HISTORY OF THE EARTH IV

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Foreword

As a child, I was fascinated by the physical world around me. Why was that river there? Why was that mountain there? Where did the wind come from? Why was it blowing? How could that rock be a picture of the history of the earth? Of past life? Past life where? When? How did we get here? How do we know? These questions consumed me. The world around me was endlessly fascinating, sparking intense curiosity and a career in science and geology.

In my adulthood, I have come to appreciate that the answers to the questions I had as a young girl are not static. That is part of the fascination! The answers are based on the evolution of past thinking. Like the geologic record, they are a snapshot. A snapshot of our current culture, technology, agendas and political time, grown from the evolution and stratigraphy of our past thinking and technologies. The truth is only our current thinking. The answers to my questions are changing rapidly!

To realize that our current thoughts and explanations of what is fact is ephemeral, is both frightening and freeing at the same time. To be convinced of the momentary nature of our knowledge of the earth and all life on it, one has only to study the history of the people, the times, and the thinking that has led to the 'facts' of our current understanding. That is what this book is all about.

This book is a wonderful exploration of the history of mankind's thinking about this planet we call home. It touches Earth, space, time, chemistry, religion, evolution, history, physics, philosophy, scientific thought, math, climate, life, and of course, geology. In other words, how we make sense of our world. How we got to our current thinking.

Please explore it. You will better understand our current reality. You will realize that it will change.

Susan Cunningham
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Introduction

The fundamental distinction between science and belief is the need for evidence in order for something to be considered the truth. With new evidence generated and old evidence refuted as science and technology progresses, it is clear that what we accept as evidence is constantly shifting. As evidence continues to change over time, what we know and accept to be true also changes. In a sense, scientific truth is inherently plastic, allowing for concepts to change and challenging whether anything is ever fully "proven". However paradigm shifts seldom come smoothly, and new perspectives have been both fuelled and rejected in the passionate debates of great minds in past centuries.

Since the birth of civilization, humans have been constantly fascinated with learning about the world they live in and the reasons why things happen. Innately curious, we are never quite satisfied with the amount of information we have come to possess, and continue to question and challenge what is generally accepted today. This persistent cycle of discovery and investigation has spun a perpetually evolving web of scientific theories, and is well illustrated by the history and evolution of scientific thought regarding the processes that have happened on Earth.

As scientists continue to discover remnants of past environments that are indicative of processes that differ from what has been originally hypothesized, our interpretation of the history of the Earth is one that is incessantly edited and rewritten. Gaining new knowledge allows us to adapt our understanding, and can be applied in various ways. From locating valuable mineral deposits, understanding the impacts groundwater flow, and predicting climate change, this information serves to show that understanding the past is vital for our future. This book endeavours to describe the progression of ideas and scientific theories pertaining to the Earth sciences from the Precambrian to the present, and its implications for the modern world.

The Earth, its Moon, and the Sun encompass a small part of outer space as we know it today

"In questions of science, the authority of a thousand is not worth the humble reasoning of a single individual."

GALILEO GALILEI

Chapter 1: Origins of the Earth

The Earth is, in many respects, a rather mysterious sphere. Humans have always been amazed by our changing surroundings and desired to comprehend their origin. It is this desire, combined with innate human curiosity that gave birth to the science we know today as geology.

Within any science, theories constantly evolve as new evidence is revealed and interpreted. Geology is no different; at any given point in human history, there have been numerous competing explanations for the many observable geologic phenomena. These differences have given rise to many long lasting conflicts. For example, divergent philosophies concerning how and when the Earth came to be generated a rift between scientific and religious communities which has lasted for centuries. Some of these conflicts have been resolved, but many geologic debates persist to this day.

This chapter outlines several milestones in the succession of ideas that led to contemporary theories on the origin of the Earth. It sheds light on many ideas we take for granted, from the rock cycle to the structure of the solar system, and from the age of our planet to the material from which it is made. While it is inevitable that many of today's theories may one day be overturned, presented alongside each historical topic is a snapshot of the topic in its current state, as a demonstration of how these ideas are still progressing. Only by looking at present-day theories through the lens of their predecessors do we develop a true appreciation for how far these theories have come and insight into where the future may take them.

Rock Creation: From Genesis to Geology

Explaining Earth's geology is a key facet in understanding its origin. Because of this, debates between schools of thought in the area of Earth geology have been animated and drawn out over centuries. The most well-known and pertinent of these debates still resound into the 21st century, even if those who started the arguments have long since passed away. One such scientific squabble was that between the neptunists and plutonists in the 18th century, with the two groups superseding both prevalent religious theology and current ideas focussed on catastrophism. Although neither the neptunists nor plutonists achieved a complete understanding of the entire nature of geology, both contributed to our modern grasp of the subject. Much of what we now know pertaining to rock formation has deep roots in each theory, which acted at the very least as stepping stones toward a more holistic understanding of the Earth. Examining these past debates lends insight into the evolution of thought and development of contemporary geology.

Figure 1.2. An early 15th century artist's rendition of God.

Figure 1.3. An artist's rendition of the biblical flood as an example of global submergence events.

In the early 18th century, the stage was set by creationism, the prevailing global opinion on the origin of our planet. This theory on the origin of the Earth is the oldest and longest-standing idea that still retains widespread support today. Although creationism deviates in part from the progression of geological science present in catastrophism, neptunism, and plutonism, it is still a theory that has a key place in the progression of thought pertaining to geology. Creationism is the belief that the Earth was created by a supernatural entity. Based principally on the creation narrative in the biblical book of Genesis, the creationist account involves an intelligent being bringing the Earth into existence in seven days (Numbers and Lindberg, 1986). Creationism is not mutually exclusive to scientific findings for all believers, as some creationists choose to accept facets of other theories while maintaining that "in the beginning" it was a God (an interpretation of which is illustrated in Figure 1.2) or another deity who sparked creation.

Emerging from this religious beginning, catastrophism, originally a hybrid of biblical history and science, explains the origins of the Earth as the result of a series of sudden, relatively short, violent geological events; the cumulative effects of these account for the current geology of Earth. Such catastrophes were initially thought to be events such as the biblical flood (as depicted in Figure 1.3); however, the predominate theory evolved to encompass other events such as volcanic activity, meteorites, and extreme sea level changes. This idea of the Earth forming in a succession of events was ultimately contradicted by the dominant paradigm of modern geology, uniformitarianism (Clarence, 1877). As a result, catastrophism dissipated with the cascade of geological science that characterizes the 18th century.

Following catastrophism, two main geologic theories took flight, the first of which was neptunism. Neptunism is an outgrowth of catastrophism, and puts forth the notion that Earth's geology formed underwater from suspended sediment material and chemical precipitates, which were deposited to form massive sheets of sedimentary rock. As the water retreated, these masses became the continents, onto which further layers were deposited by mechanism of global floods (Rappaport, 2011). The theory aptly derives its name from Neptune, the Greek God of the sea.

The second theory was named Plutonism, and takes an opposing stance, suggesting that the Earth is comprised of rocks that formed by heat and fire. Named from the classical god of the underworld, Pluto, this theory identifies volcanic activity as the driving force behind both the formation of rock as well as the geologic processes involved in the rock cycle (Rappaport, 2011).

The Neptunists

Neptunism developed in the mid 18th century as one of the first generally accepted theories that diverged from the Genesis creation narrative and catastrophism, which were previously robust geological explanations of the Earth's rocky façade. The first step towards neptunism was taken by the French naturalist, cosmologist, and mathematician Georges-Louis Leclerc (1707-1788), who proposed that the Earth was likely 75 000 years old, or even considerably older, which boldly contested the church's longstanding claim that the Earth was only a few thousand years old. Breaching this hurdle prepared the scientific community for another radical idea which was presented by German geologist Abraham Gottlob Werner (1749-1817), seen below in Figure 1.4.

Figure 1.4. A portrait of the father of German geology, Abraham Gottlob Werner.

Werner, known today as "the father of German geology," developed an extensive understanding of sedimentary rocks and structures as a mine inspector and professor of mining and mineralogy at the Mining Academy of Freiberg. During his career, an abundance of fossil evidence was unearthed, which led Werner to start to approximate the age of rocks. He outlined this in his publication *Short Classification and Description of rocks of 1787*. The more Werner observed, the more he was driven to conclude that, based on the nature of sedimentary rocks and the prevalence of marine fossils, the globe must have existed completely underwater for an extensive duration of time (Master, 2009). This idea was the backbone of neptunism, which he expanded to explain that water contained all rock material that settled out of suspension and formed the successive layers of the Earth, from the core to the crust (based on structures similar to those in Figure 1.5). The oldest and hardest rocks, he

Figure 1.5. Horizontally laminated sedimentary rock formations, the likes of which led neptunists to believe that the layering of rock continues deep into the earth.

noted, were predominantly granite, and the younger rocks were softer and fossil rich. Werner acknowledged that volcanoes had a minor effect on the geology; however, he concluded that volcanoes were simply anomalies as opposed to key contributors (Master, 2009). Ultimately, Werner's new idea, which he coined "neptunism," suggested that the Earth formed from a mass of water, and that mineral materials were chemical precipitates. To some, it seemed as though the idea of rock formation underwater had obvious overlaps with catastrophism, which suggested that the "global ocean" could have been Noah's Biblical flood. However, Werner did not acknowledge these parallels (Master, 2009). In addition, neptunists differentiated themselves from the plutonists, chiefly in their view of the basaltic rock which forms the majority of ocean basins. While plutonists held that basalt was a volcanic rock, neptunists maintained that the presence of fossils in the oceanic basalts indicated that basalt was a sedimentary rock.

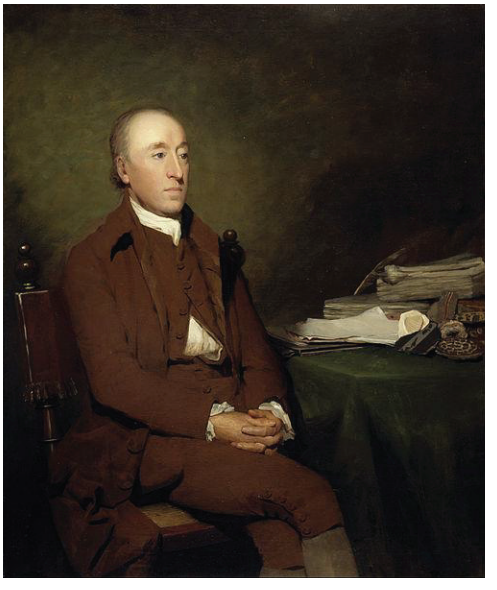


Figure 1.6. A portrait of the father of geology, James Hutton.

The theory of neptunism acquired a great deal of support from notable scientists such as Robert Jameson (1774-1854), who became the primary proponent of neptunism in the United Kingdom. Outside of the scientific community, authors and playwrights also favoured the neptunist perspective on the formation of the Earth, as evidenced by the fourth act of Johann Wolfgang von Goethe's famous 1806 play *Faust*. This act contains a dialogue between a neptunist and a plutonist, in which the plutonist is portrayed as the devil. Atypically, today we consider neptunism to be an obsolete theory in terms of the origins of the Earth; however, processes of sedimentary rock formation which are readily observed today were first described by neptunism.

The Plutonists

Plutonism originated in 1750 as the primary postulate of the Italian abbot, geologist and naturalist Anton Lazzaro Moro (1687-1764). Moro dedicated his life to the study of rocks, and in doing so was the first to discriminate sedimentary rock from igneous (volcanic) rock, by studying the rock formations on volcanic islands. As a result, his analysis led him to discover fossilized crustaceans preserved in mountains high above sea level, which suggested that these rocks were once submerged underwater (Master, 2009). His observations indicated that even rocks from submarine environments were produced by the action of volcanoes or extreme heat. With his data amassed and analyzed, Moro channeled the entirety of his findings to conclude that the world's geology was derived from volcanism, the principle which forms the foundation of plutonism.

Although Moro is considered the father of plutonism, it was not until several years later, when "the father of geology" supported Moro's theory, that the idea of plutonism took flight. The support of James Hutton (1726-1797), a Scottish geologist, physician, and naturalist known as "the father of geology" (depicted above in Figure 1.6), marked a turning point in the universal validity of plutonism, which up until the late 18th century had sparse support in academia due to its counter-biblical nature. Hutton was initially more inclined towards neptunism in his early career, stating that "the solid parts of the present land appear in general, to have been composed of the productions of the sea, and of other materials similar to those now found upon the shores" (Hutton, 1785). Despite his early proclivity toward a more neptunist view of geology Hutton abandoned this premise upon observing rock formations in the Cairngorm Mountains in the Scottish Highlands in 1785. There, Hutton discovered granites penetrating metamorphic schists in a fashion that was only achievable had the granite been molten at the time of penetration. He realized that this contradicted the neptunist theory that the granite had precipitated out of the ocean, and concluded, rather, that it had cooled from magma. Similar findings where volcanic rock penetrated sedimentary structures, as in Figure 1.7, further substantiated the principles of plutonism, and therefore James Hutton adopted its doctrines in publishing his renowned work *The Theory of the Earth*, in which plutonism appeared beside still-standing notions such as uniformitarianism and Deep Time (Master, 2009).

It is arguable that, at this point, plutonism became the dominant theory over neptunism, but there was still much evidence withstanding before the theory of Plutonism could become universally accepted. This necessary evidence was delivered several years later by Hutton's friend and colleague, John Playfair (1748-1819). Playfair directly argued against the neptunist postulate that the basalt which lined the ocean basins was sedimentary in nature. Instead, he declared that the absence of fossils in the rock, along with its massive, as opposed to bedded, structure, indicated the rock was cooled magma from ancient volcanic activity. Neptunism was further discredited on the basis that the plutonists called to the academic stand the neptunist view that rocks had been rapidly formed by processes which no longer operate. This stance directly opposed Hutton's uniformitarianism, "the present is the key to the past" (Simpson, Pittendrigh, & Tiffany, 1957), which had gained widespread support. Thus, the neptunist theory was broadly abandoned, paving the way for plutonism to become the predominant theory of the formation of rock moving through the 19th century (Master, 2009). This crescendo of credibility in the 1800s dissipated as other geologists developed more true-to-life theories, and so, although plutonism was sufficient to outcompete neptunism, it is not what we consider realistic today.

Figure 1.7. Rock formations observed by Hutton at the Salisbury Crags in 1785, known today as "Hutton's Section." The volcanic rock penetrating sedimentary structures supported his conclusions pertaining to plutonism.

Geology: The Aftermath

Two centuries later, what has been gained from this geologic argument? For, although neptunism bears little scientific merit today and plutonism has drastically evolved, both are milestones in the ongoing debate on the origin of the Earth. Science aside, the thought progressions produced by debates of this class are invaluable propellants towards deciphering the blueprints of planet Earth.

Ultimately, debates fuel research and expedition, which progressively reveal the nature of our planet. It appears unlikely that a conclusive and all-encompassing explanation of the formation and processes of the Earth will ever be encompassed by any one theory. Thus, the contrast of conflicting theories is perhaps the key to the accelerated pursuit of understanding in this field.

Mars: A Neptunist Planet?

To a scientist studying Earth processes, there is always the inherent flaw of sample size. Fortunately, within the past few decades, observations of other planets in the solar system have allowed us to apply our theories to more than just Earth, and test their veracity experimentally. The most studied of these planets is Mars. By using our terrestrial knowledge, we can investigate the rock cycle on Mars, and double the sample size in our current investigation of how rocks form.

The Martian crust is older than the terrestrial crust; the oldest rocks on Mars predate 4 Bya. There is no plate tectonics or crust recycling on Mars, and so its stratigraphic record is both older and better preserved than Earth's, making Mars an excellent model to study rock formation (McLennan, 2010; Grotzinger, et al., 2011).

Martian History

Mars formed around the same time as Earth, ~4.5 Bya. There is abundant evidence that Mars, even though it probably cannot support water now, had a wet ancient climate. Over time, Mars evolved through three eras, from a wet, neutral Noachian era (4.5-3.7 Bya) to a wet, acidic Hesperian era (3.7-3.2 Bya) to its current, dry Amazonian era (3.2-0.0 Bya) (Grotzinger, et al., 2011).

Early Mars is believed to have had an active hydrological cycle; the Noachian era saw an abundance of rainwater and groundwater. The planet eventually began to lose water due to impact events and abrasion from the solar wind, beginning to dry towards the late Noachian era. This is believed to have formed a number of transient seas and playa lakes across the planet, whose water levels fluctuated throughout the early Hesperian era (Andrews-Hanna and Lewis, 2011).

In addition to its early hydrological cycle, Mars also had a volcanic past, which diminished as its crust became more rigid. Mars' lithosphere is suggested to be an order of magnitude thicker than that of Earth, which accounts for its highly reduced activity. Although the planet was deemed inactive by three spacecraft in the 1960s, the Mariner 9 space probe detected active volcanism in the Tharsis uplift near the equator of Mars but a few years later (Mutch, et al., 1976).

Sedimentary Rocks on Mars

The presence of sedimentary rocks on Mars has been known for the past 20 years. Two decades have been sufficient to establish not only that Mars has had a dynamic sedimentary rock cycle throughout most of its geologic history, but also that sedimentary rocks on Mars have undergone transport, deposition, and diagenesis mechanisms akin to those on Earth. Martian sediments are composed of both particulate debris and chemical precipitates, but, unlike terrestrial sediments, are basaltic rather than felsic (McLennan and Grotzinger, 2008).

Most of the sedimentary deposits that have been identified on Mars are in its southern hemisphere and near its equator, including deposits at Meridiani Planum and in the Valles Marineris. These tend to be found in craters, many of which do not have evidence of fluvial infiltration, implying a groundwater source of sediment (Andrews-Hanna, et al., 2009).

Sedimentation Patterns

There is abundant evidence that the high precipitation rates in the Noachian era led to the formation of phyllosilicates (clay minerals produced by chemical weathering) across Mars (Fernández-Remolar, et al., 2011). Over time, Martian sedimentology transitioned from phyllosilicate alteration to sulfate deposition as the planet's climate shifted near the start of the Hesperian era (Andrews-Hanna & Lewis, 2011). This is supported by the order of sediments in places such as the Gale Crater (Grotzinger, et al., 2011). Rocks deposited in this late Noachian/early Hesperian era have been shown to be playa evaporites. These were formed when Martian groundwater actively upwelled as the planet dried, evaporating to leave behind sulfate salts. This playa-like environment was commonly found as water collected in craters, which filled with evaporites as the water evaporated. The evaporites cemented into sediments, sometimes undergoing diagenesis, and this process repeated for as long as Mars remained wet (Andrews-Hanna & Lewis, 2011).

Arabia Terra and Meridiani Planum

The rocks in the Arabia Terra region of Mars were deposited over a span of tens of millions of years, and show highly rhythmic bedding patterns. Although the region has been linked to possible volcanic activity, the periodic stratification is too regular to have been formed by such a stochastic process. The best explanation of current data is that the rocks were formed from periodic bedding in a hydrological, as opposed to volcanic, cycle (Lewis, et al., 2008).

The Meridiani Planum region enclosed within Arabia Terra has some of the best preserved evidence of playa evaporites, and has been explored by the Mars rover *Opportunity* since 2004. Data from the rover, as well as Mars orbiters, have shown a high concentration of sedimentary rocks at Meridiani Planum, whose surface was shaped by liquid water both at and below the surface, as in Figure 1.8. There, groundwater is believed to have upwelled in the early Hesperian era to form playa lakes in various craters upon reaching Mars' surface, before evaporating. This left evaporites which, coming in contact with aeolian material moving across the surface, formed erosion-resistant deposits. These ranged from pure evaporitic salts to weakly cemented sand and dust, and are responsible for the sedimentary layers observable today (Andrews-Hanna, et al., 2009).

Martian Neptunism

Unlike on Earth, the most important processes of rock formation on Mars are hydrological, rather than volcanic. Mars' thick lithosphere and basaltic rocks are clear indicators of this fact, and Martian sedimentary evidence supports it. Instead of igneous intrusions, the rocks on Mars were formed from sediments in ancient seas. With but a little imagination, it is easy to argue that plutonism may have triumphed on Earth, but on Mars, a form of neptunism prevails.

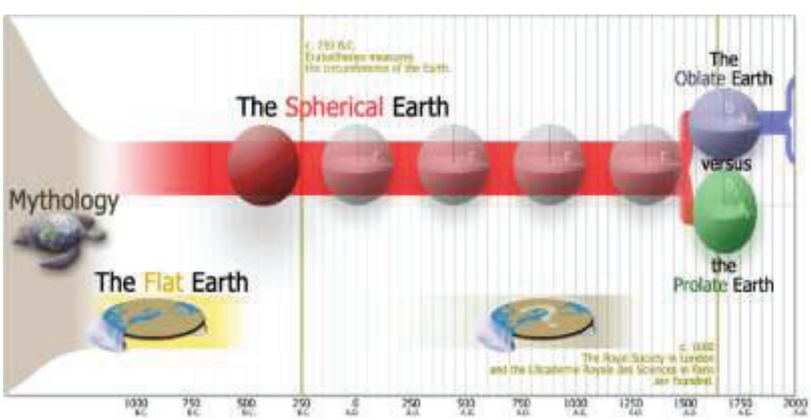
Figure 1.8. Photograph of the Burns Cliff inside of Endurance Crater in Meridiani Planum, taken by the Opportunity *rover. The sedimentary structure of the cliff is clearly visible.*

The Shape of The Earth: Changing Theories Through Time

The shape of the Earth can be linked to many natural phenomena. Different seasonality at different latitudes, Plate tectonic activity, oceanic currents, and the length of a day can all be related to the shape and size of the Earth. Today, the Earth's shape is known to be an oblate ellipsoid with an equatorial radius of 6 378 136.6 metres and an inverse flattening of 298.25642 metres (IERS, 2003). The modern understanding is that the Earth is shaped this way due to billions of years of gravitational and rotational forces acting upon it. Originating as a cloud of dust travelling around the Sun, gravitational forces acted to clump these particles together (Frankel, 1996). These clumps naturally became spherical in shape due to a uniform gravitational force acting between the core of the planet and the surface in every direction.

The Earth's rotation on its polar axis and the resultant centrifugal force is responsible for the non-spherical shape of the Earth. Over time, Earth's equatorial region was stretched, subsequently flattening its poles. This process created the modern ellipsoidal shape of the Earth. These intricate details of the Earth's shape, and the reasons behind its formation were not always known however. In fact, it was only in the last few centuries that the mystery surrounding the Earth's shape was removed, and its general shape was agreed upon. The journey to this understanding can be traced back as an accumulation of theories, debates, and journeys over thousands of years involving the greatest civilizations and some of the most curious minds in scientific history. From the earliest Mesopotamian settlers to modern day scholars, many cultures have speculated about the shape of the Earth ranging from flat planes to three-dimensional shapes. Each of these was based on the common or growing societal values of the specific civilization. Three of the most prominent theories produced were those of a flat Earth, a spherical Earth and finally an ellipsoidal Earth (see Figure 1.9).

Figure 1.9. A timeline outlining the general evolution of the understanding of the shape of the Earth. Spanning from 1000 BCE – 2000 CE it shows the three main theories of the flat, spherical, and ellipsoidal Earth, and how they overlapped with each other throughout history.



The Flat Earth Theory

The earliest theory of the Earth's shape can be traced back to 4500 - 500 BCE. At this time, civilizations such as the Sumerians and Babylonians believed the Earth was flat. They had a triple-decker model of the world where the Earth was sandwiched between the sky and the underworld (Garwood, 2007). The Egyptians had a similar triple-decker arrangement where the sky was resting on four pillars found at the edges of the flat Earth (Garwood, 2007). The foundation of this theory is believed to stem from biblical references, which hinted at a 'flat Earth'. In this hypothesis, mountain ranges would have probably been the 'four pillars at the edges of the Earth' that the sky was supported by (Garwood, 2007). The flat Earth theory was also believed to be prevalent in Ancient Greece. Thales (625 - 547 BCE) argued the Earth was a circular disk floating in space (Garwood 2007). Similar theories would be given by Anaximander (611 - 545 BCE), who proposed the Earth to be a layer of a cylinder of mass in space (Garwood, 2007). In fact, it would be a few more centuries before any suggestions of a spherical Earth were made by the Greeks.

