there is not naturally a high level of iridium at the Earth's surface and large amounts of iridium often are deposited from extraterrestrial sources (Kolbert, 2014). The Alvarezes, Frank Asaro (1927-2014) and Helen V. Michel (1932-present) published their paper 'Extraterrestrial Cause for the Cretaceous-Tertiary Extinction' in June of 1980 (Kolbert, 2014). This paper gained a lot of attention, not only within the scientific community, but also through popular media, making a large impact on society at the time.

***Figure 5.17**: A rock sample showing the iridium rich layer which marks the K-T Boundary.*

Reaction to the Alvarez Hypothesis

The Alvarez hypothesis, as it was dubbed, became widely accepted as the cause for global mass extinctions 65 Ma at the K-T boundary. The theory was both exciting and provided a clear explanation for the sudden disappearance of the dinosaurs and other marine life that went extinct. Despite this strong explanation of what happened to the dinosaurs, in a survey in 1984, many geologists and paleontologists did not agree that an asteroid was what caused the K-T extinctions (Officer and Page, 1996). Paleontologists had studied this event for decades and felt they had come close to a reasonable conclusion based on gradual processes such as climate change and sea level regression.

In the 1980s two important pieces of evidence that backed up the gradual theory of extinction were the Deccan Traps and sea level regression. The Traps would have released large amounts of harmful chemicals into the environment, poisoning species and increasing atmospheric CO_2, while causing an increase in global temperatures and further affecting the dinosaurs (Officer and Page, 1996). The sea level regression was a world-wide event that contributed to the loss of epeiric seas in North America which were important to North American biota. The sea level regression would have changed the environments in North America, with the loss of a major inland sea and affected other species worldwide with a change in landscape (Officer and Page, 1996). These two events combined put a great amount of stress on the biota at the time and are possible factors that could have led to mass extinctions

With these two opposing theories proposed in the 1980s a war between paleontologists and physicists began, with one side supporting gradual theories, and the other supporting the catastrophic impact theory. The debate was based on the fact that paleontologists believed that the dinosaurs were already nearing extinction, rather rapidly, before the asteroid hit the Earth (Parsons, 2004). Furthermore, the paleontologists believed the increase in iridium could have come from the Earth's core, where there is an increased concentration of iridium, which could have been released with increased volcanism (Officer and Page, 1996). Despite the reasoning behind each side, the battle became fierce, colleagues turned on each other, and with no new evidence coming to light, the scientists resorted to name calling. In an interview with The New York Times in 1988 L. Alvarez was quoted as saying "I don't like to say bad things about paleontologists, but they're really not very good scientists. They're more like stamp collectors." (Browne, 1988) Although this feud fueled scientists drive to back up the theory they believed in, it hindered them from taking a step back and looking at the issue from a new perspective that might better explain what had happened.

The Hybrid Theory of Extinction

In recent years, the two main camps of extinction theorists, once bitter rivals, have found much common ground. With the Alvarez Hypothesis enjoying broad acceptance from the 1990s and onward, some ideas from the older gradualist theories have seen a revitalization in recent years. A new theory of dinosaur extinction, which is still in its nascent stages, looks to bridge the gap between the ideological differences between catastrophists and gradualists. The hybrid theory, proposes a combination of catastrophic and gradualist causes to the K-T Boundary Extinction. Proponents of the theory propose that the dinosaurs may have already been on the wane towards the end of the Cretaceous due to slowly cooling climates. Although few can deny the wealth of evidence that supports the Chicxulub Impact at the K-T Boundary (**Figure 5.18**), hybrid theorists believe that this cataclysm may have been merely the final blow to the dinosaurs.

With increasing technology in recent years scientists have been able to date events surrounding the K-T boundary with higher precision. The Alvarez Hypothesis gained further ground in 1991 when a 180km wide impact crater was discovered in the Yucatan Peninsula in Mexico, this crater was named Chicxculub, after a nearby town (Parsons, 2004). Recent dating of tektites found in Haiti places the impact as occurring very precisely at 66,038,000 years ago, around the same time as the extinction of the dinosaurs (Than, 2013). Based on the size of the crater, it is estimated that the the asteroid would have been approximately 10km in diameter and had major effects such as destructive pressure waves, global wildfires, tsunamis, a 'rain' of molten rock and particles in the atmosphere blocking solar radiation (Than, 2013). This kind of impact would have killed off most plant life and animal life, causing many species to decline.

Although scientists agree that an asteroid did hit Earth 66Ma, and that it would have killed off most life on Earth, there is still evidence that the dinosaurs were already starting to go extinct. As previously mentioned the Deccan Traps in India were very active around the K-T boundary and had the potential to cause mass extinctions. The exact dates of the eruptions are not known although they are estimated to have lasted between thousands and millions of years around the time of the K-T boundary (Than, 2013). The next step in unveiling what happened to the dinosaurs lies in dating the volcanic ash in India to determine when and for how long the eruptions occurred. The global effect of these eruptions also needs to be determined. It has been hypothesized that the eruptions could have caused short term cooling from ejecting dust into the air. Alternatively it has been proposed that the eruptions would have caused long term warming of the Earth from the excess of emitted CO2 in the atmosphere (Than, 2013).

***Figure 5.18**: Location of Chixculub Crater in the Yucatan Peninsula, Mexico.*

The K-T boundary continues to present a mystery to scientists despite recent advances in the scientific understanding of what was occurring around 66Ma. The most recent theory, the hybrid theory of dinosaur extinction, best covers the possibility that dinosaurs were already in decline around 66Ma. The asteroid impact may have been the coup de grace in the slow demise of the dinosaurs. Understanding the mechanisms which played into the demise of the dinosaurs remains a valid area of research. History has a tendency to repeat itself and undoubtedly, there will be another mass extinction in Earth's future. An understanding of extinctions of the past may help humans to survive, if not avoid, the mass extinctions of the future.

Conclusion

The history of the Earth is a complex and dynamic story with a myriad of perspectives and viewpoints. Delving into all these perspectives can at times be challenging, but it is only through this that we garner a complete understanding of our collective history. The path to our current understanding of the Earth has been wrought with missteps and blunders. It is from such mistakes that our current body of scientific knowledge is based-on. By knowing what did not work in the past, scientists have been able to develop novel hypotheses and increasingly accurate theories. Furthermore, through the combined curiosity of those who have come before us and new advents in technology, we have come to acquire an unprecedented level of insight.

At the core of the human race lies the curiosity to understand the world surrounding us. Scientists are constantly intrigued as to not only how things form but rather why. Time and time again great philosophers have made huge strides forward, gaining incredible new insights into the workings of the world, only to find the original question to be ever more complex than imagined. These new questions have fueled the fire of curiosity for generations. Answering these arguably infinite questions has been made significantly easier with exponential increases in technology in the past few decades. Technological advances have a prominent place in modern history. From modern applications such as telescopes and radiometric dating, technological advances are crucial agents of change. Their innovation has shaped our understanding of the Earth and will continue to affect future insights. It is often said that in order to comprehend the present, one must fully understand the past. This book has analyzed the evolution of the study of the Earth and the scientific method from a historical lens. It is from this historical viewpoint that we uncover how society, religion and science have harmoniously changed with time and how their constant change impacts modern science. Undoubtedly, our understanding of the planet we call home will continue to grow as curiosity remains.

Figure 0.2: The famous Blue Marble photo taken onboard Apollo 17.

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