Speculations of a Spherical Earth

Being the first to mention the new idea of a spherical Earth, Greek astronomers and scholars did not have time to accumulate much evidence to support their view. In fact, there is almost no evidence of how this conclusion was ever reached (Evans, 1998). The little evidence available suggests that as frequent travellers around the Mediterranean, Greeks would have experienced the change in the location of circumpolar stars (see Figure 1.10). This idea is well accepted as the change is quite extreme around the Mediterranean Sea (Neugebauer, 1975), and the spherical shape of the Earth is the only reason to explain it. Historians have also found it difficult to point out the first Greek to label the Earth as round. A few likely philosophers are Hesiod (730-650 BCE), Parmenides (515-440 BCE) and Pythagoras (575-495 BCE). Although not much is certain, historians do know that by the end of the 5th century BCE, no well-studied Greek astronomer believed the Earth was flat. The consistency in their thinking was something the Pythagorean school of music, astronomy and mathematics had a lot to do with. Founded in the 5th century, Pythagoras's school taught about the spherical shape of the Earth, and had an especially profound effect on Plato who lived from 427-347 BCE. Plato based many of his theories on his Pythagorean education and started his own school in Athens where he passed on the teachings of a spherical Earth to his students (Cornford, 2004). Like Greek astronomers before him, he offered little evidence, let alone mathematical proof, for his belief. He instead stated, "My conviction is that the earth is a round body in the centre of the heavens, and therefore has no need of air or of any similar force to be a support" (Plato, 360 BCE).

Figure 1.10. Stars appear to rotate around a point as the Earth rotates on its polar axis. Circumpolar stars are stars that never dip below the horizon. Depending on one's location in relation to the pole, different stars fit these criteria. The closer one is to either of the poles, the larger the number of circumpolar stars is. The Ancient Greeks who relied heavily on the stars for navigational purposes noticed this phenomenon. This is seen as the basis for the Ancient Greek concept of a spherical Earth.

Aristotle, who lived from 384-322 BCE, was Plato's most well known student. He was also the first Greek to provide observable and physical evidence that pointed to the spherical shape of the Earth. Aristotle noticed stars that could be seen from Egypt but not from more northerly cities (Aristotle, 350 BCE). Furthermore, he spoke to the fact that if everything is being drawn towards the centre of the Earth, from every direction, then it would only be natural for a sphere to form, presenting no irregularities in the force drawing the "segments of the Earth" towards its centre (Aristotle, 350 BCE). As a final piece of evidence, he noted that the shadow of the Earth that appears on the moon during a lunar eclipse is round (See Figure 1.11). Aristotle wrote all of this in his work *Meteorology* which describes his views on the Earth sciences. In it he describes his understanding that the earth is a sphere surrounded by water, which is surrounded by a layer of air and finally the air surrounded with a layer of fire (Aristotle, 350 BCE).

By the 5th Century BCE, Greek astronomers and mathematicians had assumed the Earth was a sphere and began to estimate its circumference. The first to do so was Eratosthenes in 240 BC (Dutka, 1993). He had heard that at the time of the summer solstice, the sun produced no shadow in Syene, while producing one in Alexandria. Eratosthenes used his knowledge of geometry to use the shadow created by a specific tower in Alexandria, along with the known distance

Figure 1.11 The round shadow of the Earth is clearly visible on the surface of the moon during a lunar eclipse. Aristotle used this as one of his main pieces of evidence in believing the earth was spherical in the 4th century BCE.

from Syene to Alexandria in order to estimate the circumference. Eratosthenes completed his calculation under the assumption that the sun was far enough away from the Earth, that the rays were hitting the earth completely parallel to each other (Dutka, 1993). Eratosthenes's estimation of circumference was 250 000 stades. Although the exact value of a 'stadion' is unknown, it is roughly a tenth of a modern mile (Engels, 1995). This means his estimation was equivalent to 40 233.6 km, which is astoundingly close to the Earth's actual circumference of 40 075 km (Van Helden, 1985). Posidonius, who lived from 135 - 51 BCE, was another Greek astronomer to estimate the circumference of the Earth. Posidonius referenced the maximum altitude of the star Canopus while being observed at Rhodes compared to Alexandria (Thurston, 1993). He found that at Rhodes it touched the horizon, whereas from Alexandria, Canopus could be observed seven and a half degrees above it. Using this difference and the distance from Rhodes to Alexandria, Posidonius calculated the circumference of the Earth to be 240 000 stades. Although Posidonius's calculation was in fact less accurate than Eratosthenes', Perhaps due to its more recent production it was favoured and included in Ptolemy's (c. 90-c. 168 CE) famous *Geographia* (Ptolemy, c. 130 CE).

Adopting many of the beliefs, philosophies, and scientific theories of the Greeks, Roman scholars believed the Earth was spherical, and continued to build up convincing evidence to support this idea (Kruger, 1492). Strabo was a geographer who lived from 64 BCE - 24 CE and pointed out the phenomena experienced at sea as proof for a spherical Earth. Being able to only see the tops of mountains or highly hung lights, but not the bottoms of mountains or low-hung lights were two of these features. He also stated that Mediterranean seafarers probably held this knowledge from as early as the time of Homer, as he pointed out the Earth's shape is mentioned in the Odyssey (Thurston, 1993). This intrigues historians as if Homer truly believed the Earth wasn't flat, then that would push the Greek understanding of a spherical Earth back to the 7th or 8th century BCE.

The Greek scientific, astronomical, and mathematical findings also had a large influence on the beliefs of Indian scholars. Especially during the first few centuries CE, Greek philosophies strongly dictated what was being written in Indian literature. It was during this period that the Greek idea of a spherical earth replaced the accepted theories of a disk shaped Earth (Pingree, 1978). In the 5th century CE, the famous Indian astronomer Aryabhata (476 - 550 CE) estimated the circumference of the earth at 39 968 km, which is just shy of the actual circumference of 40 075 km, yet not as accurate as the estimation of Eratosthenes (Pingree, 1978). This is testament to both the astounding advancement of Greek civilization, and the amazing accuracy of Eratosthenes' estimation, which was completed almost 750 years prior.

Christian view of sphericity

The understanding of a spherical Earth was passed on from the Roman Empire into the times of Neoplatonism and Early Christianity. These scholars studied Plato's *Timaeus*, which was one of a few ancient Greek works seen as especially relevant by scholars of the day (McClusky, 1998). Throughout Christian history, the majority of scholars believed the Earth was spherical. However there were a few Christian scholars who believed that the current scientific beliefs should be realigned in order to fit within a biblical context. The flat Earth concept represented in the Old Testament therefore influenced a handful of Christians such as Chrysostom (347-407 CE), Athanasius (296-373 CE), and Isidore of Seville (560-636 CE) to take a step back 1 000 years and insist the Earth was a flat disk (Isidore, 629).

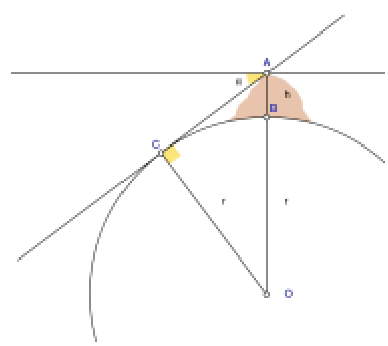


Figure 1.12. A diagram of the trigonometry used by Biruni in the 10th century to estimate the circumference and radius of the Earth from one location. Biruni used the angle of created from the line created from his line of sight and the top of a mountain and the horizontal. His estimation of the Earth's radius of 6 339.6 km is within 1% of the modern measurement of the radius.

Due to the large amount of evidence supporting the contrary however, the revival of the flat Earth theory within the Christian world did not last long. By the 8th century CE, no cosmographer would have questioned the sphericity of the Earth (McClusky, 2000). Bede the Venerable was one of these cosmographers. He lived from 672-735 CE and was the author of the very influential work, *The Reckoning of Time*, in which he described the Earth as being a perfect sphere in the middle of the universe (Bede, 725). This work was copied many times as it was made mandatory for all priests to study it. This indicates the large number of priests at this time who would have understood the Earth to be perfectly spherical, while also believing it to be a perfectly equal shape due to its divine creation.

Eastern Astronomy

Between the 7th and 12th century CE, little scientific progress was made within the Christian world. This is in stark contrast to the flourishing of Islamic astronomy at the time. Known as the Islamic Golden Age, Islamic scholars expanded on the works of Aristotle and Ptolemy's spherical Earth theories. Muslim mathematicians improved spherical trigonometry, which provided precise travelling distances between any point on the Earth to their central city of Mecca (King, 1993). This allowed them to always know the direction in which they should pray. Abu Rayhan Biruni who lived from 973-1048 CE was a mathematician who estimated the radius of the Earth from one city (Selin, 1997). To do this he measured the angle from a location on the ground to the tip of a mountain in the distance (Goodman, 1992; see Figure 1.12). Using trigonometry, Biruni determined the radius of the Earth to be 6 339.9 km, which is less than 17 km different from modern calculations. This was a measurement that was not come upon by the Christian world until the 16th century CE (Goodman, 1992).

During this entire evolution of the understanding of a spherical Earth in the West, astronomy in ancient China was making little progress. Throughout the middle ages, it was still strongly believed that the Earth was a flat rectangle with four distinct corners (Cullen, 1980). It was not until the 17th century when Western astronomers journeyed to Ming China, and successfully argued for the spherical shape of the Earth, that the Chinese accepted the fact to be true (Cullen, 1980).

The European Debate

The final revolution in the understanding of the shape of the Earth did not occur until the 18th century. While measuring the force of gravity at different points on the Earth, scientists happened to come across discrepancies in the force of gravity. These irregularities lead to the realization that the Earth could not be exactly spherical (Hoare, 2005). This triggered a race to determine in what way the Earth's shape varied from a sphere. The two major organizations which proposed various theories over the 17th and 18th century were the Royal Society of London which was dominated by Sir Issac Newton's published work in the first edition of *Principia* of an oblate spheroid (see Figure 1.13 left; Hoare, 2005). Newton assumed the Earth was a fluid body and thought it would originally be spherical if not for the rotation (Greenburg, 1995). With the rotation, he believed the centrifugal force was the cause for the differing gravitational forces between the equator and Paris and this would mean a flattening of the Earth's poles was necessary producing an oblate spheroid shape (Greenburg, 1995).

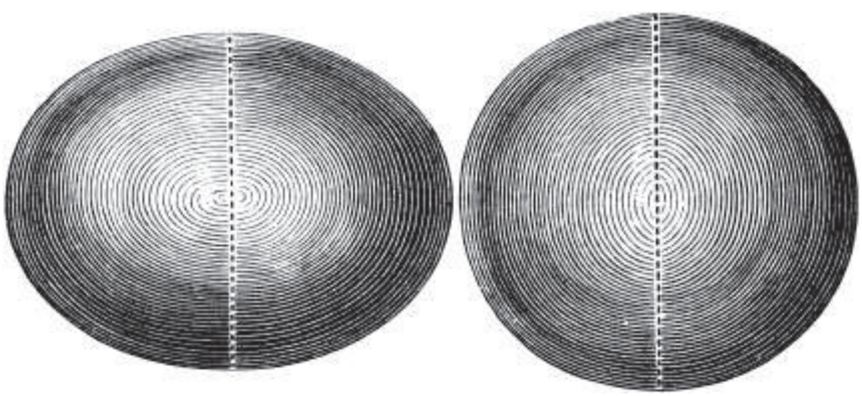


Figure 1.13. An ellipsoid is a sphere-like shape with one stretched axis. An ellipsoid can either be oblate (left) meaning it is stretched horizontally, or prolate (right) in which case it is stretched vertically. During the 18th century, a large debate occurred around the direction of the stretch of the Earth. The Academie Royale des Sciences believed the Earth was prolate, while the Royal Society of London insisted on it being oblate.

The Academie Royale des Sciences in France were convinced of the Earth being a prolate spheroid (see Figure 1.13 right), which argued against Newton and the English (Hoare, 2005). René Descartes who described the Earth as an egg shape and thus extended at the poles proposed the Earth to be a prolate spheroid. The French scientific community would practically ignore Newton's ideas even though he was part of the Academie. This dispute would eventually lead to the development of two major expeditions to provide evidence and confirm the Earth's figure once and for all.

The Journeys for the Truth

The two major expeditions stimulated by this controversy in the 18th Century were the Peru and Lapland expeditions. These expeditions were primarily organised by a member of the Academie, Pierre Louis Maurpertuis (1698 - 1759), a mathematician who had a great interest in the shape of the Earth (Hoare, 2005). The aim of both expeditions was to measure a degree of the latitude in their respective areas in order to compare the Earth's shape in different regions (Hoare, 2005). These two expeditions would make for the first scientific journeys to be carried out on a global scale.

The Peru expedition was carried out by three members of the Academie; Pierre Bouguer (1698 - 1758), Charles-Marie de La Condamine (1701 - 1774), and Louis Godin (1704 - 1760) (Ferrerio, 2011). The party departed France on May 16th, 1735 with the purpose of measuring the distance of one degree of latitude near the equator using the survey method now known as triangulation (Hoare, 2005). They would create a chain of triangles over hundreds of miles in length and use star sightings at the ends of the chain to determine the approximate distance of one degree (Ferreiro, 2011). However, upon arriving and initiating the task, various complications arose involving conflicts with

the Spanish who were dominant in the area (Ferreiro, 2011). As well, in the Peruvian terrain it was difficult to measure as it contained many different trails, hills, and rivers (Hoare, 2005). What was thought to be a quick measure of a component of the Earth's geometry would eventually lead to an expedition that lasted eight years. In spite of various difficulties, they were able to produce a measurement of 56 768 toises (110 648.8m) (Hoare, 2005). Toise was the common measurement of the French in the 18th century and converts to approximately 1.949m (Hoare, 2005).

The Lapland expedition was executed much more efficiently than the Peru expedition. Planning began as soon as the Peru expedition began and the party left Paris on April 20th, 1736 (Hoare, 2005). The plan was to survey the North, similar to the Peru expedition, to determine the distance of one degree of latitude. Originally set to the Arctic, it was determined the conditions there would be too harsh and thus the final chosen destination was south at the Swedish-Finnish border (Hoare, 2005). Though they encountered harsh climate and tough terrain, the French team did not experience as many issues as the Peru party as they had good ties with the Swedish hierarchy. It took just over a year for the team to successfully survey the land and produce a final value of 57 395 toises (111 862.9m). This determined that a degree of latitude in Lapland was greater than that in Paris (57 119 toises) (Hoare, 2005). Even without the Peru expedition, the conclusions regarding the Earth's shape could be made from this expedition. Much controversy would follow and various other scientific expeditions would occur, however it would not change the fact that Newton had been correct and the Earth was a slightly oblate spheroid (Hoare, 2005).

Modern Measurements of Earth: GRACE and Its Application in Geology

Methods of measuring the Earth's shape and size have grown exponentially in both their accuracy and complexity. A large portion of this growth occurred in the second half of the 20th century. During the arms race between the United States of America and Russia, both military powers were desperate to perfect their self-guided missile systems (Cloud, 2000). In order for this to occur, both the force of gravity acting on the missile and the exact distances between two points on the Earth are necessary pieces of data. Interestingly, this huge demand for precise geographical data provided funding for the implementation of many geoscience disciplines around the world in a number of universities. As a result, measurements of the Earth and their applications now have their own branch of Earth sciences (Cloud, 2000)

Geodesy is the branch of applied mathematics and Earth science that deals with the representation of the Earth and positioning on it. Using a combination of ground-based and orbiting surveyors, researchers have been able to measure the size and shape of the Earth to within centimetres. This has also allowed for the discovery of the most exact description of the shape of the Earth. A Geoid is the figure that represents the shape the oceans would form, taking into account the gravitational and centrifugal forces acting upon them while ignoring tidal and wind forces (Fowler, 2005). The result is a surface that has the same scalar potential at every point. As seen in Figure 1.14, this shape is much more irregular than the reference ellipsoids used for Global Positioning and navigational systems in the past. This is due to discrepancies in the exact densities and elevations of the Earth's crust.

The main obstacle to recording something as large and intricate as the shape of the Earth, and its gravitational field is the shear amount of data involved. Although originally proposed by Gauss in the 19^{th} century, the Geoid was only accurately recorded within the last couple of decades. This is because computers only recently became powerful enough to handle such large amounts of data. These technologies have also allowed researchers to extrapolate additional information such as the density of the different layers of the Earth, the exact length of days and to continue to keep track of the ever-changing shape of the Earth.

In order to capture such an intricate representation of Earth, complex gravitational measuring technologies are required. Two of the most important of these devices are the Gravity Recovery and Climate Experiment (GRACE) satellites. GRACE is a collaboration between the German Aerospace Centre and NASA to map out the irregularities in the Earth's gravitational field (Tapley, 2004). It consists of two satellites orbiting the Earth, continuously sending microwaves between each other. They are 220km apart, and can detect any variation from this distance that is greater than 10 micrometres (Swenson, 2002). A change in this distance occurs when the satellites pass over an area of gravity irregularity one after the other (Tapley, 2004). The change in gravitational acceleration changes the distance between the two satellites, which is then recorded. By collecting these data, geologists are able to study the shifts in the Earth's crust caused by earth quakes, the specific shape of oceanic basins, and even detect never before seen impact craters created millions of years ago (Zlotnicki, Bettadpur, Landerer, & Watkins, 2013). This technology also allows researchers to see into the core of the Earth, allowing them to begin to understand the magma currents that control so much of the climate, magnetic field and plate tectonics of Earth.

By using the GRACE satellites, researchers have also been able to determine the relative density of the rock in certain areas. Using the size and angular momentum of the Earth, it was calculated that the Earth should have a flattening ratio of 1:230, when in actuality it is known to be 1:298.25. (Williams, 2004). This revealed that the density of the Earth was a function of the depth of rock under observation. From the earliest civilizations, humans understood the importance of the shape of the Earth, however now technologies such as GRACE, have given researchers the ability to quantify its characteristics.

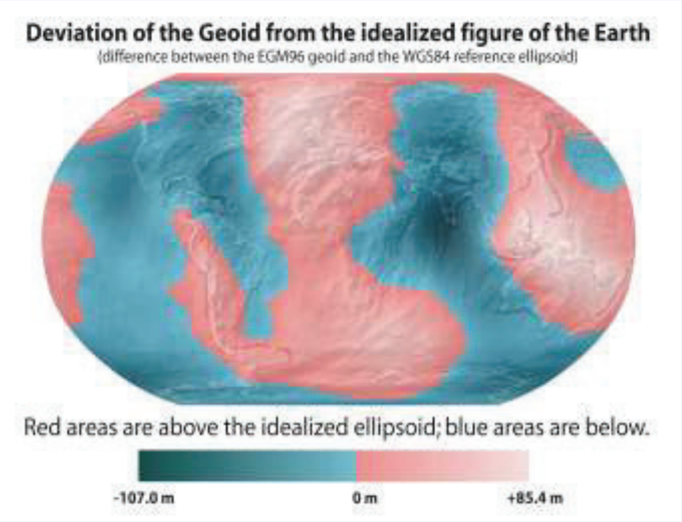


Figure 1.14. A Geoid is the most accurate representation of the Earth's shape. It is shown here relative to the shape of the Idealized Figure of the Earth. These deviations of the elevation create a surface with constant gravitational potential at every point. This is the shape oceans would form is the lunar and wind forces were ignored, and therefore only looking at gravitational and centrifugal forces acting on the Earth.

Heliocentricity vs. Geocentricity

Since the dawn of human cognition, people have wondered about the nature of the light and darkness that cyclically invaded out lives and the heavenly objects above that seemed to covary with these shifts. Today, we refer to these concepts as the Sun and Moon, the planets, the stars, day and night. We understand a great deal about these celestial bodies and the circumstances leading to their appearance.

Heliocentrism is a theory that claims that the planets in our Solar System orbit around the Sun, something that is common knowledge in today's world. Prior to Polish mathematician Nicolaus Copernicus (1473-1543) and his seminal work *De Revolutionibus Orbium Coelestium* (On the Revolutions of the Celestial Spheres) in 1543, geocentrism went relatively unquestioned (Kuhn, 1957 p. 351). This was the belief that all heavenly bodies orbit a motionless Earth which is at the centre of the universe. Through this lens, many ancient civilizations made astoundingly accurate predictions and sophisticated calendars based on their maps of the night sky. It was the progression of these ancient ideologies which eventually led Copernicus to explore a seemingly fundamental truth and to eventually change the world's cosmic perspective.

Early Stargazers

Understanding of the ideas of renowned ancient Mayan astronomers is quite common today. False apocalypses aside, these people accurately predicted eclipse events and the precise lengths of years and seasons long before modern instrumentation could confirm these phenomena (Bricker et al., 2013; Thompson, 1974). Monitoring the movement of the heavens was considered crucial for Earthly events and a way to receive information from the Gods. For all their motivation and skill, they were unaware of sidereal periods, the time it takes for an object to orbit around the Sun. Instead, they made their predictions and observations using the synodic periods of celestial bodies, observing how long it would take a particular body to come back to the same spot in the sky relative to the Sun as seen on Earth (see Figure 1.15) (Rosa, 1995). Possibly the most meaningful of Mayan innovations was their precise evaluation of time scales and creation of accurate calendars. These ancient astronomers recorded their ideas as early as c. 1000 BCE-250 CE during the Pre-Classical period of Mayan Civilization, a time when the complex nature of the necessary calculations would have been extremely daunting (Haug et al., 2003).

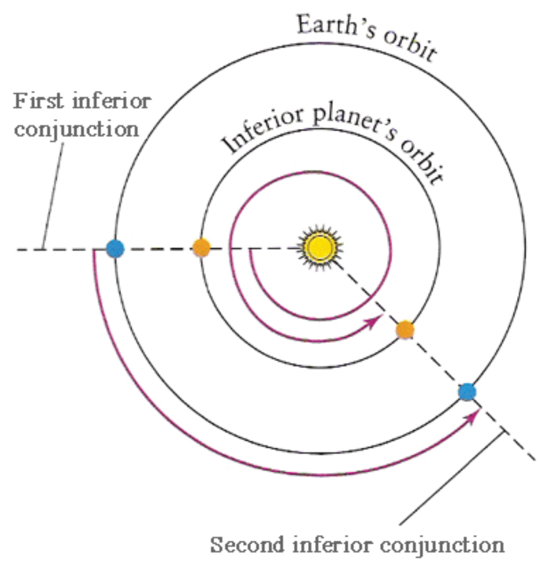


Figure 1.15. A depiction of the synodic periods used by Mayan astronomers. The time between the first and second inferior conjunctions was used to make predictions about celestial time scales.

In the Indian subcontinent, similar ideas also took shape. Evidence of this comes from the Vedas prose text *Shatapatha Brahmana* (Brahmana of one hundred paths) from the Iron Age of India in 1000 BCE-200 BCE (Glaz 2013). Within this scripture are concepts including the relatively exact length of a year and the notion that the Sun and Moon are roughly 108 times their diameters away from the Earth (Kak 1998). Ancient Indian astronomers of the Vedas faith also believed in a flat Earth and geocentricity, as well as the influence of the heavens as signals through which Gods could communicate. It was this belief that helped the subcontinent of India in playing a large (albeit controversial) role in shaping Western mathematics and astronomy throughout the course of history

(Katz 2003).

Similarly sophisticated ideas can be found in ancient Chinese astronomy dating back to the *Kai Thien* (Heavenly Canopy) cosmology of the Bronze Age Shang Dynasty between 1600 BCE-1046 BCE (Needham 1974). *Kai Thien* cosmology was a geocentric view in which the universe was a set of nested bowls, with the heavens and Earth forming concentric hemispheres resting on a circular ocean surrounding a flat Earth. These anonymous stargazers conceived accurate notions of the lengths of days, seasons and years and the radius of the Earth, as well as accurately predicting solstice, equinox and eclipse events (Krupp 2012). The most significant of these early observations from Chinese civilization was the ability to approximate Earthly distances and measures from looking outwards, a concept that is not intuitive today and most certainly would not have been at this time either (Baxter 1989).

The accomplishments and perspectives on astronomy gained from ancient Mayan, Indian and Chinese civilizations are interesting and unique, however they were relatively isolated and their ideas did not permeate the globe. Contrary to these was ancient Greek society, whose reach was long and scholars were plentiful (Krupp, 2003, p.24). Ancient Greek civilization offers us more specific and less anonymous records through which the transition from geocentricity to heliocentricity can be examined.

Progression of Ideas in Ancient Greece

One of the earliest Greek astronomers of note was Anaximander (c.610 BCE—546 BCE). Anaximander was among the first proponents of an archaic version of the scientific method, in which he attempted to discover the nature of things by recorded observations. He made efforts to move explanations of physical processes away from mythology, and theorized a mechanical model of the universe (Kahn, 1994). In his depiction, Earth was a cylinder with flat top and bottom where the world (as people knew it) existed. This cylinder was not supported by anything, simply floating in the centre of the infinite with balls of fire rotating around it on physical wheels as the Sun and moon and other prominent objects in the night sky (Graham, 2006).

In the 4th century BCE, Greek philosopher Aristotle (384 BCE—322 BCE) proposed his model of the cosmos. His biggest contribution to the advancement of astronomy was Aristotelean Physics, a set of principles that dominated western thought for nearly five centuries. Within this system, heavenly bodies were not composed of Earthly elements, but rather comprised of aether, a special and eternal substance. They were thought to be rotating in perfectly concentric paths at fixed rates and were not attached to any sort of physical wheels to allow for this motion. As well, Aristotle believed the Earth to be spherical and unmoving (Kyore, 1943).

Following the theories of Aristotle came Greco-Roman mathematician Claudius Ptolemy (c. 90-168), whose geocentric model remained a world view standard for millennia. In his 2nd century work titled *Almagest*, he proposed ideas about the cosmos that would become truths from c. 200-1500 (Pedersen, 2011, p.11). The main change he made to Aristotle's model was that heavenly bodies had two orbits: a deferent and an epicycle (see Figure 1.16). The deferent orbit described an object's motion around the midpoint of the equant and the Earth, and the epicycle was a smaller orbit which described an object's motion around a continuously moving point on the deferent orbit (Toomer, 1998, pp. 27-

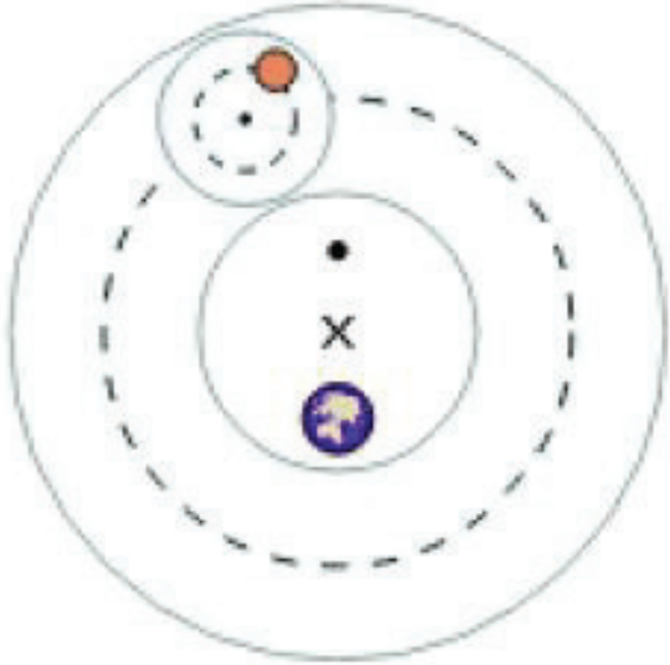


Figure 1.16. A depiction of the Ptolemaic model of the cosmos, including the deferent and epicyclic motions. The X represents the location of the midpoint of the equant and the Earth.

32).

Misconceptions Surrounding Geocentricity and Heliocentricity

Historical evidence suggests that we should be far less dismissive of past opponents to heliocentricity. Though today there is irrefutable evidence of the Earth's rotation around the Sun heliocentricity, many factors impeded the theory's acceptance. A lack of empirical evidence along with the implications that came with heliocentricity made it difficult to accept for a long time. This changed with successors of the ancient Greek astronomers like the Italian astronomer Galileo Galilei (1564-1642), the German astronomer Johannes Kepler (1571-1630), and the English physicist Isaac Newton (1642-1727) contributing by consolidating the theory later on (Danielson, 2001).

Copernicus started compiling work in 1514 and finished his seminal piece *De Revolutionibus orbium coelestium* (On the Revolutions of the Celestial spheres) in 1543. His model had two fundamental tenets: The solar system was heliocentric and that the Earth was geokinetic. The latter refers to the notion that Earth in fact rotates and is not stationary. This contrasted the Ptolemaic model which was geostatic, meaning that the Earth was motionless. Heliocentricity also contrasted with the view proposed by Ptolemy of geocentricity that suggested all celestial bodies rotated around the Earth (Price, 1969, pp. 197-218).

While common perception of geocentricity is that the Earth is the centre of the universe, the actual theory states that it is **at** the centre of the universe. This fine distinction reflects the actual as opposed to perceived view of the scholars referring to Ptolemy and Aristotle (Singham, 2007). American historian Thomas Kuhn (1922-1996) clarified that the Earth was not considered to be especially important in the grand scheme of things (Kuhn, 1957, p.57).

The universe was believed to be finite and the Earth was believed to be the most massive object in it. This was a physical explanation of why celestial bodies were orbiting around the Earth simply because the Earth's centre coincided with that of the universe. The selfish, anthropocentric view is overturned by the notion of the squalid basement; the closer one was to the stagnant, motionless center of the earth the further one was from the heavens orbiting up and away from the center (Kuhn, 1957, p. 70). Resistance to changing geocentricity was thus not brought by a sense of pride or egocentric human views, but in fact by seemingly logical conclusions derived from the existing understanding of the physical world at the time.

The Catholic Church is associated as being a vehement opponent to heliocentricity. However, little resistance initially came from the religious community. A scientist-cleric himself, Copernicus was invited to present the ideas from his manuscript *De Revolutionibus orbium coelestium* to disciples of the Catholic Church. There was little controversy of Copernicus' heliocentric viewpoint for several decades until Protestant Reformation leaders extended their influence on the Catholic Church. To proponents like Martin Luther, the Bible was a valid scientific authority on matters of the physical world. Copernicus' theories also contradicted fundamental tenets like where the physical location of God's throne would be if the universe were infinite (Singham, 2007).

Historically, the issue was more complicated than delineating the two sides of science and religion. During the mid-16th century as Copernicus' theories started to spread, the ideas were initially contained within the astronomical and then the greater scientific community (Hess & Allen, 2008, p.26). These scholars were interested in making better predictions of planetary motions and acknowledged the usefulness of Copernicus' theory. However, since the heliocentric model did not provide significantly better results than Ptolemy's model and raised many physical and theological issues it was treated more as a tool than conceptual framework (Singham, 2007).

Obstacles to Scientific Paradigm Shifts

When considering obstacles to the acceptance of new scientific paradigms, one of the first issues to examine would be prevailing scientific concepts of the time. According to Aristotle, there were four fundamental elements which had affinities to travel up (towards the heavens like fire and air) and travel down (toward the ground like earth and water). If the Earth was not at the centre of the universe then how could objects thrown up fall back down at the same spot? There was no reason to believe that Earth was not the most massive object in the universe. If it was not at the centre then this would imply that the universe had no center. Questions like these represent a tendency to use Occam's razor. Though Copernicus' theory was more complex, it lacked the mathematical accuracy needed to compete with the Ptolemaic model and produce a paradigm shift (Kuhn, 1957, pp. 266-269).

Copernicus himself experienced little of this opposition as these debates came about in the early 17th century, decades after his death. However, proponents of his theories were warned against defending Copernicanism on suspicion of heresy. Galileo was one such follower of Copernicus who could have brought the necessary observational evidence to bolster heliocentricity. Galileo's contribution to science is all the more meaningful due to his objective reasoning amidst external pressures. Famous scientists like Albert Einstein look to Galileo as a historic figure, dubbing him the father of modern science.

Strengthening Copernicus' Theory

Despite being put on trial and sentenced for life under house arrest under the conviction of heresy, Galileo was doing more than just defending the views of Copernicus and heliocentricity (see Figure 1.17). In his book *Dialogue on the Two Chief World Systems, Ptolemaic and Copernican,* he weighed in arguments from both viewpoints while incorporating his new telescopic evidence into this ongoing discussion (Finocchiaro, 2011).

Though his work significantly strengthened the case for heliocentricity, it by no means provided ultimate proof for the theory (Pamerino, 2008). The necessary progressive framework describing the changing speeds of planetary motion would not be proposed until 1687 by Newton. The elliptical orbit of planets which was also missing from Copernicus' theory was available to Galileo through Kepler's first law outlined in *Astronomia Nova* (Russeull, 1995). This law stated that the planets moved in elliptical orbits around the Sun. However, it was not readily accepted at the time and Galileo dismissed Kepler's theories. Since the evidence for heliocentricity was not conclusive and his argument was lacking, Galileo was forced by the Roman Catholic Inquisition to confess that heliocentricity was false.

Figure 1.17 Portraits of Galileo Galilei (left) and Nicolause Copernicus (right)

Today, we know that the Earth is orbiting the Sun in an elliptical fashion and we are also aware of how insignificant our planet really is amongst the grand scales of the universe. The terms Heaven and the heavens are no longer synonymous, and previously invisible celestial bodies such as Jupiter's moon Europa and binary star systems are being investigated (Hussmann et al., 2006; White & Ghez, 2001). Perhaps the most crucial modern initiatives directly concern us and focus on our planet's orbit.

The external challenges put on the scientific process seem timeless since even rigorous methods can be subject to misinterpretation and miscommunication. Looking at past scientific knowledge, there were many gaps in understanding of the dominant theories of the time. The public perception is that the Catholic Church was undermining Copernicus' efforts. Looking at the historical evidence a different, more balanced perspective emerges.

With all our knowledge now, it is easy to wonder how scientists could have missed something so seemingly obvious. The problems our predecessors faced is part of a cycle of scientific discovery that continues today. Ultimately, this is what separates science from the realm of belief and gives it a unique place in our society. As unpopular or popular as a finding may be, if there is sufficient evidence and the experimental methodologies are sound then science accepts it as fact, continuously updating our previously conceived ideologies and theories along the way.

Misinterpreted Milankovitch: Earth's Orbit and Climate Change

In the last several years, one would be hard pressed to find a topic that is more prevalent and controversial than global warming and climate change. There are those who would say that we are reaching a critical juncture where our societal development has us on the precipice of a biogeochemical tipping point, and others who would claim that changes in climate are a part of the planet's history and nothing new. The latter groups would not be wrong, as the Earth's climate is influenced by the eccentricity of its orbit, angle of axial rotation and the rotation of this axis, however it seems that current climate trends vary from historical patterns (Kaufman et al., 2009; John Imbrie and John Z. Imbrie, 2013).

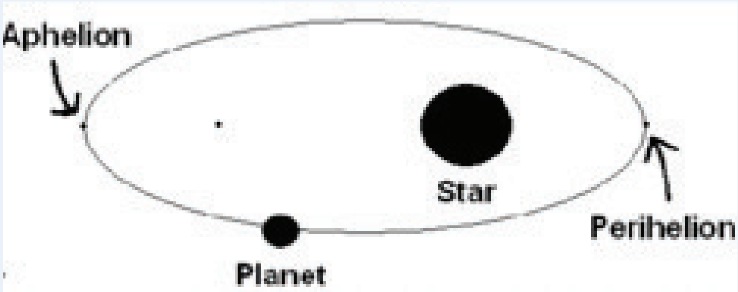


Figure 1.18. Representation of an elliptical orbit. The perihelion (closest distance to the Sun) and aphelion (farthest distance from the Sun) are illustrated.

Milankovitch Cycles

These variations in the Earth's orientation with respect to the Sun and their subsequent impact on climate patterns are known as the Milankovitch cycles. They are named after Serbian astronomer Milutin Milankovic (1879-1958), who first theorized that eccentricity, axial tilt, and precession could have such an effect in 1914 (see Figure 1.18). These attributes combine to influence the amount of solar radiation, or insolation, that different parts of the globe receive at different times of the year. The changes in insolation can have an impact on climate by influencing temperature, glaciation, and sea levels (Kaufman et al., 2009).

The eccentricity of the Earth's orbit operates on a 100 000 year cycle, ranging from nearly circular to slightly elliptical. Currently, we are slightly more eccentric than average over the course of the cycle (Berger, Loutre, & Mélice, 2006). The causes of the changes in elliptical shape are the interactions the Earth has with other large masses such as Jupiter and Saturn. In times of increased eccentricity, there is an overall increase in insolation, as the Earth is closer to the Sun at the perihelion point of orbit. In times of a more circular orbit, climate tends to favour glaciation as the Earth does not pass as close to the Sun and insolation values are lower (Berger, Loutre, & Mélice, 2006).

The axial tilt or obliquity of the Earth shifts from 22.1°-24.5° and back on a 41 000 year cycle. As obliquity increases towards 24.5°, higher latitudes in each hemisphere respectively have increased relative insolation during their summer and see a decrease in their winters. When obliquity is at the other extreme, the opposite is true, with high latitudes experiencing relatively lower insolation in their summers and higher in their winters (Williams & Pollard, 2003). Periods of lower obliquity encourage glaciation by melting ice accumulations less during the summer. Currently, we are near the midpoint of the cycle and are not experiencing effects of either extreme.

Axial precession refers to the 26 000 year cyclic spinning of the Earth's rotational axis in a gyroscopic fashion. When the axis is pointed towards the Sun in the perihelion point of the elliptical orbit, the northern hemisphere experiences more seasonal fluctuation in insolation while the southern hemisphere regresses towards milder insolation, as the axis is also pointed away from the Sun at the aphelion. The opposite is the case when the axis is pointed away from the Sun at the perihelion, as it is currently (Williams, 1994). This gyroscopic motion occurs because the Earth is an oblate spheroid as opposed to being perfectly spherical. Due to the axial tilt, an extended portion of the Earth (either the north or south hemisphere) is closer to the Sun and experiences increased gravitational pull. The subsequent torque produced is perpendicular to the axis of rotation, resulting in gyroscopic motion (Williams, 1994).

Evidence for Milankovitch Theory

Evidence for the cyclic nature of these phenomena and their effects on the Earth's climate is found in ice core samples. Danish scientist Nicolas Steno's (1638-1683) principle of succession applies to ice and snow as well as sediments. The top layers are more recently accrued, while lower layers are older (Berthault, 2002). With this in mind, scientists are able to extract core samples from ice sheets. They then use the composition of air bubbles trapped in the ice as a proxy to reconstruct the atmospheric environment at the time of freezing. The composition of the atmosphere and local temperature can be determined using this method. Using this data, a time scale can be constructed to show the trends over time (Bender, et al. Sowers and Brook, 1997). For temperature, it appears that Milankovitch cycles and the phenomena they predict do in fact covary with the measured climate changes. This is evidenced in the pivotal work of Shackleton and Opdyke in analyzing stratigraphic cores, specifically one in the Pacific named core V28-238. The oxygen isotope levels and magnetic stratigraphy of the sample details sediment deposition over the past 870,000 years. The findings lead scientists to believe that ice had historically accumulated in the Northern Hemisphere, in line with Milankovitch theory. While it does seem as though Milankovitch cycles play a role in global climate change, they are not necessarily the only factor and are simply the best current explanation for historical patterns (Ewing, 1999).

Scientific Illusions on Global Cooling

Just as with Copernicus' contemporaries, public perception of scientific consensus is not always accurate. During the 1970's a mixture of unfamiliarity with primary literature and scientific journalistic sensationalism led to the concept of global cooling. Writers for journals relating science to the masses such as Science Digest and National Geographic made premature assumptions with grave implications (Cooligan, 1973; Matthews, 1976). Journalists would both oversimplify the literature and selectively refer to certain findings (Weart, 2010). At the time, a popular topic was cold weather and certain studies fit well within the media's narrowly constructed narrative (Peterson, Connolley & Fleck, 2008).

The echoes of the scientific writers who cried global cooling can still be heard today. Pulitzer Prize-winning journalist George Will stated findings on levels of floating ice in the sea as counter-evidence for global warming. Increased glaciation tends to lead to lower sea levels, however in this instance the findings were sensationalized and taken out of context (Will, 2009). These assertions can be refuted by the following two reasons. The first reason is that global warming today has accumulated evidence over the decades when compared to the relatively inconclusive evidence for both global warming and global cooling during the 1970s (Bryson, 1974), (see figure 1.19). Second, the majority of scientists believing in global cooling held this view consistently (Sarewitz, 2004). Thus this so called paradigm shift of scientific consensus from global cooling to global warming never actually occurred.

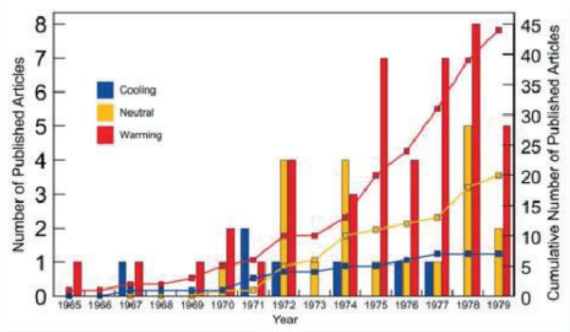


Figure 1.19 Number of papers supporting different theories of climate change.

Linking Challenges Faced by Galileo and Today's Climatologists

The astronomers in the 17th and the scientists in the 21st century can be thought in terms of the Buddhist allegory of blind persons trying to describe an elephant. Through our limited means, we try our best to decipher the bigger picture. There will be disagreements in what the object in question is, but this is inevitable in the search for knowledge. As new data put the scientific debate of heliocentricity to an end, the same will eventually happen for the debate of global warming. Going forward, we will continue to better understand the world in which we live and hopefully be better informed on global decisions regarding environmental policy and climate change.

Deep Time: The Discovery of Geologic Time

Scientific theories are shaped by the historical and philosophical perspectives of the era from which they arise. Historically, the acceptance of scientific theories has often been determined by the religious and political arena in which a scientist lived. The pathway to discovering the true age of the Earth is a series of convoluted interpretations and perspectives of a variety of cultures and scientists.

Sacred Perspectives of Time

"When Adam was 130 years old, he had a son...and named him Seth. After the birth of Seth, Adam lived another 800 years...and then he died. When Seth was 105 years old, he had Enosh"

(The Bible, Genesis 5:3-6)

Using this biblical account of the desendents of Adam, James Ussher (1581-1656), an Irish Archbishop of the Elizabethan period, determined how much time had passed between the creation of Adam and the birth of Jesus Christ. His calculation dated the beginning of the Earth to the evening of Saturday, October 22nd, 4004 BC. Ussher's belief of a 6000-year-old Earth was held as an absolute truth by both Protestants and Catholics for well over a century, and is still held by some today (Jackson, 2006).

Ussher's time frame did not take into account the formation of any of the geological structures or fossils seen around the world. In Ussher's time, it was widely accepted that fossils were the remains of the creatures that once lived on Earth. The story of the Great Flood of Noah's Ark was thought to explain the existence of marine fossils on mountain tops. While this theory has now been proven to be false, the idea that water erodes and deposits sediment to form stratified layers is correct (Lewis, 2000).

Early Geologic Time

By the end of the 17th century, religious dogma was being challenged by empiricists who believed the Earth was much older.

Edward Lhywd (1660-1709) was one of the first to attempt to scientifically determine the Earth's age. He calculated that the Earth was two to three thousand-years-old based on the rate of boulders falling in the Llanbens Valley, in Wales. His theory was as follows: two to three boulders will fall down the valley during the average lifespan of a person, which Lhywd estimated to be 60 years. This gives the frequency of falling boulders to be one boulder every 20-30 years. He counted the number of boulders lying in the valley, and estimated this value to be at least 10 000. Under the assumption that the valley was present at the formation of the Earth, he estimated the age of the Earth to be two to three hundred thousand years old (Jackson, 2006).

In 1715, Edmond Halley (1656-1742) took a very different approach to Lhywd. Halley proposed that the age of the Earth could be determined by analyzing the salinity of the ocean, with the assumption that at the time of creation the concentration of salt was zero. His theory had numerous control flaws and a lack of sufficient historical data, preventing him from calculating an actual estimate (Eicher, 1976).

Around the same time, Benoît de Maillet (1656-1738) also calculated the Earth's age based on the oceans. His tactic was quite different from Halley's, as he proposed estimating the age of the Earth by studying seashell fossils on Italian mountain ranges. Based on his own observations, he calculated the rate of sea level depletion to be approximately three inches per year. Using the altitude of these seashells he estimated the age of the Earth to be over two billion years. His work remained unpublished due to the perceived preposterousness of this immense timescale (Jackson, 2006).

Georges-Louis Leclerc (1707-1788), Comte de Buffon, diverged from the previous attempts to date the Earth by land formations and the oceans; instead, he took an extraterrestrial perspective. He used the newly developed techniques of Newton's calculus and physics to estimate the Earth's age at 70 000 years. Leclerc believed that the planets had begun as molten balls of rock ejected by the Sun. Although his hypothesis was not correct, it opened the idea that the world may be incredibly old. However, his work was not well received as it differed too much from the biblical account of the Earth's creation, and thus was generally considered sacrilegious (Jackson, 2006).

Although these diverse methods to estimate the age of the Earth were flawed, they are integral to the scientific discovery process. They are notable for their courageous attempts at empirical determination of the age of the Earth, and for being some of the earliest endeavours to separate scientific thought from religious belief.

The Discovery of Deep Time

James Hutton (1726-1797) was responsible for one of the greatest paradigm shifts in the earth sciences (see Figure 1.19). He initially studied medicine and chemistry, but as a farmer Hutton spent much of his time studying soil composition, erosion, and deposition. Hutton joined the Royal Society of Edinburgh, an organization of amateur and professional scientists. Along with two of his Royal Society friends, chemist Joseph Black (1728-1799) and economist Adam Smith (1723-1790), Hutton founded the Oyster Club discussion group, which gave him access to newly published papers and exposed him to new ideas in science (Gould, 1987).

In the 1750s, Hutton travelled around Britain and mainland Europe examining the diversity of landforms as they related to various geologic processes. Hutton's greatest geologic observation occurred on the cliffs at Siccar Point while on a boating trip with fellow scientist John Playfair (1748-1819). Hutton noticed that there was an unconformity consisting of layers of vertically bedded wacke overlain by younger, horizontally bedded sandstones. This site has since been named Hutton's Unconformity (see Figure 1.20). Hutton recognized that both types of rock were marine deposits. He postulated that the wacke must have been deposited horizontally under the sea, cemented, and uplifted out of the sea, then tilted until it stood vertically. It then was eroded and covered by new deposits which were later cemented. Finally, the entire structure was uplifted out of the water to its current location on land. The amount of time this would have taken is unfathomable, especially considering that this structure sits on top of still older rocks. Playfair was awed by Hutton's interpretation, and encouraged him to publish his ideas (Gould, 1987).

Hutton's first publication, *Concerning Systems of the Earth, Its Duration and Stability* (1785), was a lengthy abstract describing his belief that sediments could be cemented together by heat or precipitates, creating new rocks that could in turn form their own sediments through erosion. He also explained that these cemented rocks could be uplifted by the same heat that formed them, causing the land to expand and move to higher elevations. Hutton proposed that this subterranean heat caused twisting and breaking of the rocks as they moved, and thus caused the folding and fractures we see today. He described, with incredible accuracy, the cyclic processes of rock formation, uplift, and erosion that result in modern geologic structures. Hutton believed these processes were ongoing, and had likely been cycling for a very long time. Thus he speculated that the Earth must be incredibly old.

Figure 1.20. Hutton in the field. He was infamous for breaking off pieces of rock with a small hammer, a practice frowned upon by his colleagues.

Hutton edited and republished his work as a true paper, *Theory of the Earth* (1788) which introduced an interesting idea about the age of the Earth. In Hutton's words, the world has "no vestige of a beginning - no prospect of an end" (Hutton, 1788 pg. 304). The Earth's constant cyclic process of creating, uplifting, eroding, and then recreating rock gives no indication of its age, only the assumption that it must be unfathomably old. Hutton termed this massive span of time as "Deep Time", and described its magnitude as simply too long for humans to imagine (Jackson, 2006). Hutton believed that the Earth had been created at some point in the distant past, but that the processes that formed the Earth must have been quite different from the ones that currently shape it. The cyclic nature of geologic processes makes it impossible to determine how many cycles have occurred. Thus, estimates based on salt concentrations in the ocean or the height of fossils above sea level, are inconclusive as these conditions may have occurred multiple times (Jackson, 2006).

Charles Lyell (1797-1875), who wrote the widely read *Principles of Geology*. Lyell used Hutton's idea of an extremely old Earth with observable, repeating processes, to develop the theory of uniformitarianism. Lyell's uniformitarianism claims that current geologic processes are the same as those in the past, and will be the same as those in the future. Lyell used Hutton's idea of Deep Time to account for the slow rate of geologic cycles (Gould, 1987).

Hutton was undeniably an intelligent and observant man, however, his theories were as much a product of his society as his own mind. Edinburgh in the 18th century had an atmosphere of humanism and reason, making it more acceptable to challenge the biblical idea of a young Earth. Thus Hutton's ideas were met with less resistance than they would have been met with at other points in history. A strong community of fellow intellectuals allowed Hutton access to the ideas of other geologists, which in turn helped him develop his own theories (Gould, 1987). In short, Hutton was born in the right place, at the right time, and had the right connections necessary for the creation of the paradigm-shifting idea of Deep Time.

Figure 1.21. Hutton's Unconformity at Siccar Point. The vertically bedded wacke deposits predates the nearly horizontal overlying sandstone beds. The amount of time needed to arrange this structure must have been immense, prompting Hutton to theorize Deep Time.

Unfortunately, Hutton was a rambling and dry writer, and so few ever read his work. This resulted in little recognition during his life, however, this also prevented Hutton from the criticisms of those who strongly believed in the biblical account of a young Earth. Hutton's friend John Playfair wrote the book *Illustrations of the Huttonian Theory of the Earth* after Hutton's death which made Hutton's work easier to understand. The largest proponent of Hutton's work was

Geologic Time After James Hutton

Although neither James Hutton nor Charles Lyell actually proposed an estimate for the Earth's age, they opened the idea that the Earth was much older than originally thought. This paved the way for further empirical study with fewer cultural and religious restrictions.

Despite Hutton's claim that ocean salinity could not predict the Earth's age, this idea was revisited in 1899 by John Joly. He theorized that the Earth was 90 million years old based on his assumption that the ocean was originally freshwater, and that amount of salt deposited into the ocean by rivers from the erosion of rocks was uniform (Jackson, 2006).

Many geologists of Joly's era began to look to rock formations in an attempt to estimate the age of the Earth. They tried to determine the rate of deposition of modern sedimentary environments and then extrapolate from this data on the assumption that the rate of ancient deposition is equivalent to modern values. Weaknesses in these estimates include erosional processes introducing gaps in the geologic record and problems in accurately estimating rates of deposition. Due to these errors, estimated ages of the Earth based on deposition ranged from 3 Mya to 1.53 Bya, averaging just under 100 Mya (Eicher, 1976).

Like Leclerc's idea of an originally molten Earth that cooled over time, William Thompson (1824-1907), known as Lord Kelvin, also looked to heat for an answer. Kelvin used a three factor approach in attempting to determine the Earth's age. Firstly, he concluded that the age of the Earth was limited by the age of the Sun. He utilized the theory that the Sun was hotter in its infancy due to the gravitational energy required to pull in the meteorites which comprised its mass. Kelvin varied his estimates but finally settled on a solar age of 20 million years. Secondly, he estimated the age of the Earth based on the thermal gradient of heat flows from the interior to the exterior crust, with the assumption that the heat of the Earth was dissipating from its originally molten state. Based on inaccurate data of the heat of fusion of rocks, he estimated the Earth's age to be 98 million years old. Lastly, Kelvin assumed that tidal friction would alter the shape of the Earth, and as the Earth has essentially retained its shape, he concluded that it must be relatively young. Due to his highly technical and quantitative analysis, his estimate was accepted by the scientific community and society at the time. This, however, caused much conflict in the work of the previously mentioned geologists as well as evolutionary biologists, such as Charles Darwin (1809-1882). Many of the geologists adjusted their interpretations of geologic processes to fit the widely accepted estimate of Kelvin (Jackson, 2006).

The Earth is 4.6 Billion Years Old

In the late 1800s and early 1900s, renowned scientists such as Antoine Henri Becquerel, Marie Curie, Pierre Curie, and Ernest Rutherford discovered and developed the study of radioactivity. The concept that decay occurs as elemental transformation and emissions of waves of varying intensities was the missing puzzle piece in determining the true age of the Earth. It also has applications in dating the finite age of many rocks associated with different geologic time periods (Eicher, 1976).

One of the first uses of radioactivity in studying geochronology was in 1905. Robert John Strutt (1875-1947) used the principles of radioactivity to determine the age of gases trapped in ancient rocks. This idea gave precise estimates, but they were not accurate due to the leakage of gases from the rock (Jackson, 2006).

Building on Strutt's work, Bertram Borden Boltwood (1870-1927) discovered that radioactive uranium decays into a stable isotope of lead. He theorized that the ratio of radioactive uranium to stable lead could be used to determine the age of any uranium-lead bearing rock. He was able to examine mineral specimens and determine their age range to be between 400 Mya and 2.2 Bya (Jackson, 2006).

In 1911, Arthur Holmes (1890-1965), a student in Strutt's lab, narrowed these estimates by dating Archean rocks from Sri Lanka at 1.64 Bya. Holmes discovered that decay rates were constant, and used Alfred Nier's (1911-1994) theory that lead-containing rocks acquire their lead from the decay of uranium and from lead that was present at the formation of the solar system. By plotting the ratios of the primeval and radioactive lead in two lead containing rocks, Holmes was able to plot isochrons. The isochrons were linear plots of the two rocks, in which intersecting points create a line whose slope indicates the age of the Earth to be 3.4 Bya. However, it was difficult to determine which lead was truly primeval, and which had been formed at a later date (Lewis, 2000). Harrison Scott Brown (1917-1986) theorized a way to overcome this problem. Brown hypothesized that meteorites were formed around the same time as the Earth, and thus dating lead in meteorites would reveal the age of the Earth. He also knew that meteorites contained lead, but no uranium. Therefore, all the lead contained in the meteorite must be primeval. He set his student Clair Cameron Patterson (1922-1995) to date the lead in the Canyon Diablo meteorite found in Arizona. Patterson cut the meteorite open and removed pieces of black sulphide. He dissolved it in acid to separate tiny fragments of lead that he then placed in a mass spectrometer. The mass revealed which ratio of lead isotopes were present. He repeated this process on other meteorites and developed an isochron (see Figure 1.21) that dated the Earth at 4.55 Bya (Lewis, 2000).

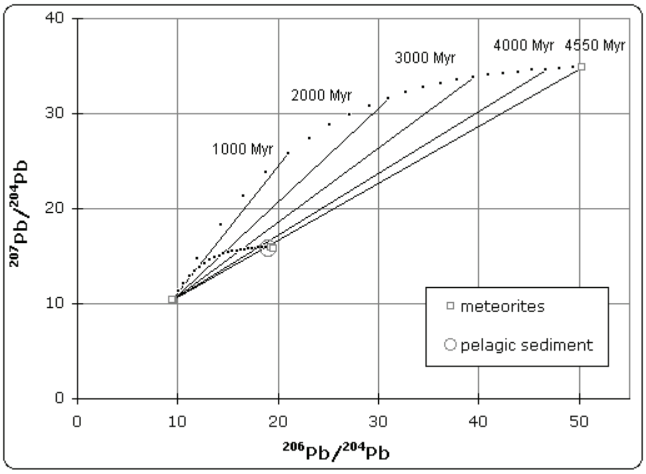


Figure 1.22. Isochron used by Patterson in 1956 to compare the ratios of primeval lead isotopes in meteorites. This isochron indicates the formation of meteorites, and thus the formation of the Earth, to have occurred 4.55 Bya.

After thousands of years of disproven estimates and speculation, Patterson was able to give a clear answer to a fundamental question. His answer gave a new perspective on the Earth and the extent of time itself. Patterson was only able to successfully determine the Earth's age using the methods discovered by the aforementioned scientists. To this day 4.55 billion years remains the scientifically accepted age of the Earth. However, like so many dates before, it is subject to change as new technologies and discoveries are made.

Modern Perspectives of Geologic Time

"The key to the present lies within the past" is a famous claim made by Charles Lyell; however, the past is equally useful in predicting the future (Simpson, Pittendrigh, and Tiffany, 1957 pg. 741-742). Through a modern lens we can better understand humanity's place in the Earth's vast timescale, and see how far the Earth has come. This modern perspective also allows us to look to the future of our planet by extrapolating what we have learned from the past. Our perspectives and understanding of Earth's history are continuously evolving as we collect and interpret more data from the geologic record.

Current Geologic Time Scale

Although it is now common knowledge that the Earth is about 4.6 billion years old, this is still a relatively recent discovery. It is only within the last 60 years or so that we have understood the vast timescale of the Earth with any accuracy. Billions of years is difficult to comprehend, especially when we consider that things we believe to be ancient, like the Pyramids of Giza or the dinosaurs, are actually quite recent in terms of Earth's history. In short, the world is old, much older than we can truly imagine. The discovery of the age of the Earth puts into perspective the incredibly small period of time that humans have been in existence (see Figure 1.22). With the ability to radiometrically date rocks and fossils, comes a better understanding of how recent human development is relative to other forms of life and geologic events. 4.6 billion is such a large number that the immensity of it can be easily be lost. Consider that a billion seconds before this book was published it was the 1980s, a billion minutes ago was the year 100 CE, and a billion hours ago *Homo sapiens* had recently evolved (Kramer, 2013). Therefore, a billion years, let alone 4.6 billion years, is a tremendous amount of time.

Imagine the entirety of geologic history could be compressed into a single year, with the formation of the planet culminating at 12:00 am on January 1st. If this were the case, continental land would not appear until March. The first life would develop in the oceans during May, while the first land plants and animals appear in November. Dinosaurs would go extinct on the 26th of December. Early humans do not appear until the evening of December 31st, and Hutton wrote his *Theory of the Earth* less than a second before midnight (Eicher, 1979).

Clues to the Future

Predicting the future of the Earth may be even more perilous than interpreting the past. There is no way to know with certainty how long the Earth will persist, however that has not stopped researchers from devoting their lives to estimating this complicated event. In the modern world, doomsday warnings of global warming and asteroid impacts are practically commonplace. Although climate change and catastrophes have the ability to cause mass extinctions, the Earth itself will still remain. The most recent estimates have determined that life as we know it will cease to exist on Earth in about 1.75 billion years. At this point, the Sun will have expanded and caused high enough temperatures to render the Earth uninhabitable to even the most resilient organisms (Rushby et al., 2013). The final demise of the planet itself is a topic of much debate. The Sun expanding and engulfing the Earth as it transitions to a red giant star is a popular theory. Current estimates generally place this event at around 6.5 billion years in the future (Sackmann, Boothroyd and Kraemer, 1993). If this is correct, then the Earth is a little over one third of the way through its existence. However, as the Sun expands it will lose mass, thus causing changes to planetary orbits. Some models have suggested that Earth's orbit will have increased in radius enough to avoid becoming consumed by the Sun. If this is the case, then there is no way to know when the Earth will end. The planet will continue to orbit around the dense mass of the Sun's collapsed core in darkness and at extremely low temperatures. By this point all water will have evaporated, the atmosphere will be non-existent, and the Earth's inner geothermal heat will have disappeared thus stopping tectonic processes. Without these factors geologic cycles will cease to exist and the Earth will continue on as a solid mass of rock. Although it is possible that the Earth could be destroyed by a collision with a larger extraterrestrial body, the incredible vastness of space makes this unlikely (Sackmann, Boothroyd and Kraemer, 1993).

As such, there is no clear evidence pertaining to the timing of the end of Earth, and it is possible that the planet could exist on a nearly infinite time scale. Although Earth's current age has been well theorized and substantiated, there is no concrete theory as to how long the Earth's lifespan will ultimately be.

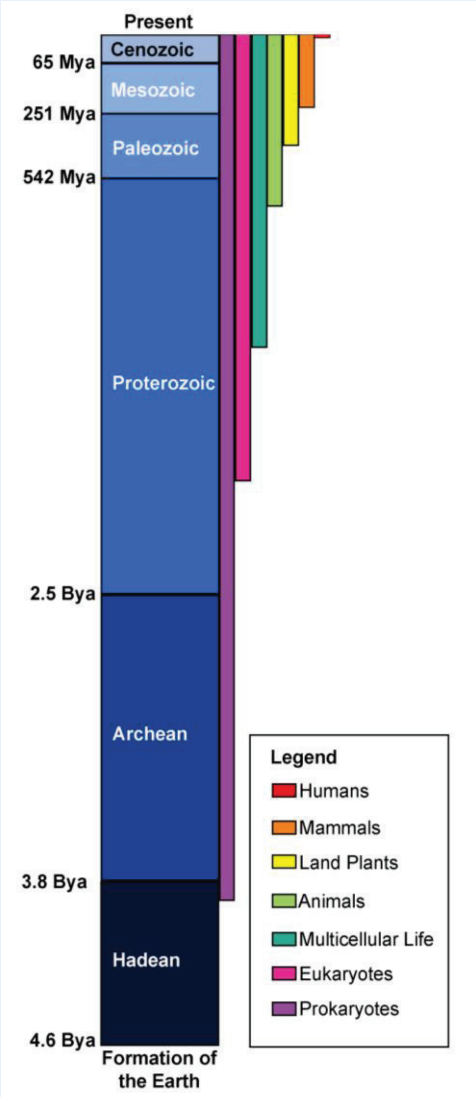


Figure 1.23. Modern interpretation of the Earth's timescale, depicting the development of different life forms in relation to the formation of the Earth. Note how late humans appear.

Tracing Our Atmosphere: The Development of Ideas from 400BCE to the 18th Century

The recurring theme in this chapter so far is documenting the development of theories and ideas related to the Earth's origins. Previous sections illustrate the diverse amount of history involved in the formation of ideas and theories related to topics such as the shape of the earth and the discovery of geologic time. This section however, seeks to highlight and explain the evolution of the understanding of the atmosphere. From Greek antiquity to the chemical revolution, this section will focus on the accumulation of theories that were necessary to determine the composition of the atmosphere. It will also touch on similar, yet much more complex, research being done today on the effects of trace gases.

Greek Philosophy

Discovery of the composition of the atmosphere dates back to the ideas proposed by ancient Greek philosophers of the early 3rd century BCE. Aristotle (c. 384-332BCE) proposed theories about the different phenomena he witnessed through a process of thinking known as natural philosophy (Lindberg, 1992).

At the time, Aristotle was striving to find an explanation of the physical world without including the notion of divine intervention (Brutsaert, 1982). His ideas worked towards explaining the *kosmos,* which means the "ordered world" in Greek, and finding a division between the natural and the supernatural (Lindberg, 1992). Aristotle's viewpoint on metaphysics allowed him to analyze the various phenomena he witnessed in nature through his theory of change. The theory is based on four causes; formal cause, material cause, efficient cause, and final cause (Lindberg, 1992). Out of the four different causes, the final is arguably the most pertinent as it aims to explain the role of purpose – 'teleology'. The purpose of a substance is based on the nature of its behaviour. This natural tendency is sought out by using past experiences to deduce the common characteristics for the substance. According to Aristotle, discovering the nature of a substance is much more valuable than determining minor differences or irregularities (Wilson, 1999). Hence, the four different postulates in his theory of change are intended to assist in analyzing a foreign situation and trying to make sense of it.

Aristotle uses this theory to understand cosmology. A sub-discipline which he investigated further is meteorology, which led him to author a treatise called *Meteorologica* (Aristotle, 350BCE). In this treatise, he agrees to a previous idea proposed by Empedocles (c. 490-430BCE) that the terrestrial region in which everything on Earth is found can be broken down into four elements; earth, water, fire, and air (figure 1.23; Aristotle, 350BCE). The presence and certain combinations of these four elements fill up a "void" area in space, also known as the upper atmosphere (Aristotle, 350BCE). He goes on to further develop an idea stated by Herakleitos (fl. 500BCE) of dual exhalation (an idea of evaporation) by stating the following; "…the vapor [atmis] cools and condenses again as a result of the loss of heat and the height and air turns into water: and the generated water falls again into the earth…The exhalation containing the most amount of moisture is, as we have said before, the origin of rain: the dry exhalation is the origin and natural substance of winds" (Aristotle, 350BCE). Aristotle's ideas stem from speculation based on the ideal of natural philosophy. Another concept he proposed that supported his theory of a void which filled the sky is that plants obtain food from various combinations of the four elements (Sherman,

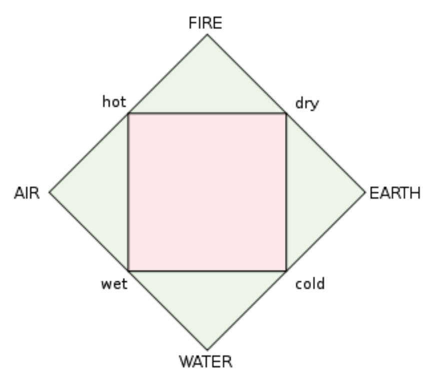


Figure 1.24. The four elements that make up the terrestrial region.

1933). The manner in which he deduces these concepts is alluring to say the least. He constructs his ideas based on observing the natural world, and both his own writing and novels written by modern authors convey a similar outline of Aristotle's deductive reasoning. From a modern scientific approach, Aristotle's theory would stand for nothing unless proper evidence is provided through experimentation, but for that aeon, his ideas were a radical change from the standard at the time. As a result of this, Aristotle's theories proposed in *Meteorologica* were widely accepted within society at the time.

Development of the Phlogiston Theory

The birth of natural philosophy undoubtedly had a large influence on the method in which science was taught and understood. In the 1200s, the teachings of this philosophy started to become an integral part of the undergraduate curriculum, showing that Aristotle had a lasting effect on history even after his death (Lindberg, 1992). Aristotle's influence is notable due to its impact and creation of a unique and imaginative method of thinking. The birth of natural philosophy undoubtedly had a large influence on the method in which science was taught and understood. In the 1200s, the teachings of this philosophy started to become an integral part in the undergraduate curriculum, showing that Aristotle had a lasting effect on history even after his death (Lindberg, 1992). By analyzing the literature, Aristotle's influence is notable due to its impact and birth of a unique and imaginative method of thinking.

Moving into the 17th century, several scholars started to realize that they were intellectually limited by following Aristotle's philosophy of thinking (Lindberg, 1992; Wilson, 1999). Scientists such as Galileo and Robert Boyle strived to propose new ideas for comprehending the "nature" of substances as proposed by Aristotle. These new ideas had to include derived concepts that could spark debate, provoke criticism, or further scientific ideas (Lindberg, 1992). This led to a greater appreciation for the hypothetical status of scientific claims and the importance of conducting experiments in order to challenge relevant theories.

Before advancing into the 18th century, it is critical to mention the scientific attempts of Joachim Becher (1635-1682) and his pupil, Georg Ernst Stahl (1660-1734), to advance theoretical chemistry (Wisniak, 2004). Founded by Aristotle's deep-rooted concept in *Meteorologica*, Becher considered that perhaps all material consisted of a relative ratio of earth and water, which could be aggregated by air (Aristotle, 350BCE; Wisniak, 2004). The addition of fire matter was suspected to be the cause of a metal's calx (see Figure 1.24 for an image of a crumbly residue of lead carbonate after the process of calcination). Soon afterwards, Stahl elaborated upon his teacher's theories of combustibility to include the inflammable principle of a suggested "fifth element", phlogiston (Wisniak, 2004; Woodcock, 2005). A number of materials were thought to combust due to their contemporary composition of phlogiston, derived from the Greek term for "fire of the Earth" (Woodcock, 2005). Deviating from his instructor's assumption of calcination, Stahl suggested that a calx was deprived of the original metal's phlogiston and should ultimately weigh less, when in fact, the product was later found to weigh more (Wisniak, 2004). There were no precise notions of the gas phase around the time, yet many respected European chemists adopted the concept of phlogiston for the 50 years preceding Stahl's death. The accumulation of opposing discoveries caused an appearance of confusing adjustments to the phlogiston theory, resulting in the labeled "decadence period" (Wisniak, 2004).

Figure 1.25. A white metal calx (powdery substance formed after an ore or mineral is heated) of lead carbonate after being heated.

Extinguishing the Theory of Phlogiston

The first major scientific contributions to atmospheric chemistry can be traced back to the late 18th century (Marini-Bettòlo, 1986). Many suggest that this point in time may have been the most compelling in the history of chemistry due to an unintended rivalry between the era's two leading chemists, Joseph Priestley (1733-1804) and Antoine Lavoisier (1742-1794; Woodcock, 2005). Moreover, findings on the composition of water by Henry Cavendish (1731-1810) once complemented those of Priestley's research. However, the contributions of both of these chemists are often overlooked since they were later refined by Lavoisier to support his theory of combustibility and promote the chemical revolution (Seitz, 2005).

Well before the chemical revolution began, Henry Cavendish had been experimenting on the precise measurements of gaseous elements and the composition of water (Seitz, 2005). By 1766, he began to focus his personal research on the study of gases and realized that ambient air could be divided into more than its primary component; he then compared the chemical and physical properties of each isolated chemical component. Cavendish considered the plausibility of phlogiston and postulated that it was hydrogen or the 'inflammable air' that was the cause of combustion (see Figure 1.25). Around the time that Priestley began experimenting on dephlogisticated air in the 1770s, Cavendish returned with more precision and emphasis on the composition of water. It was in 1781 that Cavendish thoroughly analysed an earlier experiment, in which inflammable air (hydrogen) exploded with a mixture of air (containing oxygen), and detected a thin film of pure water that had previously gone unnoticed (Seitz, 2005). As aforementioned, Cavendish followed the views of the phlogiston principle and hypothesized that dephlogisticated air was a form of water that lacked the inflammable air (phlogiston). Nearing the start of the chemical revolution, Cavendish had uncovered a range of atmospheric and elemental knowledge, but could not generate a unifying theory to account for the atmosphere. The task required a profound and imaginative perspective to revolutionize the science of chemistry and overthrow the theory of phlogiston (Seitz, 2005).

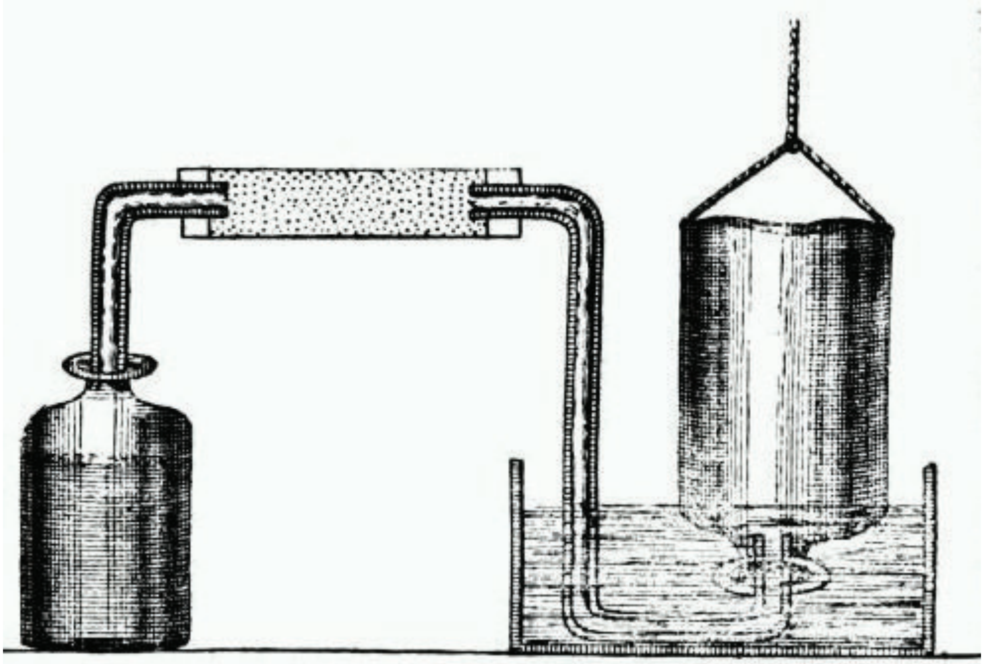


Figure 1.26. A drawing of Cavendish's apparatus for making and collecting hydrogen gas, which he called "inflammable air", by dissolving metals in various acids.

Journeying into a time period where new methodologies in science aimed to obtain knowledge which can be put to use, Joseph Priestley made great discoveries based on this novel method of thinking. Growing up as a child, Priestley was grounded in a religious background and inevitably grew up to become a minister (Hiebert et al., 1980). However, he didn't limit himself to a divine perspective on everything. Priestley was a firm believer in the fact that both religion and science could co-exist in a relationship that would not try to contradict each other.

The prevailing theory at the time surrounded the idea of phlogiston as previously mentioned, but he thought this was too general to further the area of chemistry (Gabriel and Fogel, 1956). Between the years 1771-1774, Priestley conducted several experiments in order to generate a new theory within this topic area (see Figure 1.26; Gabriel and Fogel, 1956). The process of making these discoveries employed a very different method than that of previous centuries. In his notes, he follows an organized method where he makes many observations about the experiments that he conducts and follows-up with analysis on how to further develop the research question (Hiebert et al., 1980; Priestley, 1970). Most notably, Priestley conducted an experiment in August 1774 concerning the formation of what he coined to be "dephlogisticated air" produced from the burning of mercuric oxide (Priestley, 1774). Amazed and perplexed by the new type of "air", the subsequent experiments involving it were performed in an isolated environment. This showed that it could cause a flame to burn intensely and could keep a mouse alive for a much longer period than without the "air". As a result, conducting this experiment led to disprove the theory of air as a single element, but rather a mixture of different "airs". The literature presenting this information shows that Priestley was very unsure about the discoveries he made and their significance (Hiebert et al., 1980; Gabriel and Fogel, 1956). Both Priestley's own notes and a recollection of events written by Aaron J. Ihde convey the message that Priestley didn't identify the importance of his findings nor did Cavendish around the time of his experiments on water. It was not until a few years later that the term oxygen was coined as a component of air by Antoine Lavoisier (Hiebert et al., 1980).

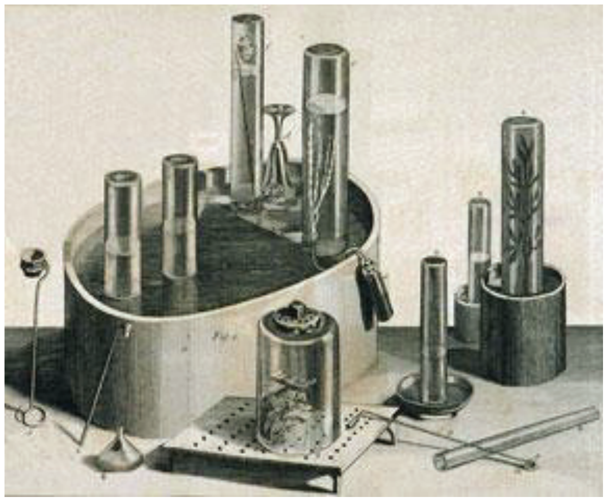


Figure 1.27. A reproduction from Joseph Priestley's book Experiments and Observations on Different Kinds of Air, 1774-1786; displays the apparatus of Joseph Priestley's experiments on gases, including oxygen.

The first child of the Lavoisier household, Antoine, originally planned to follow his father's career in law. Soon after graduating from the Paris Law School in 1764 with a legal degree, Lavoisier pursued his passion for chemistry (Bell, 2005). From a spell working with the geological survey and geologist Jean-Étienne Guettard, Lavoisier developed an interest in determining the precise quantitative analyses of geological samples. After many attempts, such as presenting his research on gypsum, the Academy of Sciences accepted him at the age of twenty-five, making him the youngest to have ever been elected (American Chemical Society, 2013; Jackson, 2005). Lavoisier first encountered the phlogiston theory during his years at law school. Although, in order to discuss the theory with his colleagues, his wife, Marie Anne Peirrette Paulze, had to translate Richard Kirwan's "Essay on Phlogiston" into French (Eagle and Sloan, 1998). This knowledge of the theory soon became extremely vital to his attacks on the phlogiston principle and his study of combustion in 1772 (American Chemical Society, 2013).

The Chemical Revolution

The year is 1774, in Paris, a formal dinner is held assembling a group of European thinkers. Priestley was the guest speaker for the evening and discussed his thoughts of experimentally obtaining "pure air" that was free of the phlogiston, hence the obsolete title for oxygen, dephlogisticated air. Two years beforehand, while Priestley was extracting unknown gases from the atmosphere, Lavoisier was concentrating on understanding combustion. Through superior weighing techniques, he found that certain substances experienced an increase in weight as they burned instead of a decrease; thus, Lavoisier believed he had identified the phlogiston theory's ultimate flaw (Perrin, 1986). It was only after hearing Priestley's views in Paris that Lavoisier envisioned the truth and would act accordingly (Jackson, 2005).

Lavoisier was able to invent a balance that could correctly weigh to 0.0005g, which aided in accurately replicating Priestley's and Cavandish's studies on mercury oxide and water respectively (Woodcock, 2005). After performing Priestley's experiment in 1777, Lavoisier trusted his own hypothesis that the process of calcination is a synthesis reaction in which metals absorb and react with atmospheric substances to gain weight, and the decomposition of these products with carbon reduces the substances back to their original weight (Wisniak, 2004). Consequently, there was no extra weight to account for the supposedly released phlogiston. This, along with many other findings, led to Lavoisier's concept of the conservation of mass. Lavoisier drew a similar conclusion in 1783 by accomplishing an accurate experiment on the formation of water, in as similar way to Cavendish (Woodcock, 2005). Lavoisier and his team of four had an incredible knack for inventing popular nomenclature for chemical elements and compounds; hence, a renamed system was developed in which the term oxygen was created to formally represent dephlogisticated air.

Lavoisier executed a widespread range of analytical work in his French arsenal laboratory before he was guillotined to his death. Ultimately, he was able to recognize the properties of new elements, identify the constituents of minerals, and properly document his results to present them to the scientific community. Amateur and professional scientists began developing an interest in the ever-growing field of chemistry and the composition of the atmosphere. After which, new elements and different compositions of materials were rapidly being unearthed. The chemical revolution allowed for exciting research to be conducted in a variety of disciplines, including that of atmospheric chemistry (Seitz, 2005).

Trace Gases: Small Changes, Big Effects

The increase in overall average temperatures of both the atmosphere and oceans on Earth is thought to be the result of climate warming. Since the Industrial Revolution, the increase in these temperatures has gained an increasing amount of societal attention as the effects of climate change become more noticeable (see Figure 1.27). Although the majority of the population is familiar with the effects of increased carbon dioxide in the atmosphere, it is also important to note that there are various other gases that may have an impact on global temperatures. In the 19th century, chemists were highly intrigued by the composition of the Earth's air and strived to isolate its specific elements. Yet, it was not until the 20th century when a group of gases known as trace gases, were discovered and found to be involved in the greenhouse effect and other toxic implications (Marini-Bettòlo, 1986). Trace gases today in the atmosphere include dimethyl sulphide (DMS), ammonia, methylamines, organo-halogens (e.g. bromomethane), some volatile trace metals (e.g. mercury, selenium, antimony), and a few persistent organic pollutants (Pacyna and Hov, 2002). Despite the fact that these gases only occupy a combined 1% of atmospheric composition, the subgroup of greenhouse gases are known to be the most important because of their impact on the Earth's climate. Greenhouse gases such as carbon dioxide, nitrous oxide, ozone, and water vapour are involved in the changes within the atmosphere. These changes led to a number of environmental issues such as photochemical smog, toxic air pollutants, and acid rain (Ma et al., 2012). The focus in the scientific community today is based around understanding how these trace gases go into the atmosphere and which factors contribute to this. One of the reasons is attributed to anthropogenic events.

Anthropogenic Events

The burning of fossil fuels and biomass produces a lot of pollution due to the formation of elements of gas and aerosol phases (Devyatova and Yurkevich, 2013). This interaction between humans and the environment occurs worldwide and is hypothesized as a fundamental reason why global temperatures have been steadily rising. In addition to this, anthropogenic activity (i.e. industrialization, urbanization) greatly influences the exchange of trace gases between the ocean and the atmosphere. Numerous scientists are focusing their efforts on sea-air fluxes because oceans provide a source for many of the trace gases present in the atmosphere (Pacyna and Hov, 2002). These studies are based on the fact that oceans act as a heat sink for these gases. Two processes mediating this transfer of gaseous elements into the atmosphere are molecular diffusion and turbulent mixing (Pacyna and Hov, 2002). The latter of the two is more significant to trace gases because of the decrease in distance to the interface which exists between air and water according to Pacyna and Hov. Measuring the amount of a specific trace gas in the atmosphere is accomplished through various techniques. These range from using a Fourier transform spectrometers to an ion mobility spectrometer to measure gas phase compounds present in air to determine the quantity of a specifc gas (Viitanen et al., 2011).

Coastal Regions

New ideas are being proposed to suggest that coastal regions have an equal or even bigger contribution to trace gas composition of the atmosphere. Evidence to support this claim stems from the reasoning that anthropogenic activity affects coastal regions more so than larger bodies of water (Pacyna and Hov, 2002). An example of this can be seen in studies conducted by European research programs that focus on the role of continental margins in the transfer of gases between air and sea through biological organisms (Wollast and Chou, 2001). The resultant carbon based deposits are much more predominant in coastal regions. A similar relationship is observed for depositional events triggered by precipitation and runoff, that cause an increase in chromophoric dissolved organic matter to be delivered to coastal areas (Pacyna and Hov, 2002). These new research initiatives are advancing the current knowledge of how trace gases are transported in the first place and how they are mediated to standards. Further research into this matter will have to be done through a multidisciplinary approach because the factors affecting trace gas elements in water bodies are also related to socio-economic issues.

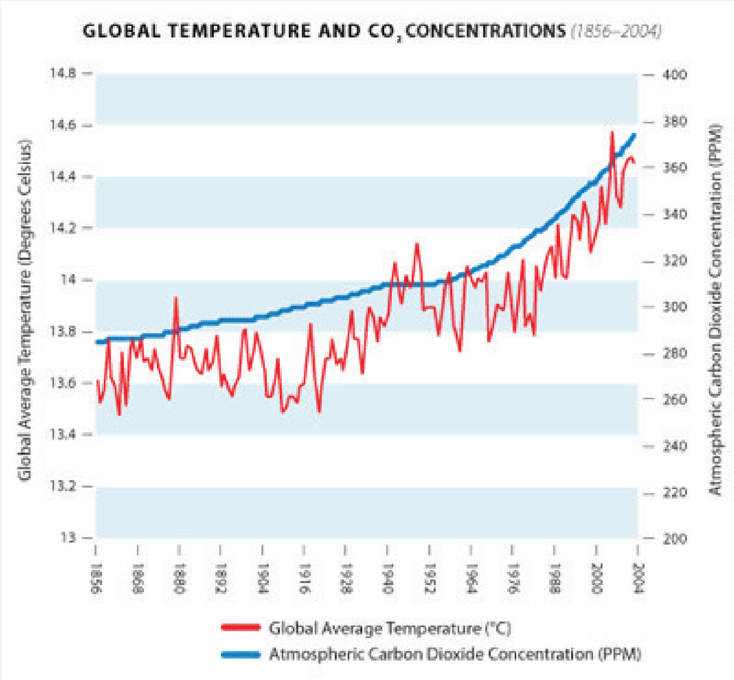


Figure 1.28. The graph depicts the steady rise in both global temperatures and atmospheric carbon dioxide concentration from 1856-2004.

Next Steps

Spending time on this issue, as well as discovering the processes and factors by which trace gases accumulate in the atmosphere is very important because efforts in reducing pollution around the world will emerge directly from new discoveries in this area. Countries such as China who rely heavily upon industrialization as a means to boost their economy have been facing a decade of severe photochemical smog and haze pollution as a result of increased ozone accumulation in the atmosphere (Ma et al., 2012). Situations similar to these Chinese environmental issues are the reasons why scientists are focusing a lot more of their time on this issue, and are testaments to the importance of understanding trace gases within the atmosphere.

Agaricocrinus americanus of the Paleozoic era

“It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is the most adaptable to change”

CHARLES DARWIN

Chapter 2: Shaping Life As We Know it

One of the most spectacular and unlikely events that has occurred on our planet is the development of life. But how did the story of life begin? Perhaps it originated in a hydrothermal vent at the bottom of the ocean, or perhaps on a meteor arriving from space. Regardless of how life began, what is certain is that through every stage of life, the Earth and its geologic processes have played a critical role in its progression. Today, species including humans permeate the globe and have adapted to fill every niche imaginable.

There are perhaps two periods of time most critical to the development and dispersion of human life. The first is the Cambrian Explosion of the Paleozoic, where multicellular life first began to take the great diversity of forms we see on Earth today. From this diversification sprang the many necessary predecessors to human life. The second is the development and spread of humanity itself, during the Pleistocene epoch. Climatic factors, coupled with the opening of new niches, provided the evolutionary pressures that initiated the rise of modern humans from more distant mammalian ancestors. Eventually, these humans would move to inhabit every region of the Earth.

Fossils have been critical in studying both of these events; they provide one of the very few windows through which to view the past. In the case of the Cambrian Explosion, one fossil bed in particular has provided key pieces of knowledge: the Burgess Shale. However, since its discovery, the Burgess Shale has bred controversy over the interpretation of its organisms and the processes which may have created them. Similarly, the first hominid fossil discovered was hotly debated before being accepted as a precursor to humans.

A recurring theme in paleontology is the difficulty associated with interpreting new information from a fragmented and imperfect fossil record. This has resulted in a scientific history rich with competing theories, unanswered questions, and periods of intense debate. In the pages that follow, the discoveries and controversies associated with the Cambrian and Pleistocene periods are examined.

The Cambrian Explosion: 200 Years of Debate

The Cambrian Explosion refers to the rapid rise of multicellular life that occurred 542 million years ago, signifying the transition between Neoproterozoic and Paleozoic Eras (see Figure 2.2). The first notion of what would later be named the Cambrian explosion was explored by geologist William Buckland in 1837, as an example of scientific based evidence of creation. That a reverend would seek to defend his views via science may seem odd to some, but is perfectly reasonable in context of the early 1800s. For most of the past 2000 years, the Bible has been interpreted literally (Prothero, 2007). It wasn't until the scientific revolution, which began in the 16th century, that science began to be accepted as a rival to theology among intellectuals. Following this, a second shift occurred during the Enlightenment, where science gained acceptance as the method for determining truth. The first of these shifts was rooted directly in scientific successes. Among the most important of these include the rise of heliocentricity, a deeper understanding of human anatomy and circulation, as well as the birth of the scientific method (Fitzepatrick et al., 2004). Inspired by the explanatory power of science, outspoken philosophers began to champion empiricism and reason. In employing this new framework for thought, many had issues interpreting the Bible and religious doctrine. John Locke and other prominent intellectuals began to advocate a reduced interpretation of the Bible (Locke, 1824). What followed was a strong shift away from biblical literalism, and a general weakening of the perceived position on the Bible (Prothero, 2007).

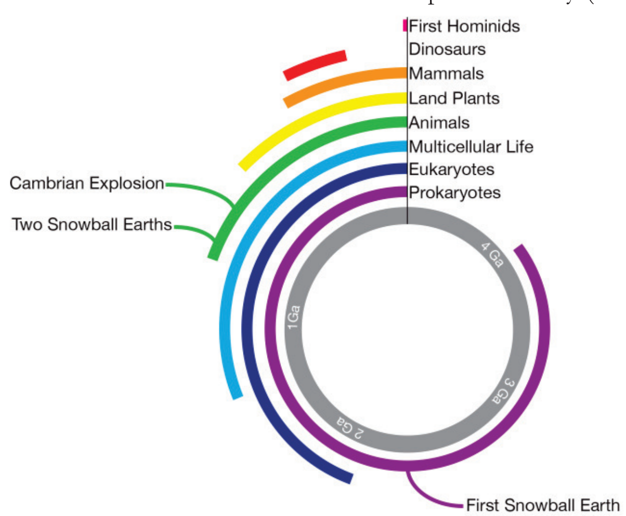


Figure 2.2. A projection of Earth's history and the diversification of life over 4.5 Ga.

As science usurped theology, some believers undertook the task of reconciling the two. One man caught in the middle of this conflict was William Buckland (1784-1856). A geologist educated at Oxford, Buckland was commissioned by the Earl of Bridgewater to write a novel that married recent geologic findings with a literal interpretation of the Bible (Gordon, 1894). One point of much contention was the age of the Earth. Buckland stood by the conclusion that the Earth is drastically older than the age commonly cited by Christianity. However, he amends this by positing there was a large gap in time between "those actions performed at the beginning" and those "performed in a number of days." In his quest for the remnants of creation, he stumbled on the finding that "ancient marine animals occur in the same division of the lowest transition strata with the earliest remains of vegetables." This apparently spontaneous appearance of life – both animal and plant – fit Buckland's criteria for a creation event (Buckland, 1836). While it had not garnered the bombastic title we know it by today – this mention marked the Cambrian Explosion's debut in academia.

The rapid appearance of complex fauna in the Cambrian fossil record was also a significant contributor to Charles Darwin's doubt concerning his theory of evolution by natural selection in the late 1850s (Gould, 1989). The appearance of these skeletal remains put Darwin's well-accepted theory of evolution into question; there was no evident transition period pre-dating the fauna of the Cambrian time (Morris, 2006). Darwin viewed the explosion as a reflection of the inaccuracy of the fossil record. He believed all evidence of a rich Precambrian period was not represented in the geological record due to the specificity of environments needed for proper fossil preservation(Gould, 1989). In 1859, Darwin acknowledged the views of geologist, Sir. R. Murchison, in his book *On the Origin of Species*. The anti-evolutionary geologist was "convinced that we see in the organic remains of the lowest [Cambrian] stratum the dawn of life on this planet" (Darwin, 1859). The clash of evolutionists and Creationists was a consistent theme until the discovery of a rich Precambrian record 50 years ago (Gould, 1989).

The first discovery of a rock sample that provided evidence for unicellular life came from Stanley Tyler and Elso Barghoorn in 1953 who found fossil-containing chert in two billion year old rocks in Canada. The presence of sediments that are indicative of organisms paved the way for many more discoveries, eventually dating life back 3.75 billion years (Prothero, 2007). Although the oldest sedimentary rocks were altered by extreme heat and pressure 3.75 billion years ago, radiometric dating of these sediments can provide insight into the potential for organic activity. The discovery of such rocks in the Precambrian record, however, resulted in further complications concerning rates of diversification. Single-celled organisms dominated the Earth for 2.4 billion years after the earliest sediments were dated. Eukaryotes followed in their wake and are represented in the fossil record 1.4 billion years ago. However, the time span dividing the first eukaryotic cell and complex multicellular life forms is far longer than the period of multicellular triumph since the Cambrian explosion (see Figure 2.2) (Gould, 1989). This posed a new challenge for paleontologists and evolutionary biologists alike. Why was there no evidence of a gradual rise to complexity, as Darwin would have predicted?

It was not until 1967, with the discovery of soft-bodied Ediacaran fossils (see Figure 2.3) in Newfoundland by Indian geologist S.B. Misra that the idea of Precambrian multicellular life gained acceptance (Misra, 1969). These fossils were encased in volcanic tiff, which preserved the soft-bodied organisms in detail (Gould, 1989). Despite these significant findings, a complete solution to the Cambrian Explosion did not lie within these sediments. This led scientists to investigate major geological processes and ecological events to better explain the rapid rise to complex multicellular life.

In 1968, Preston Cloud became the first prominent scientist to speculate about a possible relationship between evolutionary eruption and changes in the environment. Preston Cloud was a scientist in the US Geological Survey who studied banded iron formations (BIFs) in an attempt to reconstruct the environmental conditions present on Earth during the Precambrian era (Levinton, 2008).

Cloud then proposed the idea that primitive microorganisms relied on Fe2+ as a final electron acceptor. This theory therefore explains the pattern of BIFs; when concentrations of Fe2+ were high, photosynthetic oxygen was able to react with Fe2+ to form a precipitate as evidenced by the red bands. At times of low Fe2+ concentrations, the population of photosynthetic microorganisms declined, which is represented by grey banding patterns and the exclusion of biological matter within these layers (Konhauser et al., 2002). Cloud sought to apply his understanding of BIFs to better understand the chert found in the rocks of southern Ontario by Stanley Tyler in 1953. He believed that the presence of microorganisms was strongly correlated with BIFs (Cloud and Licari, 1968). From 1963-1965, Cloud searched for similar occurrences in rocks of the Biwabik Iron Formation, which were perceived to be equivalent to the formations observed by Stanley Tyler. Cloud found a correlation between BIFs and nannofossils that represented biological activity. This relationship suggested that the presence of oxygen directly influenced the potential for life forms (Cloud & Licari, 1968). Cloud then applied his findings to that of the Cambrian Explosion, suggesting that a major oxygenation event would have been crucial in the development of complex multicellular life. However, Steven Stanley (1995) argued that more evidence was necessary in order to draw such significant conclusions about the geological events preceding the Cambrian Explosion (Stanley et al., 1995). Stanley supported the notion that a relationship between oxygen and biological processes existed, but pushed for a more specific explanation for the Cambrian events (Stanley et al., 1995).

Figure 2.3. Dickinsonia costata, a soft-bodied Ediacaran organism.

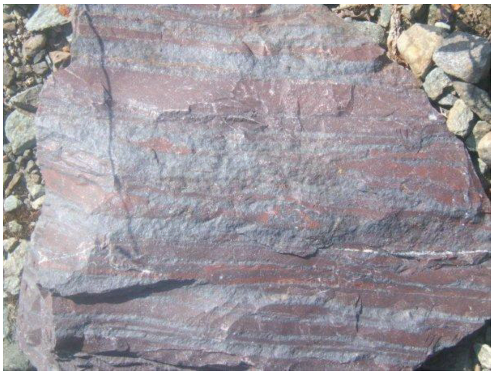


Figure 2.4. Preston Cloud used BIFs to support his idea that a relationship existed between biological processes and oxygenation events

Don Canfield, Simon Poulton, and Guy Narbonne (2006) applied the concept of using BIFs (see Figure 2.4) to assess past geological conditions in Neoproterozoic sediments found in Newfoundland. These sediments, located in the Avalon Peninsula, preserved 15 million years of Neoproterozoic time; these sediments span a period of glaciation and explore the implications of glacial melt on ocean oxygenation (Canfield, Poulton and Narbonne, 2007). The appearance of Ediacaran fauna in the fossil record coincided with the retreat of Gaskier glaciers 580 Mya (Glaessner, 1984). This is represented in the fossil record, as Ediacaran fauna only become present 5 million years after the glacial terminus was represented in the sedimentary layers. Canfield and his colleagues extracted successions of these sediments and analyzed the ratio of highly reactive iron to unreactive or inert iron. A high ratio, one that is above 0.38, indicates anoxic oceanic conditions. Conversely, ratios below 0.38 indicate oxygenation within the water columns of the ocean. The discovery of rocks with this ratio could indicate the necessary conditions to support multicellular life (Canfield, Poulton and Narbonne, 2007). Canfield et al. reported that diamictite deposited by the Gaskier glaciers show iron ratios far exceeding the lower limit of 0.38. This indicates that during the deposition of glacial sediments in the late-Neoproterozoic, levels of oxygen in the water columns were low. Sediments that were analyzed from the 15 million year period immediately after the Gaskiers glaciation, however, told a different story; the ratios were virtually all less than 0.38. These values support the notion that the glaciation gave rise to oxic marine environments, which were suitable conditions for the establishment of multicellular life (Canfield, Poulton and Narbonne, 2007). In 2008, Ian Campbell proposed a different mechanism for the oxygenation of marine environments in the late Precambrian. Campbell compared the timing of known atmospheric oxygen increases with dates of zircons in large rivers worldwide using isotopic dating. He then cross-referenced this information with dates he studied in literature surrounding the formation of supercontinents in Earth's history. He discovered that peaks in atmospheric oxygen coincided with the assemblage of many supercontinents, and therefore, periods of high tectonic activity (Campbell and Allen, 2008). In particular, peaks in atmospheric oxygen coincided with the formation of Gondwana 650-400 Ma, which overlaps with the Cambrian Explosion period. Campbell then postulated that higher rates of erosion during these periods increased the amounts of available nutrients for the production of photosynthetic oxygen in marine environments (Campbell and Allen, 2008).

Once multicellular life had the potential to propagate and thrive in marine environments with higher oxygen levels, another geologic processes would have been necessary to further develop the fauna of the Cambrian. The sudden explosion of large fauna with hard parts cannot be fully understood using Cloud's methods or Canfield's sediments; a different catalyst needed to be present to induce biomineralization of fauna– seawater calcium. In 1977, Kenneth Simkiss, building on work done by Alick Jones in 1969, postulated that due to the toxicity of the calcium ion, biomineralization could have evolved in fauna as a detoxification mechanism (Simkiss, 1977). Removing calcium by precipitation is energetically favourable as compared to pumping the toxic ions out of cells. In 2004, Sean Brennan from the U.S. Geological Survey conducted experiments on 38 marine halites from the Late Proterozoic and the Early Cambrian to determine whether or not the fluid inclusions of seawater represented a rise in calcium concentrations (Brennan, Lowenstein and Horita, 2004). Brennan and his team concluded after their analyses that between 544 Ma and 515 Ma, the composition of the seawater changed as evidenced by a large increase in calcium concentrations. The geologic process that could have resulted in this large influx of dissolved calcium in marine environments is also highly debated. The spreading rates of mid-ocean ridges (MORs) have been estimated as being three to ten times faster than any rates that can be observed today.

This is interpreted as a range up to 300 mm per year in the Early Cambrian period (Brennan, Lowenstein and Horita, 2004). Changes in ocean crust production are believed to drive fluctuations in seawater chemistry due to the interaction of the new rock interfaces with surrounding cold seawater (Lowenstein et al., 2001). Shanan Peters and Robert Gaines proposed another mechanism for the increase of calcium in seawater as recently as 2012. Peters and Gaines used extensive lithological data throughout North America to determine the relationship between the formation of the Great Unconformity and the possibility for biomineralizaton (Peters and Gaines, 2012). The Great Unconformity represents a gap in the geologic record, commonly observed in the Grand Canyon, discovered and analyzed by John Powell in 1869 (Kaiser, 2011). Peters and Gaines proposed that the unconformity represents a period of extensive continental weathering and marine transgression in the Phanerozoic (Peters and Gaines, 2012). The erosion of silicate materials within these sedimentary structures affected seawater chemistry by introducing ions such as calcium and sulfate into marine environments. Sufficient erosion could have been influenced by rising sea levels, which provides a direct link to the melting of the Gaskier glaciers postulated by Canfield.

The potential for biomineralization (see Figure 2.5) could also lend evidence to another popular theory that the Explosion was fuelled by ecological changes (Stanley, 1973). Specifically, the late Precambrian marked the first appearance of herbivores (Stanley, 1976). Following this, predatory niches appeared and were populated. While the introduction of predators has been shown to increase biodiversity, this initiated a far more powerful chain of events (Janzen, 1970; Dayton, 1972). The rise of complex food webs, and the associated increase in cross-trophic interactions, introduced a huge number of novel selective pressures, accelerating evolution forward (Conway Morris, 2000). Of particular interest are predator-prey interactions, which are recorded in multiple ways within the fossil record. The early Cambrian is littered with burrows, which were likely used as protection from benthic predators (Levinton, 2008). Following this, protective skeletal hard parts became prominent (Conway Morris, 2008). In the final strata of the Cambrian, predatory drill holes are frequently found in shells of brachiopods, gastropods, and bivalves (Kelley, Hansen, 2003). These findings paint the picture of a multispecies evolutionary arms race, where novel adaptations are frequently being selected for. Such arrangements are commonly cited as driving evolution, and may have provided the selective pressures necessary to fuel the Cambrian Explosion (Dawkins, Krebs, 1979). In 2002, Nick Lane proposed a link between energy production and oxygen. He explained that in the absence of oxygen, energy metabolism is so inefficient that only ten percent of the total energy available in a food chain can be extracted. This means that if a predator eats a producer, the predator obtains less than one percent of the available energy (Lane, 2002). This model would significantly affect the evolutionary arms race hypothesis; in the absence of oxygen, food chains would be too short. When oxygen is introduced, the efficiency of the entire process is enhanced so much that six levels of trophic interactions are possible. The availability of oxygen therefore directly influences the potential for predator-prey interactions, and therefore, adaptive evolution (Lane, 2002).

Figure 2.5. Many scientists in the 21st century have attributed the appearance of biomineralization to Precambrian geological processes such as plate tectonic activity.

A review on the geological processes that could have aided evolution's big bang was recently (2013) published by Paul Smith and David Harper. One statement in particular evidences the significance of this paper: "it is unlikely that any single casual mechanism can explain the Cambrian Explosion, with many of the individual hypotheses instead acting as components of interacting feedback loops between Earth systems and biological processes" (Smith and Harper, 2013). The idea that the theories pertaining to the Cambrian Explosion are not mutually exclusive is significant and highlights the prominent idea that science is, in fact, a process.

Statistical Methods in Phylogenetic Inference

Since the concept of evolution was first articulated by Darwin, fossils have been used as the basis for determining phylogeny. That is, by studying the change in fossil morphology, paleontologists have been able to infer how life forms changed through time. Before the discovery of DNA, this relationship was held in such high regard that prominent taxonomists decreed, "without the comparative study of form, there can be no evolution" (Bower, 1926). Fossils were seen as essential in accurately deciphering evolution through phylogeny well into the 1960s. This belief is reflected in paleontologist George Simpson's declaration that "fossils provide the soundest basis for evolutionary classification" (Simpson, 1961).

Figure 2.6. Trilobites are one example of species which have had success in determining phylogeny by analyzing fossils.

Typically, fossils were sought to link ancestral forms. One classic approach was the use of stratigraphic placement of fossils to identify a species B as intermediary between A and C. This approach was supported by Thomas Henry Huxley, the president of the Geological Society in 1870, who said that if "it can be proved that [A, B, and C] occur in successively newer deposits, A being the oldest and C the newest, then … I should accept [B] without hesitation as a link in the genealogy" (Harper, Platnick, 1978).Indeed, successes in determining phylogeny by fossils have been made in certain areas of the tree of life including plants and invertebrates (Smith, 1964; Williams, 1973); (see Figure 2.6.). However, by the 1970s, biological systemists had become starkly critical of fossil interpretation. This view was championed by the well-known cladist Willi Hennig, who professed that fossils, like living organisms, are "only data in search of interpretation" (Nelson, 1978). As much less information is preserved in a fossil than is present in living organisms, Hennig saw them as poor tools in the elucidation of phylogeny (Schmitt, 2013).

Soon, even stratigraphic approaches to determining character polarity were falling under attack, on the grounds that a spotty fossil record may yield mistaken conclusions (Stevens, 1980). By 1977, well respected biologists had gone as far as saying "a new fossil has no impact on classifications" (Lovtrup, 1977). This rapid shift in opinions was due to the advent of statistical techniques in assessing phylogenies, known as phylogenetics. At the heart of this field is the understanding that evolutionary change can be detected in variation within the genetic code of an organism. By comparing changes in a given sequence or sequences, one can estimate an optimal evolutionary tree. In order to do this effectively, the DNA to be compared must be chosen conscious of the phylogenetic tree that will be created. In trees which extend further back in time, a more slowly mutating gene is desirable. The inverse is true of shorter trees and more quickly mutating genes. Another important consideration is whether one should compare nuclear DNA or mitochondrial DNA. Traditionally, the recombination that occurs in nuclear DNA has made interpretation difficult (Avise et al., 1987). This is because the meiotic process introduces apparently novel nucleotide sequences. As a result, a greater rate of genetic variation is falsely suggested and genetic similarities can be masked (Posada & Crandall, 2002). For this reason, mitochondrial DNA has historically been chosen, as it is non-recombining and effectively behaves as a single locus (Holland & Rubinoff, 2005).

However, as software for detecting recombination improves, nuclear DNA is becoming a more popular target. Nuclear DNA is useful as it exists in a great quantity within each organism and can be related to specific morphological features. This means that, in cases where species have been delineated based on changes in one or two specific features, highly relevant trees can be constructed (Popp & Oxelman, 2001). Finally, by targeting a sequence of introns where DNA is not transcribed, one can make use of the higher rates of genetic variation associated with these sequences that do not have selective pressures limiting their mutation rates (Atson, 2000).

Using this genetic data, a number of trees can be created, depicting relative genetic similarity. The task then is to optimize the tree for some metric. One of the first approaches was that of maximum parsimony. This approach, as well as the maximum likelihood approach to be discussed later, was first discussed by Anthony Edwards and Luca Cavalli-Sforza in 1964. These two innovative individuals, who had both been students of the famous population geneticist R.A. Fischer, were striving to make trees for human populations based on blood group alleles (Purivs, Gitlleman, Brooks, 2005). In their attempts to work meaningfully with this data, both depicted gene frequencies as a set of coordinates in space. From here, Edwards suggested that the best possible tree connecting them would be that which required the least amount of string (Felsenstein, 2004); (see Figure 2.7.). The value of simplicity in models has a long past, dating back to Ockham's razor which states that between competing hypotheses, that which makes the least assumptions is the most valuable (Ockham et al., 1495).

While parsimony is an attractive trait, it is not a strictly statistical method. Rather, it is a reflection of the notion that "the most correct tree is that which has the least evolutionary events" (Edwards and Cavalli-Sauza, 1964). An improvement on this method is a maximum likelihood approach (ML). Unlike parsimony, ML is a true statistical method and is derived from the laws of conditional probability (Felstein, 2004). The result of a likelihood calculation is to determine the probability that the observed data would occur, given a hypothesis. In the context of phylogeny, this amounts to calculating the probability that an observed set of substitutions would occur, given the preceding branches in a tree and an associated model for mutation rate. By finding the product of each of these probabilities for every given nucleotide site and comparing this value between trees, one can calculate the tree which has the highest chance of generating the observed genetic changes.

One final method of note is that of Bayesian Inference. This analysis has gained considerable popularity since the late 1990s. Bayesian Inference also relies on conditional probability. However, it takes the result one step further than ML; instead of calculating the probability that a given tree would lead to the genetic variation observed, it calculates the probability that a given tree is the correct one given a set of genetic data. While this statistic is the most valuable in comparing phylogenies, it's calculation requires assumptions concerning the prior odds be made (Huelsenbeck et al., 2002). That is, one must specify the probability that a given tree is the correct one before any data has been examined in order to utilize Bayesian Inference. Whether or not this can be done accurately is a hotly debated in certain circles, but is generally accepted by most (Mayo 1996).

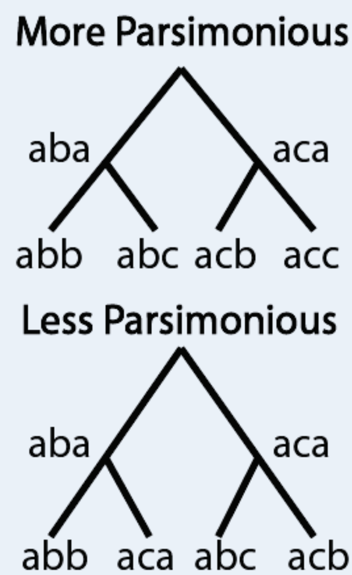


Figure 2.7. A comparison between two phylogenetic trees. The first is more parsimonious as it assumes fewer substitutions have occurred.

Beyond enriching our understanding of life's history, phylogenetics has a number of valuable applications. With a concrete description of phylogeny, one is able to imagine the environment of selective pressures acting on the population at any given time. This can be useful in reconstructing environments of the past. Conservation is another area where phylogenetic data could prove very useful (Purvis, Gittleman, Brooks, 2005). While human interaction drives extinction, certain characteristics confer additional extinction risk to species (Purvis et al., 2000b). One such example is a larger home range (Woodroffe & Ginsberg, 1998). As this susceptibility originates from traits which can be mapped to phylogeny, evolutionary trees may be able to predict species at higher risk of extinction, allowing for the better allocation of conservation resources. An opposing process in conservation is that of invasive species. As our world becomes increasingly global, the rate of non-native species becoming established in new environments has also increased (Mack et al., 2000). However, not all non-native species will become invasive. Large steps have been taken in identifying characteristics which promote invasiveness (Kolar & Lodge, 2002). As with extinction risk, many of these traits are heritable, and so may be predicted through phylogenetic analysis.

A History of the Burgess Shale: Morphological Identification

The Cambrian Explosion marked the beginning of a time when large, complex, multicellular life forms arose from the prokaryote-dominated Earth. A wide range of organisms, triggered by rising sea levels, increased erosion, and changes in atmospheric composition, formed at this time, resulting in an era characterized by the highest biodiversity in all of Earth's history (Smith and Harper, 2013). Though these creatures exhibited features mirroring modern phyla, the remaining constituents of their forms were so alien and unique to their time that nothing similar has been found since. Nowhere are the perplexing features of these animals better displayed than the Burgess Shale, where these strange organisms are preserved with exquisite detail and completeness. Debates about the appearances of the creatures of the Burgess Shale have existed since its discovery, and continue to today.

Before the Shale

The discovery of the Burgess Shale was the result of a string of events that begun in 1886 with the continued developments of the Canadian Pacific Railway, which was nearly finished at the time (Lamb, 1977). Along its passage through south-eastern British Columbia, near Mount Stephen, a massive deposit of trilobites preserved within shale now known as the Trilobite Beds was found (Ludvigsen, 1996). Trilobites have been long known to science, and were first discovered in 1698 by Edward Lhwyd and interpreted as the skeleton of a flat fish, and by the 1880s they became a well-known organism actively studied by geologists. Like all fossils, new specimens were continuously sought, and it was this interest that ultimately sparked the discovery of the Burgess Shale. Two individuals are independently credited with the discovery of the Trilobite Beds. One was the astronomer Otto Klotz, working for the Department of the Interior to determine the path of the railway using astronomical measurements to determine its co-ordinates (Jarrell, 2005). Klotz was also an amateur geologist, and collected trilobite samples at these beds. He also named Mount Burgess after the Deputy Minister of the Interior (Jarrell, 2005). The other was the geologist Richard McConnell, who also worked on the railway as a geological surveyor sent by the Geological Survey of Canada (Collins, 2009). He was alerted to the deposit of fossils on Mount Stephen by his workers, and went to collect samples. Upon the discovery of these beds, it became an attraction for many other geologists as a prime location for the surveying and collection of fossils, and as such was the trigger that led to the finding of the Shale.

Even before the official discovery of the Burgess Shale, its existence was already hinted at through a few strange specimens found in the area (Collins, 2009). Parts of *Anomalocaris canadensis* and *Orthotheca corrugata* were key discoveries that were recognized in later years. By studying a sample collected by the Geological Survey of Canada, Joseph Whiteaves described and named *A. canadensis* in a paper published in 1892. Unfortunately, Whiteaves only had the feeding appendages, a portion of the whole organism. He interpreted this segment as a type of shrimp from the segmented shape of the fossil, and thought its legs and head was badly preserved. The genus name *Anomalocaris* reflects this early interpretation, and is from the Greek ἀνώμαλος *(anomalos)* and καρίς *(karis)* meaning "strange" and "shrimp" respectively. Thus the name, reflecting the headless shrimp appearance of the fossil, was coined (Collins, 2009). Another paper was published on what is now known as a partial fragment of spine form *Wiwaxia corrugata* by George F. Matthew in 1899. Along with some other non-trilobite samples from Mount Stephens, Matthew described a thin, ridged, tapering specimen and named it *Orthotheca corrugata*, interpreting the organism as an annelid. Both of these early classifications would be investigated again with more complete specimens unearthed from the Shale.

Discovery and Early Contributions

The discoverer of the Burgess Shale, Charles Doolittle Walcott (right), a notable geologist and palaeontologist, started his fieldwork around the Rockies in the early 1900s (Yochelson, 1967). He was attracted to the Mount Stephen area by McConnell's reports on trilobites, and visited the newly established Trilobite Beds in 1907. He revisited the area in subsequent years, and in 1909 searched nearby mountains for more fossils. At the foot of the ridge between Mount Field and Wapta Mountain, he discovered talus deposits, a product of the weathering of the Shale, which quickly captured his interest with its unusual organisms (Yochelson, 1967). In the next year, he visited the area again, and found the shale layer, which is the source of these organisms, higher up the mountain. A small quarry, now known as Walcott Quarry, was excavated there. After this discovery, Walcott and his family would revisit this location regularly during the summer field season to collect more specimens.

One of the first organisms Walcott described and published was *Sidneyia inexpectans*, in a paper in 1911. This curious specimen, whose name meant "Sidney's discovery", was named after his son, who found the fossil (Collins, 2009). Walcott presented the specimen as a drawing with a fossilized claw that was also found at the quarry. This composite was used to create a reconstruction of *S. inexpectans* by Lancaster Burling in 1917. Though both fossils used in the drawings were from the same time period, they proved to not be from the same organism. In the same paper by Walcott in 1911, he described and classified the organisms *Peytoia nathorsti* and *Laggania cambria*. *P. nathorsti* was described by Walcott as a jellyfish in the adult stage, while *L. cambria* was classified into its own genera as a new organism bearing a roughly circular mouth surrounded by plates. *L. cambria* was reclassified a sponge by Simon Conway Morris in 1978, with the mouth reinterpreted as another specimen of *P. nathorsti* that was preserved on top of the sponge by chance. Walcott's initial interpretation of *L. cambria* proved to be more accurate, and along with Whiteaves's shrimp, it was classified as a marine predator that kept the name *A. canadensis* (Wittington and Briggs, 1985). Walcott went on to collect and catalogue more than 60 000 fossils from the Shale in subsequent years, but his collection and work were largely forgotten after his death for almost forty years.

By the 1920s, the Burgess Shale was widely known throughout the scientific community. Walcott attracted another geologist to the area, Percy Raymond (Ludvigsen, 1996). While both Walcott and Raymond conducted fieldwork and accumulated extensive collections of Shale fossils, Walcott merely described his specimens in contrast to Raymond who tried to reconstruct the once living organisms. Raymond reopened Walcott Quarry in 1930 and also started another quarry of his own further up the mountainside, now known as Raymond Quarry. He published papers on reconstructed organisms such as *Leanchoilia superlata* and *Marrella splendens* in 1935. Despite Raymond's subsequent contributions to the investigation surrounding the Burgess Shale, his collection was largely ignored by the scientific community, along with Walcott's.

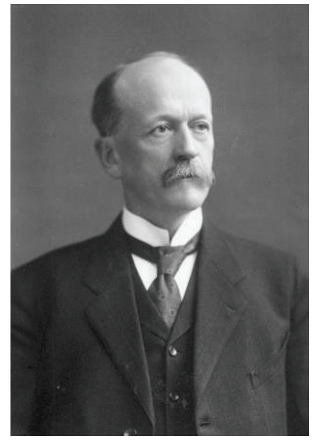


Figure 2.8. Photograph of Charles Doolittle Walcott from the 1900s.

H. B. Whittington

Of the many palaeontologists affiliated with Burgess Shale, there is perhaps no one more significant than Harry Blackmore Whittington. Whittington's research on the Shale started around 1967, and has contributed greatly to understanding the morphologies of a variety of these creatures, especially trilobites (Whittington, 1985). Whittington noticed that among the Shale, not only hard-bodied fossils could be found as in the rest of the world, but soft-bodied organisms as well which were unique to the area. The proportions of soft versus hard-bodied organisms within the Shale suggested that soft-bodied organisms were vastly dominant in terms of population size, but the ratio of genera are consistent with modern day fauna around continental shelves (Morris and Whittington, 1979).

Whittington also noticed through his various studies among the many fossils of the Burgess Shale that their feeding methods are synonymous with today's marine organisms. Of these, the most notable are the ingestion of water-suspended particles by brachiopods, sponges, and *Dinomischus*; the ingestion of organic particles within mud by the *Naranoia*, as shown by consistent specimens with mud in their gut; predation by *Olenoides, Sidneyia, Ottoia*, and *Anomalocaris*; and scavenging by a variety of arthropods (Whittington, 1985). These findings show a continuity of feeding mechanisms that have survived through a multitude of significant environmental and ecological changes in the last 530 million years and support the success of these methods.

Whittington was not ignorant of the fact that the Burgess Shale held unique organisms and gave unparalleled insights into life at that time. While many palaeontologists believed that the fossils of the Shale occurred as the result of a strange and isolated environment, Whittington was one of the first to suggest that it was not the fossils that were strange, but rather the depositional environment that led to the preservation of soft-bodied organisms in what is known today as the Burgess Shale (Whittington, 1980). This paradigm shift also suggested that the organisms of the Shale were common of the era. Whittington also proposed that the organisms of the Shale only inhabited Laurasia, as there are no preservations to suggest the opposite, but that similar soft-bodied organisms inhabited the rest of the world. The basis of this thought was the multitude of modern soft-bodied organisms that could not be morphologically related to any Shale ancestor, and that the extremely rare preservation of soft-bodied organisms in later periods were as different to those of the Shale as they are to those of today (Whittington, 1980).

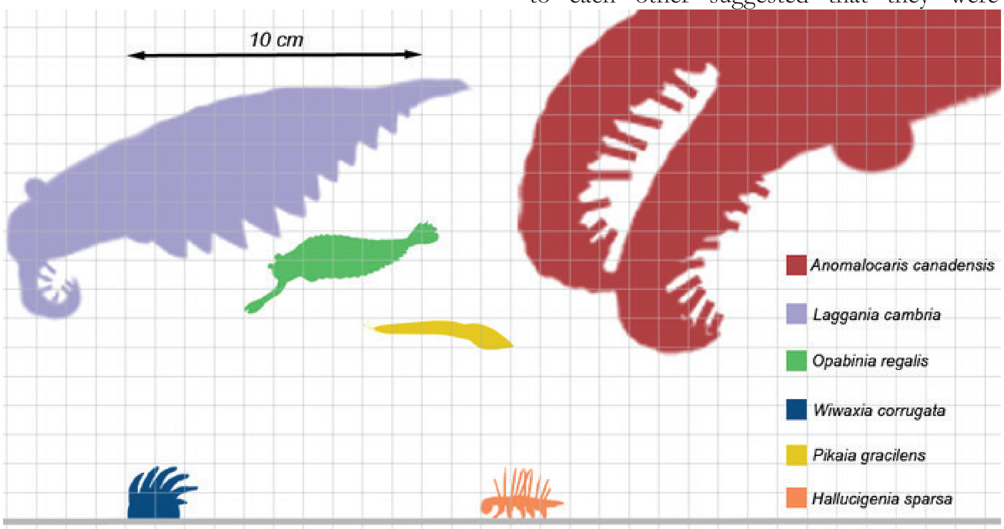


Figure 2.9. Scale comparison of organisms from the Cambrian Explosion. The organisms of the Burgess shale had various sizes and physiologies, and had little resemblance across species.

What is known today as the "Cambrian Explosion" originated early on from Whittington's observation about the numerous fossil physiologies of the Burgess Shale. He found that while a portion of them fit into modern phyla, the majority did not (Whittington, 1985). Furthermore, not only did these miscellaneous animals vastly differ from modern phyla, they were dissimilar among themselves (see below). The notion that these organisms had little resemblance to each other suggested that they were separate, unrelated groups of species. This all led to the question that would spur decades of research and debates: why is there such a diverse range of physiologies between ancestral species and these organisms? This is the key to understanding the Cambrian Explosion, which today, still has no definite answer.

Whittington's legacy continues with his graduate students, Simon Conway Morris and Derek Ernest Briggs, both of which upheld his name and became giants of palaeontology in their own right. While Briggs's research is fundamentally an extension of that of Whittington's, Conway Morris made significant leaps in the interpretation and elucidation of the Shale (Fortey, 2012).

S. Conway Morris

Of the many works of Conway Morris, perhaps the most insightful is his book *The Crucible of Creation,* written in 1998. While Conway Morris's work largely mirrors that of his mentor Whittington, their interpretations of the Burgess Shale are vastly different.

Whittington saw the Shale as a peephole into the Cambrian world, finding a variety of bizarre fossils that did not fit into modern phyla (Whittington, 1985). This laid the framework for the Cambrian Explosion theory. Conway Morris, however, saw a dichotomy between these species as macro-evolutionary jumps (Conway Morris, 1999). He found that the Shale shed new light on the mechanisms and implications of evolution, which was a recent theory at the time without a fully understood mechanism. For Conway Morris, the Shale served as a set of body plans that could be compared to modern ones, which turned out to be critical to the theory of evolution as known today. Charles Darwin's original theory looked at specific cases where slight mutations combined with natural selection rendered slightly different organisms that would fulfill a niche and become a new species, as seen in the Galapagos finches (Darwin and Mayr, 1964). The Shale, as seen by Conway Morris, was comparable to the ancestral finch, whose progeny specialized in relation to their environments slowly over millions of years to yield modern phyla.

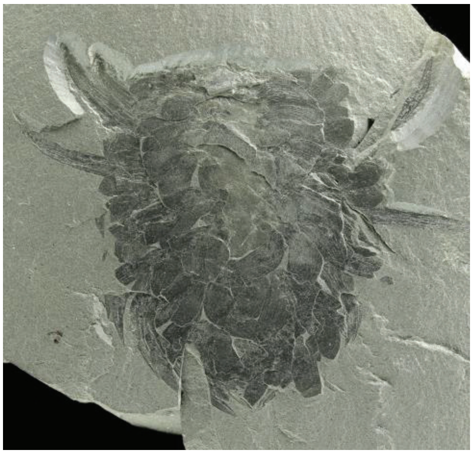


Figure 2.10. Fossil of Wiwaxia corrugata from the Burgess Shale. Sclerites can be seen on dorsal.

This profound view led to the development of Conway Morris's interest in the origin of body plans, which would be the focus of his career in later life. Conway Morris attributed the origin of body plans as seen in the Cambrian Explosion to predatory diversification (Morris and Whittington, 1979). As predators became more efficient at preying through natural selection, organisms of the Cambrian developed natural defenses in response. Conway Morris noticed peculiar boreholes in the bodies of *Cloudina* fossils, and presumed that this was a result of a predatory event to ingest the inner soft tissues of *Cloudina* (Conway Morris, 1999). This would have led, as Conway Morris suggested, to the development of exoskeletons using calcium carbonate, which was abundant in the marine environment at the time. *Hallucigenia* and *Wiwaxia,* two prominent organisms Conway Morris worked on supported this hypothesis as intermediaries with spines and sclerites but not a full exoskeleton (Conway Morris, 1999).

Another important feature that was presumably developed at this time was wound healing mechanisms. A variety of trilobite fossils found by Conway Morris were shown to have bite marks on their bodies, which would have been fatal without the development of wound repair (Conway Morris, 1999). The gradual development of wound repair would have stemmed from non-lethal attacks, namely those not to the head or vital organs. Thus organisms with repair mechanisms would out-compete their irreparable brethren, and wound repair would become a major component of modern phyla. In addition, a census of bitten trilobite fossils in Conway Morris's time showed that the majority of bites occurred on the right side of the trilobite (Conway Morris, 1999). This suggests that either their predator, or the trilobite themselves, had a dextral preference.

Conway Morris devoted his later life to studying the body plans of organisms, that is to say, the similarities in physiologies of modern and Cambrian phyla to determine ancestral groups that would give rise to classes of animals seen today. Conway Morris reasoned that these body plans would transcend phyla as a method of classification for fossils discovered in the future (Gee, 2000). This utilitarian approach stems from Whittington's own observations of Cambrian organisms not fitting into modern phyla. Conway Morris paid particular attention to *Wiwaxia,* which did not fit into any modern groups of phyla.

Wiwaxia (see Figure 2.10) was thought by Conway Morris to be the ancestor of all mollusks, and the quintessential molluscan body plan (Conway Morris, 1999). While modern mollusks are widely varied, a portion of them, namely gastropods, are similar to *Wiwaxia* in that they both have protective skeletons and a soft underbelly which serves as a creeping muscular foot. In the case of *Wiwaxia*, the shell is composed of several skeletal plates called sclerites, as opposed to the shell of modern gastropods, which is of one single piece. The gastropod physiology is considered to be the most ancient of all mollusk structures due to its placement in the fossil record (Conway Morris, 1999). In addition, the jaw of the *Wiwaxia* bears similarities to the radula, the mouth of the modern mollusk. While both these points by Conway Morris were valid, the key to the relationship between *Wiwaxia* and modern mollusks was determined by a man by the name of Nicholas Butterfield. Butterfield isolated the sclerites of *Wiwaxia*, and using microscopy, found their microstructure to be of thin, parallel slices (Conway Morris, 1999). This was found to be the same as other mollusk-like fossils, and of modern mollusks themselves. Thus the *Wiwaxia* were shown to be similar to ancient and modern mollusks, suggesting the ancestral relationship of *Wiwaxia* to the molluscan group.

Conway Morris's contribution to the understanding of the transition between Cambrian and modern organisms paved the way a new generation of geologists, palaeontologists, and zoologists to classify novel fossils using the body plan method. His early thoughts on the mechanisms leading to the explosive radiation of species during this time set the stage for new investigations into the causes and mechanisms behind the Cambrian Explosion. While they did not know it at the time, Conway Morris, like Whittington before him, ushered in a new field for modern palaeontologists, which is still full of vigour today.

The Preservation of Soft-Bodied Fossils

Fossils are a key component of understanding the Earth's biological history in modern times. While understanding the structures and functions of fossils contributes to the main area of paleontology, understanding the process of fossilization is key to understanding the differences between the organism in life and in death. The preservation of fossil material is largely dependent on the resistance of the material to decay.

As diagenesis of organics to rock and minerals typically takes much longer than decomposition, organisms are not usually fossilized as decomposition occurs much too quickly for remains to be transformed into a preservable state (Briggs, 2003). As a result, environmental conditions that can slow or prevent decomposition are essential to fossil formation. Organic materials vary in their resistances, with those more resistant tending to be structural macromolecules that are tougher to break down. Through diagenesis, these structures can then be transformed into more stable long-chain hydrocarbons (Stankiewicz et al., 2000). Preservation of less resistant organic material typically requires rapid replacement by minerals, processes that can be driven by bacteria involved in decay. Precipitation of minerals on tissue or microbial film allow for the preservation of less resistant tissue (Martin et al. 2004). This mineralization may be localized to a certain part of the organism, which allows previously less resistant tissue to be preserved even when later conditions cause more resistant parts to deteriorate. Overall, diagenesis is crucial to the preservation of organisms.

Soft tissues are typically preserved by permineralization, where mineral bearing water infiltrates tissues and replaces the organic material chemically (Schopf, 1975). This process happens gradually as decay occurs and opens up space for minerals to grow. Authigenic mineralization is another very similar biological process where bacteria facilitate the movement of minerals from the surrounding sediment into the decaying organism (Sagemann et al., 1999). Some minerals are produced by the bacteria through anoxic respiration. This usually creates a more accurate replication of morphology. These two processes of permineralization and authigenic mineralization are key to soft body fossil preservation.

The Burgess Shale is an exceptional location which contains abundant soft-bodied fossils. Since its discovery, similar deposits of soft-bodied organisms from the Lower and Middle Cambrian have been identified across the globe (Hagadorn, 2002). All of these locations share similarities in both the preservation methods and depositional environment. Rapid burial of the organism in silts and muds was common. The organisms found usually lived in deeper marine environments, in areas that were below the storm wave base (Robison 1991). In the Burgess Shale in particular, the organisms lived at the edge of a submerged reef now known as the Cathedral Escarpment (Parker, 2003). The flow of muds down the underwater cliff created by the reef wall created periodic rapid turbidity flows that buried the organisms almost instantaneously. This deep marine depositional environment lacked environmental disturbances such as waves and the low oxygen content was not conducive to burrowing organisms, avoiding bioturbation as reflected in the finely laminated shale without trace fossils. Together these conditions allowed for the exquisite preservation of the organisms.

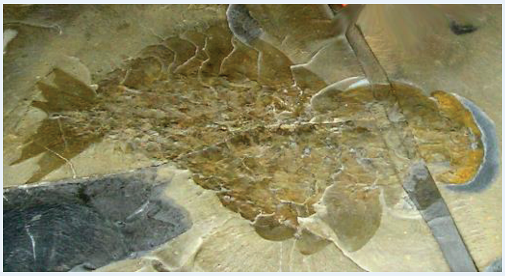


Figure 2.11. Fossil of Anomalocaris canadensis preserved through carbon and aluminosilicate films (Butterfield, 2007).

In the Burgess Shale, soft tissues are preserved as both carbon and aluminosilicate films (Butterfield, 2007) (See above). The carbon films are organic in nature, being composed of carbon material that originally made up the organism's tissues and was chemically changed through diagenesis. The aluminosilicate films come from permineralization of organic material by minerals in the clay within which they were buried. Minerals such as quartz and kaolinite are able to stick to biological tissues as they break down, preserving an impression of the organism in the shale (Martin et al. 2004). These minerals could have also replaced earlier films of carbon or other materials depending on post depositional conditions.

Due to changes induced in a specimen through the preservation process, the morphology of preserved organisms must be carefully interpreted. Different rates of decay of tissue may displace the position of organs, or leave some parts of the organism intact while losing others. Thus identification should take into account shrinkage of tissues and the likelihood of certain organs to survive (Briggs, 2003). Preservational biases do not only have effect within organisms, but between organisms as well. Soft-bodied organisms are much less likely to be preserved than hard bodied organisms, thus skewing modern interpretations of ancient ecosystems. The preservation of soft tissues on fossils in a particular location can be used to determine the amount of loss due to environmental processes (Allison and Briggs, 1991). The dimensionality of the fossil can also be important. 3-dimentional fossils could indicate rapid mineralization and more complete preservation, while 2-dimentional fossils may indicate slower preservation during which overlying sediments were able to compact the remains before preservation (Briggs and Kear, 1993).

Preservational biases can even occur across time periods on the geologic timescale. Fossilization favours certain periods in which particular environments or ecosystems were widespread (Briggs, 2001). While the proliferation of decomposers, scavengers, and burrowing organisms discourage preservation, periods of sudden episodic sediment influx can create an abundance of preserved organisms. These biases do not stay constant through time; instead they change as ecosystems evolve. While more ancient eras favoured preservation within calm deep marine settings more recent time periods favour lacustrine environments due to their high sediment input (Allison and Bottjer, 2011). Fossils are a window into life's history going back millions of years, and for many of the organisms that have come and gone long before today, these are the only records of their existence.

Pathway Through the Pleistocene

Out of the countless species that exist or have existed on planet Earth, few are as complex as modern *Homo sapiens*. Perhaps fittingly then, the story of human evolution is one riddled with unexpected surprises and controversies.

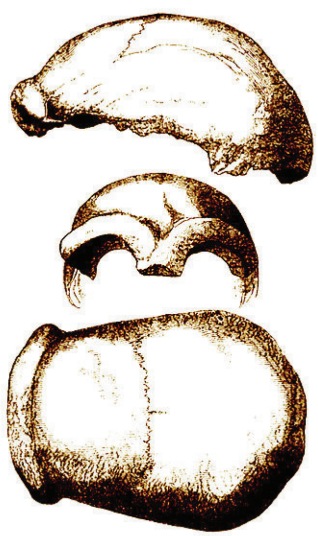


Figure 2.11. Drawing of Neander 1 Skull. This is the first hominin fossil ever discovered. Recognized as an ancient human skullcap by some intellectuals, and as a modern, diseased individual by others, this skullcap triggered an intense debate that marked the beginning of paleoanthropology.

For much of human history, knowledge of human origins had been deeply ingrained in religion and creation myths. In particular, much of early western thought was based on Aristotle's (384 BCE-322 BCE) observation that there was order in nature, and that species were fixed in the form in which they were created (Tattersall, 2009). By the 19th century, enough fossil evidence had been found to suggest that extinctions had occurred, and that species had changed from what they once were. With the publication of Charles Darwin's famous *On the Origin of Species* (1859) and the introduction of natural selection, the idea that humans had descended from a common primate ancestor began to permeate the scientific community, although it was far from being accepted (Tattersall, 2009). Then the discovery of a few inconspicuous bones changed the world forever.

Initial Discovery

In 1856, quarry workers discovered an ancient human skeleton in a small cave in the Neander Valley (Tattersall, 2009). This find immediately triggered an intense debate, as it had thick, bowed bones and a skullcap with a prominent brow ridge, reminiscent of the great apes (see Figure 2.11). Hermann Schaaffhausen (1816-1893), an anatomy professor who was an evolutionist even before Darwin published his famous work, argued that the skeleton had belonged to an ancient human (Regal, 2004). This was opposed by Rudolf Virchow (1821-1902), a pathologist and a non-evolutionist who proposed that the skeleton was in fact a modern human with severe rickets or arthritis. August Franz Mayer (1787-1865), one of Schaaffhausen's rivals, argued that the lack of an ape-like sagittal crest disproved that the skeleton was an ancient human. Apes had a sagittal crest on their skulls while modern humans did not, so had humans evolved from apes, Mayer reasoned that an ancient human would have the vestiges of a sagittal crest (Tattersall, 2009). A few years later, the realization that several fossils found in other regions matched this fossil led to the conclusion that it belonged to a normal, healthy individual (Regal, 2004). The discovery of this fossil marked the beginning of paleoanthropology, and as more hominin fossils were discovered, the focus of human origins shifted from simple creation beliefs to a more complex story of human evolution.

Early Thoughts

Up until the 1880s, all hominin fossil finds had been by-products of other ventures, but in 1887, a Dutch physician by the name of Eugène Dubois abandoned his medical career to deliberately search for an ancient human fossil (Tattersall, 2009). The Aryan hypothesis, or belief that modern Europeans had migrated from Asia, was the accepted theory at the time, and so Dubois set out for the Dutch East Indies (modern Indonesia), home of the orangutan. There, by the Solo River near the village of Trinil, Dubois dug a 15 metre deep trench and exposed layers of sandstone and volcanic ash. In one of these stratigraphic layers, he found a femur and a skullcap (Tattersall, 2009). At the time the only dating methods available were relative methods employing laws of stratigraphy such as the Law of Superposition, and so using the surrounding fossilized fauna, Dubois dated the human fossil as being from the early Pleistocene (Dunsworth, 2007). As the absolute date of the Pleistocene had yet to be elucidated, the absolute age of the fossil in Trinil was very much subject to interpretation.

Upon further analysis, the fossil was found to have many ape-like characteristics such as heavy brow ridges, but the most notable observation was that when comparing the femur to ones belonging to a human and a chimpanzee, the fossil had clearly belonged to an early hominin that was bipedal (Tattersall, 2009). In particular, the femur angled inward from the hip, a necessary adaptation to keep balance as the biped moved forward. The development of more accurate dating methods such as radiometric Carbon-14 dating and Potassium-Argon dating allowed paleoanthropologists to later compare the fossils and show that bipedalism had been the first trait to arise in hominin evolution (Tattersall, 2009). A suite of further fossil finds such as the famous Lucy and Laetoli footprints from Hadar, Ethiopia, confirmed this when they were shown to be 3.5 million-years-old (Leakey and Harris, 1989). The Laetoli Footprints (see Figure 2.12) are suggested to have been produced when two hominins walked on top of wet volcanic ash that was then immediately covered by another layer of ash (Leakey and Hay, 1979). In the following years, the reason for the development of bipedalism was avidly debated.

Paleoenvironmental analysis of Africa has shown that during the period when bipedalism arose, Africa experienced a great cooling and drying event, in which the forests shrunk drastically and much of Africa became an open savannah. Evidence for this event exists in airborne dust records that indicate cooler and drier times in Africa (Richmond, Begun and Strait, 2001), and also in the morphologies of other fossilized fauna such as bovids (Kappelman, et al., 1997). Additionally, in the region in which the Laetoli footprints were found, there is evidence of lacustrine and fluvial deposits that indicate the presence of an ancient lake (Taieb, et al., 1976). This probably led to a variety of adaptations that favoured bipedalism. In 1993, a physiologist by the name of Pete Wheeler showed that in the hot savannah, early hominins had to evolve a mechanism to cool their sensitive brains. Bipedalism would have been an effective solution, as an upright stance reduces the amount of solar radiation that reaches the body and allows more wind for cooling (Wheeler, 1993). Opposition to this idea came when other intellectuals argued that bipedalism was not energetically efficient when compared to quadrupedalism. However, in 1980 Peter Rodman and Henry McHenry argued that bipedalism was in fact more efficient when compared to the arboreal nature of the great apes, as they were not full quadrupeds. Although the debate over efficiency continues to this day, Owen Lovejoy suggested in 1981 that bipedalism would have freed the hands to allow early male hominins to bring food back to females that were nursing offspring. This, in turn, would have produced healthier offspring, thus selecting for bipedalism (Tattersall, 2009).

Other Developments

As intellectuals continued to debate over the rise of bipedalism and its role in human evolution, emerging fossils pointed toward other developments in the story of human evolution. The first evidence of the preparation and use of tools surfaced in the 1930s when Louis Leakey excavated Olduvai gorge in modern Tanzania. Previously, scientists that had searched for stone tools in Africa were of the belief that the tools would be made of flint, much like those discovered in Europe. Yet the region surrounding much of Olduvai gorge consisted of coarse, granular material such as basalt and quartzite, so any search for flint tools in this region was for naught. Leakey, having grown up in Africa and collected stone tools as a child, was accustomed to tools consisting of the coarse material, and he immediately recognized the tools in Olduvai gorge that had evaded other paleontologists. The tools Leakey found were next to a hominin fossil dated to be from the early Pleistocene. The fossil resembled another hominin fossil that had been previously named *Australopithecus africanus*. Leakey was of the belief that tool use indicated advanced cognitive abilities that could only be attributed to the genus *Homo*, and so he named his find at Olduvai gorge as belonging to a new species he called *Homo habilis*. These finds had been found in the oldest beds of the Olduvai gorge, which were essentially layers of tuff (volcanic ashfall) and lava flows. By using Potassium-Argon dating to date the strata above and below the fossils, the tools and the hominin were dated to be 1.75 million-years-old (Tattersall, 2009).

Figure 2.12. Laetoli Footprints Replica. The footprints belonged to two hominins, and were preserved as they walked across volcanic ash. This fossil is one of the early indications of bipedalism.

Symbolism

As more and more hominin fossils were discovered in several parts of the world, it became clear that bipedalism, tool-making, the development of hunting, the controlled use of fire, and the changing diet of early hominins all contributed to increasing brain size and changing body proportions. Yet the difference between modern humans and all their predecessors was the presence of cultural symbolism, or the ability to attribute meaning to an object, to pass this meaning on to later generations, and to impose this meaning through social behaviour. This had been proposed relatively early by Frederich Engel in 1896, when human evolution was gaining acceptance in the scientific community (Holloway, 1981).

Figure 2.13. Ochre Plaques in Bombos Caves. These plaques are the earliest indications of symbolism created by hominins.

Although anatomically modern humans appeared around 200-150 Kya, evidence of symbolism did not arise until at least 100 Kya (Tattersall, 2008). The oldest symbolic artifacts discovered were ochre plaques with geometrical designs (see Figure 2.13), found in the Blombos Cave, South Africa, in the year 2000 (Henshilwood, et al., 2002). There are skeptics who deny the symbolism behind these ochre plaques, but by 75 Kya the existence of cultural artifacts, such as beads strung together to form a necklace, is undeniable (Henshilwood, et al., 2002). The origin of this symbolism, however, is a relatively current controversy.

Ian Tattersall (1945-present), a renowned American paleoanthropologist, suggested that the rise of symbolism can be traced back to a genetic event that triggered the development of the modern human anatomy (Tattersall, 2008). This event would have caused a drastic anatomical change that may have primed the human brain for the development of symbolism much later on, as made evident by the period in the fossil record in which modern humans were present, but symbolism was not. Contrary to this belief, Richard Klein (1941-present) proposed that this genetic event directly triggered the appearance of symbolism (Dunsworth, 2007). Klein reasoned that this event could have been a bottleneck effect where the human population was greatly reduced. However, if this were to happen, all hominin species would have been very quickly and successively replaced by symbolic *H. sapiens*.

Dispersion

Over the years, an abundance of various hominin fossils has been found, and with the use of radiometric dating, the evolutionary lineage of *H. sapiens* has become more clear. Many uncertainties however still exist in the story of human evolution. One such area is the topic of dispersion. As previously mentioned, the widely accepted Aryan hypothesis that existed in the 19th century was that modern Europeans had migrated there from Asia (Tattersall, 2009). However, the discovery of new fossils and the advent of more precise dating methods have caused this perspective to change. Numerous running theories of human origins and dispersion have been developed over time, and as scientific understanding changed, so too have these theories.

Out of Africa Hypothesis

The theory that is most commonly expressed in literature is the Out of Africa hypothesis, which proposes one main source of development and subsequent dispersion. Once *Homo erectus* had developed, it became the first hominin to disperse outside of Africa, as evident by the fossil record (Willoughby, 2007). A variation of this theory proposes that this initial wave of dispersion was followed by another wave of modern humans, and upon arrival, modern humans displaced the other hominins. This theory had been proposed in the 1980s by

Günter Braüer, and was supported by the little to no genetic mixing of hominins observed, as evident by the few intermediate fossils between the two species (Willoughby, 2007). These two superseding waves are predicted to have occurred at 500 Kya and at 80-55 Kya (DeSalle and Tattersall, 2008). Once the early *H. sapiens* had dispersed, they may have out-competed the populations of *H. erectus*, be it by natural selection or by warfare (Dunsworth, 2007). Warfare is supported due to abundant gaps in the fossil record, which could be indicative of sudden extinctions, as well as poor fossil preservation (DeSalle and Tattersall, 2008).

Another variation on this theory predicts three waves of dispersion that are aligned with the periods of glaciation, suggesting that climatic fluctuation controlled much of the movement into Europe (DeSalle and Tattersall, 2008). This theory proposes that glaciation propagated dispersion when glaciers formed in the south and pushed hominin migration to more northern, warmer climates. It is unclear what propagated migration to Asia, however much of the dispersion of hominins is thought to be associated with the hunter-gatherer society (Dunsworth, 2007). In these societies, early hominins followed the migrational paths of the different game that was hunted (Dunsworth, 2007). Although the order of colonization is unknown, the migrations to Europe and Asia are theorized to have been earlier than the migrations to North America and Oceania, based on the fossil record and the tracking of mitochondrial and Y chromosomal DNA (Dunsworth, 2007).

Multiregional Hypothesis

Another commonly accepted theory is the Multiregional hypothesis of dispersion, initially proposed by Milford Wolpoff in the 1980s (Dunsworth, 2007; Tattersall, 2009). This theory hypothesizes that *H. erectus* dispersed from Africa and later evolved into modern *H. sapiens* due to interbreeding between the various species and populations (Dunsworth, 2007). A major component of this theory is that gene flow was a factor in maintaining parallel development of modern human species (Willoughby, 2007). This theory suggests that different adaptations seen in the different races that exist today are geographical variations (Dunsworth, 2007). The main support for this theory is morphological, as modern humans in specific regions are similar in body size and facial structure to prehistoric *H. erectus* species in those regions. This is most notable between the *H. erectus* fossils found in eastern Asia and the current inhabitants there, and between the *Homo heidelbergensis* fossils found in Europe, the *Homo neanderthalensis* fossils, and modern humans of European descent (Willoughby, 2007). Similar to the Out of Africa theory, the Multiregional theory can be supported by the abundance of fossils that have been documented in Africa, due to the large population that originated there (Willoughby, 2007).

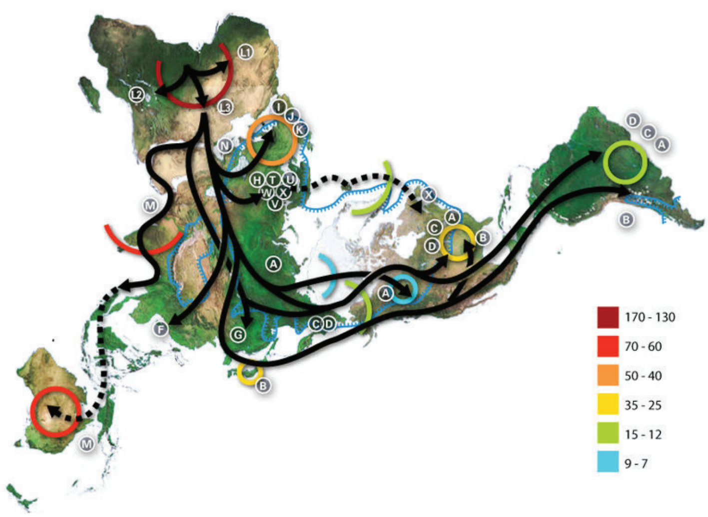


Figure 2.14. Dispersion Path Map of the Earth. This map displays an extensive interpretation of migrational paths out of Africa (top left corner) without being exclusive to one theory of dispersion. The letters represent haplogroups and the colours and numbers represent the timing of the migrations in thousands of years before present.

Dispersion Paths

After research began on the dispersion of humans, other aspects of migration became of particular interest. Such aspects include the paths taken during dispersion. These dispersion paths predict the continents which were inhabited, as well as the succession of inhabitation. The common thread to the path is that *H. erectus* originated in Africa, and later inhabited Asia, Europe, North America, and Australia, in various predicted orders (see Figure 2.14).

The strongest evidence for dispersion paths came to light when genetic distance was introduced in the 1970s as a measure to quantify the evolutionary relatedness of populations. Shortly thereafter, in 1974, Masatoshi Nei and Arun Roychoudhury examined blood proteins among the various human races, and found that modern Europeans and Asians were more closely related to each other than they were to Africans (Nei and Roychoudhury, 1974). This evidence suggests that Europeans and Asians split from each other much later at around 55 Kya, and that they had split earlier from Africans at around 115-120 Kya. Allan Wilson supported these findings when he examined mitochondrial DNA in the 1980s. Wilson found that the mitochondrial DNA was more diverse in African populations of modern humans than in Europeans or Asians, further confirming that modern humans had first arisen in Africa at around 130-140 Kya. This strengthens the Out of Africa model, because it suggests that modern humans originated in Africa as opposed to parallel evolution in multiple regions of the Earth.

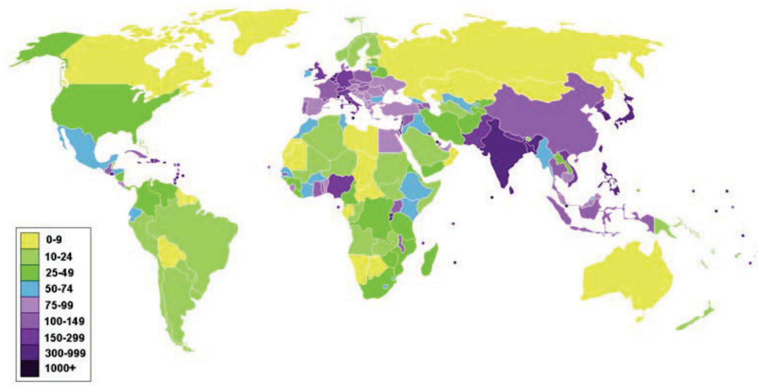


Figure 2.15. Population Density Map of the Earth. This map illustrates the current population densities by country, displaying the ability of modern humans to extensively cover the globe since dispersion and migration millions of years ago.

Expanding on Wilson's work, a prominent method now of determining the timing of different wave dispersions is through analysis of the DNA of what paleoanthropologists call Adams and Eves, or the men and women of early hominin species (DeSalle and Tattersall, 2008). Movement of mitochondrial DNA and Y chromosomal DNA is tracked to determine potential migration patterns (DeSalle and Tattersall, 2008). This tracking is done through analyzing similarities in DNA of various fossils in different locations. Similarities in genetics can be indicative of location similarity. For example, if the DNA of a species found in Siberia is similar to one found in North America, then it is likely that those hominins travelled from Siberia to North America. This in fact is predicted by many paleoanthropologists, although specific theories vary (DeSalle and Tattersall, 2008). Different dating techniques such as electron-spin resonance, thermoluminescence, and uranium-series dating are also used to determine the age of different fossils, and thus determine the timing of these predicted migrations.

Human migration is an area of evolution that leaves many avenues open for discussion. Much information has been recorded but little has been concretely understood or interpreted. Dispersion theories are vast and varied, with some predictions common and many differing.

The Big Picture

Thus, in closing, it can be shown that the competing theories in evolution make for a rich history and a puzzle that is not mutually exclusive, but that can be pieced together in many different ways. As the fossil record unveils more information with time, the running theories may change, they may be disproven, or new theories may arise. One thing remains true though: however modern humans evolved, and however migration occurred, humans have covered the globe (see Figure 2.15), and thus accomplished an extraordinary feat in doing so. In this there is hope and confidence to say that in another uncertain aspect of the Earth's phenomenal history, the challenge of understanding human evolution in all its facets may be accomplished as well.

Re-evaluating the Fossil Record

In understanding the various facets of human evolution, paleoanthropologists rely heavily on the fossil record. As with many scientific disciplines, interpretations of the fossil record are constantly changing. Traditionally, there have been two types of paleoanthropologists. 'Lumpers' group various fossils into one species, arguing that morphological variations can be attributed to normal variation within a species. 'Splitters' then categorize fossils into multiple species on the basis of the smallest morphological differences. As dating methods improved and as more fossils were discovered, current categorizations became susceptible to change, and the fossil record demanded re-evaluation.

One of the most recent developments that adds to the lumping-splitting debate is the discovery of a complete, adult hominin skull in Dmanisi, Georgia (see Figure 2.16) (Lordkipanidze, et al., 2013). First discovered in 2005 by David Lordkipanidze, the culmination of eight years of effort in analyzing the skull resulted in the publication of a ground-breaking paper in 2013. In his paper, Lordkipanidze notes that the 1.8 million-year-old skull, given the name Skull 5, possesses a small braincase and a large, prognathic face, showing the spatial orientation of features in early hominins for the first time (Lordkipanidze, et al., 2013).

When compared to the existing fossil record, Lordkipanidze made several noteworthy observations (Lordkipanidze, et al., 2013). With a braincase volume of 546 cm^3, Skull 5 was small compared to other Dmanisi fossils, and fell within the lower range of *H. habilis* skulls with typical braincase volumes of 509-687 cm^3 (Rightmire, 2004). In contrast to this, analysis of postcranial elements to give estimates of the height and mass of the hominin place Skull 5 within the lower limits of *H. erectus* and modern humans, with a mass of 47-50 kg and a height of 146-166 cm (Holliday, 2012). Using data on braincase volume, body mass, and height, an encephalization quotient (a relative measure of brain size) of 2.4 was obtained for Skull 5, placing it within the range of *Australopithecus* (Lordkipanidze, et al., 2013). In comparison with other specimens, Skull 5 resembled several fossils of different ages that had been discovered in different regions. Specifically, Skull 5 had a jaw similar to a 2.3 million-year-old *Homo* jaw from Hadar, Ethiopia (Kimbel, Johanson and Rak, 1997), while it also had a face that resembled 2.0-1.9 million-year-old specimens from Koobi Fora, Kenya (Leakey, et al., 2012).

Figure 2.16. Frontal view of Skull 5. The skulls discovered in Dmanisi, Georgia propagated re-evaluation of the pre-existing fossil record, and sparked new potential theories for speciation.

In addition, when compared to other fossils at Dmanisi, Skull 5 raises the question of intraspecies variation. The small braincase connected to a large, prognathic face in Skull 5 has features of different fossils at Dmanisi that had been previously thought to be of different species. Since the other fossils were fragmented, Skull 5 provides insight into how all the Dmanisi fossils may belong to the same species. The distinctive features that distinguished the fossils from each other may not be so distinctive after all, as they are present in a single skull. In comparison to variations in extant species of chimpanzees, bonobos, and modern humans, geometric morphometric analyses showed that the variations between these fossils fall reasonably well within the range for intraspecies variation (Lordkipanidze, et al., 2013).

These results have profound consequences for the future of paleoanthropology. The fossil record that was once thought to be a concrete source of information is now being interpreted differently. The species differentiation that was proposed is now seen as intraspecies variation. As more fossils are discovered, undoubtedly more theories will require re-evaluation.

Mayon Volcano located in Legaspi City, Philippines

“A discovery which seems to contradict the general tenor of previous investigations is naturally received with much hesitation.”

CHARLES LYELL

Chapter 3: Earth Processes

Throughout human history, what people believe to have caused the Earth to shake, spew fire and freeze over has changed dramatically. At any point, the evidence available limits the commonly accepted theories. Many of the earliest ideas were centered around ancient mythology and divine beings. Over time these have evolved as cultures accepted the scientific method and quantitative approaches to problem solving.

This fascination with the power and devastation of earthquakes, volcanic eruptions and ice ages has fuelled several major advances in understanding these geologic processes. The invention of seismology for example, has allowed scientists to observe the internal characteristics of the Earth. It was through interpretation of the unique seismic properties of each layer in the Earth's interior that they were identified. Further, advancements in volcanology have led to the conceptualization and implementation of protective measures for cities against lava flow. However, there are still debates ongoing today. For example, the extent of ice coverage in the Neoproterozoic era remains a major controversy today.

Despite incredible developments in technology, our knowledge of the inner workings of the Earth is not complete. Tangible evidence regarding the Earth's inner composition is still lacking, as samples thousands of kilometres into the Earth are currently unattainable. Should this become possible in the future, it is possible that many of the theories we accept today could be altered dramatically. This chapter aims to chronicle the development of ideas regarding the layers of the Earth, volcanism, seismology and glaciation as time progresses, and their implications for the modern world.

The Discovery of the Inner Workings of the Earth

"Of all regions of the earth none invites speculation more than that which lies beneath our feet" (Richard Oldham, 1906, pp. 456)

The processes that contributed to the Earth's formation, as well as the mechanisms it operates under today, continues to stir up many unanswered questions in a range of research fields. Since the end of the 19th century, several prominent figures in the scientific community including Lord Kelvin (1824-1907), Emil Wiechert (1861-1928) and Inge Lehmann (1888-1993) have aided in shaping our current model of the Earth's interior (Weisstein, 2007; Schroeder, 2000; Bolt, 1993).

Initially, most of the knowledge regarding the interior was based on mathematical calculations and observations regarding the properties of the Earth. When geophysicists began to interpret seismic records, our knowledge of the interior of the Earth expanded dramatically.

Eventually, with key technological advancements, it became possible to learn about the interior of the Earth by direct observation. The need to seek answers was the main driving force of the American Miscellaneous Society in the 1960's who attempted to drill deep into the interior of the Earth. They considered it the Earth equivalent of the Space Race that was occurring at the same time (Bascom, 1963). At that point in time, the accepted model of the internal layers of the Earth had been established, and has changed very little since then.

It has taken years of research and technological advances to reach the current level of understanding regarding the interior of the Earth and yet, there are still countless unanswered questions. These mysteries surround the function and mechanics of each layer, how they interact, their unique composition, and how they collectively affect the processes visible to us on the crust. In this section, the progression of ideas from the first hypothesis to the finalized model of the Earth, as well as the potential contributions of proposed explorations will be discussed.

Earliest Hypotheses

Lord Kelvin, also known as Sir William Thomson after being knighted in 1866 for his accomplishments in thermodynamics, was the first person to disprove the previous hypothesis that stated that the centre of the Earth was molten (Bascom 1963; Marvin 1973; University Of Glasgow, 2013). This molten Earth hypothesis first arose from the fact that volcanoes spew lava, which was observed to be molten (see Figure 3.2), so many scientists before Kelvin deduced that the whole interior of the Earth was simply composed of the same material (Bascom, 1963). While studying the height and force of the tides as well as the moon and sun's gravitational pull on the Earth, Lord Kelvin determined in 1882, that the centre of the Earth had to be a solid ball of iron (Thomson, 1882; Marvin, 1973). He dispelled an idea that had been held for centuries, and deduced a completely different theory, one that is much closer to the current understanding (Marvin, 1973). It was revolutionary ideas like this, and the calculation of absolute zero, that made him the first person to be knighted based on achievements in a scientific field (University Of Glasgow, 2013).

Figure 3.2 Lava flows were seen as an indication that the Earth's interior was entirely composed of molten rock.

Development of Models of the Earth

At the end of the 19th century the subfields of geography were just beginning to be formed. In 1897, Emil Wiechert was the first professor of geophysics at the University of Göttingen, Germany (Bullen, 2008a). Over the years, many famous seismologists that arose from this university dramatically changed the accepted ideas associated with the Earth's interior (Schroeder, 2000).

One day, in lecture Wiechert proposed to his students his theory that the Earth had a solid iron core based on its density (Richardson, n.d.). A year later he formally proposed a hypothetical model of the Earth based solely on a series of calculations comparing the relative density of the Earth and the density of the rocks seen on land. This three-layer model consisted of rocky outer crust, an upper layer with a density of 3.2 g/cm^3 and a core with density of 8.21g/cm^3. This core was predicted to make up approximately 4/5 of the Earth's entire radius and began 1408 km below the Earth's crust (Schroeder, 2000).

One of Wiechert's most notable achievements was the establishment of the Geophysical Institute. This institute was able to set up a worldwide network of seismic stations across several regions including the Pacific Ocean and China, providing geophysicists with a more complete seismic record (Schroeder, 2000). With this evidence, Wiechert's calculations were further supported, especially with the aid of his newly designed inverse pendulum seismograph that recorded earthquake waves precisely throughout the duration of the entire earthquake (Bullen, 2008a).

By the beginning of the 20th century there were several separate institutions working on an array of theories regarding the inner layers of the Earth. In 1909, Dr. Richard Oldham (1858-1936) a British geologist, synthesized these hypotheses and published a paper that highlighted the extent to which these were pure speculation and how little was in fact known (Oldham, 1906). In response to a book published a few years later, Oldham stated that although he approved of the records obtained by Wiechert, he did not necessarily agree with his interpretation (Oldham, 1914). By focusing purely on seismological evidence, Oldham was the first to confirm the existence of an impenetrable core, which supported Wiechert's theory. However, based on the arrival times of P and S seismic waves (shown in in Figure 3.3). Oldham calculated the radius of the core was 2/5 of the Earth's entire radius, which did not coincide with Wiechert's predictions (Oldham, 1906).

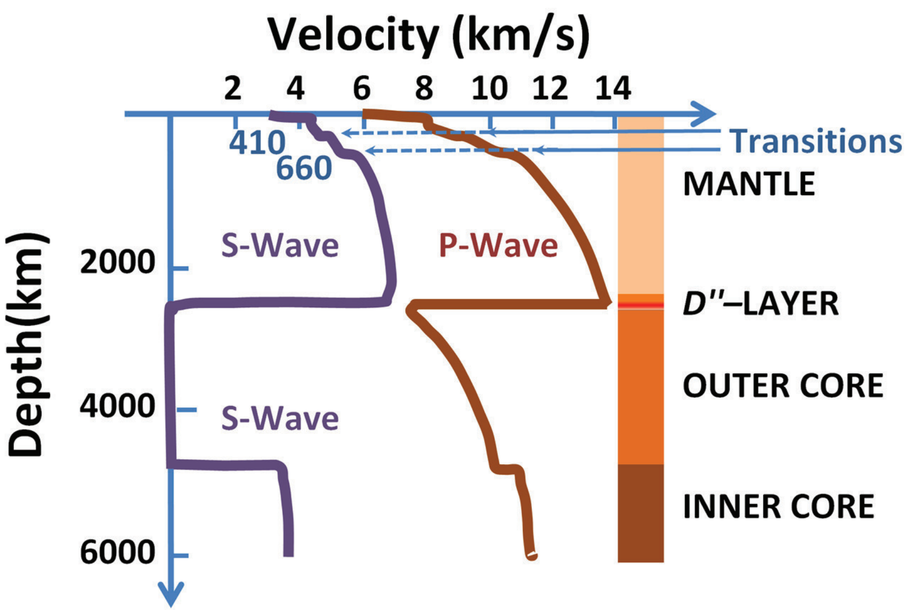


Figure 3.3 This image explains the changing velocities of Primary (P) waves and Secondary (S) waves with depth, which are produced from earthquakes. It is know that S-waves, which are shear waves, cannot pass through liquids. This is how scientists deduced that the outer core was liquid. The D" layer represents the Gutenberg Discontinuity, in which the velocities of both waves is reduced.

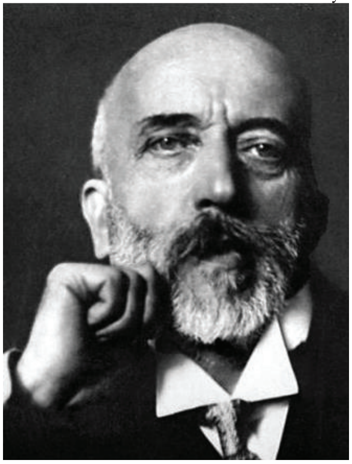


Figure 3.4 Portrait of Dr. Andrija Mohorovičić, most famous for the identification of the Mohorovičić discontinuity, the boundary between the crust and the mantle.

Near the end of Wiechert's career, the use of seismology to gain understanding about the layers of the Earth was taken up by Dr. Andrija Mohorovičić (1857-1936), a prominent seismologist in Zagreb, Croatia in the early 1900's (Figure 3.4.). His career took off in 1909 when there was a large earthquake just outside of Zagreb that produced invaluable scientific data from well-situated seismological stations (Herak & Herak, 2010). Before this point, the velocities of P and S seismic waves were thought to vary directly depending on depth. However, Mohorovičić detected two distinct sets of waves that arrived at separate intervals based on their distance from the earthquake's epicenter, not the depth of the epicenter (Bullen, 2008b). These readings allowed Mohorovičić to distinguish the boundary between two distinct layers; the Earth's upper layer and the mantle, which was appropriately named the Mohorovičić discontinuity (Moho). Mohorovičić calculated that this boundary was located approximately 52 km below the Earth's crust (Mohorovičić, 1909). The importance of this discovery was not given the immediate credit it deserved due to the poor name choice of his paper; "Earthquake of 8 October 1909" (Mohorovičić, 1909). It was not until 1911 when Hans Bendorf, a prominent seismologist, finally gave the paper the recognition it deserved by distinguishing it as being one of the most important seismological papers of the age (Herak & Herak, 2010).

Today, this Moho discontinuity has been found to mimic the crust and does not always exists as a sharp boundary. In addition, its depth varies according to the topological features found on the Earth's crust (Marvin, 1973). Under mountains the depth is approximately 60 km, 30 km beneath continental platforms and 5 km under ocean floors (Marvin, 1973). Despite all this knowledge gained, it is still unknown whether a chemical or a phase change within the rocks produces this discontinuity (Marvin, 1973). Geologists favour the argument of a chemical change, but since the boundary has not yet been physically explored there is no definitive answer (Marvin, 1973). By 1910 there was evidence from calculations as well as seismological data to support a model of the earth consisting of three layers: the core, the mantle and the crust.

As science moved into the next decade understanding of the interior of the Earth started to become more clear. Beno Gutenberg (1889-1960) was a German seismologist who studied under Emil Wichert at the Geophysical Institute in Göttingen. He used his knowledge of seismic waves to determine the composition of the centre of the Earth (Reid, 1915). In 1914, he disproved his mentor's previously accepted theory of the Earth only being composed of the core, mantle, and crust, based on the evolved understanding of seismic waves (Reid, 1915). Gutenberg found that the Earth was actually composed of three shells and the crust, due to a recent finding focused on a change in velocity around the core (Reid, 1915). At first he described this third layer as a "shadow zone" however this is known now to be the outer core, and the boundary between the mantle and outer core is called the Gutenberg Discontinuity. Based on distant earthquake data, Gutenberg accurately calculated this discontinuity to exist an average of 2900 km below the crust (Bolt, 1993).

After applying to be the successor of Wichert at the Geophysical Institute in 1920, it is speculated that Gutenberg was rejected because of his Jewish descent at a time when anti-Semitism was growing in Germany (Mitchell, 2013). He then decided to move to California to become a professor of geophysics at the California Institute of Technology after receiving a full professorship from Robert Milliken (Mitchell, 2013; European Geosciences Union, n.d.). Once established in California, Gutenberg achieved the successes that he is most famous for, such as collaborating with Charles Richter on the Richter Scale and continuing his research on determining the depth of the Gutenberg Discontinuity (Mitchell, 2013). Along with these successes, he also advised the U.S Navy during World War II against his former nation (European Geosciences Union, n.d.).

Finalizing the Model of the Earth

In seismology, most great discoveries were the result of earthquake data that provided new records. In 1929, a powerful earthquake in New Zealand provided just that for the Danish seismologist Inge Lehmann. Based on the current beliefs regarding seismic waves, P waves were expected to be deflected by the core. However, when Lehmann investigated the shock waves she found that P waves were being picked up at unpredictable seismological stations (Bolt, 1993). This brought Lehmann to the conclusion that the P waves were being reflected off another boundary. In 1936, she theorized that the core consisted of two layers: a solid inner core and a liquid outer core. This was separated by the Lehmann discontinuity (Bolt, 1993). For nearly thirty years this theory was heavily disputed, and in 1970 it was confirmed and accepted when more sensitive seismographs detected the same phenomena. In the next year, Lehmann won the William Bowie medal, the highest honor of the American Geophysical Union (American Museum of Natural History, 2000).

Throughout her early years Lehmann had excelled and out-competed men, and she worked with the top researchers in the field including Beno Gutenberg. However, in her time women were only beginning to be accepted in the field of science and mathematics, so Lehmann faced a lot of discrimination throughout her career (Bolt, 1993). It is thought that although her theory of a solid inner core and liquid outer core was radical, it was partially prejudice that led to its delayed acceptance.

As Lehmann entered retirement the modern model of the earth was formed (see Figure 3.5), consisting of four layers, each with their own composition and characteristics. The solid inner core surrounded by the liquid outer core, and the mantle, a semi plastic shell that can be further divided in to the lower mantle and an upper mantle that lies closest to the crust (Jain, 2013).

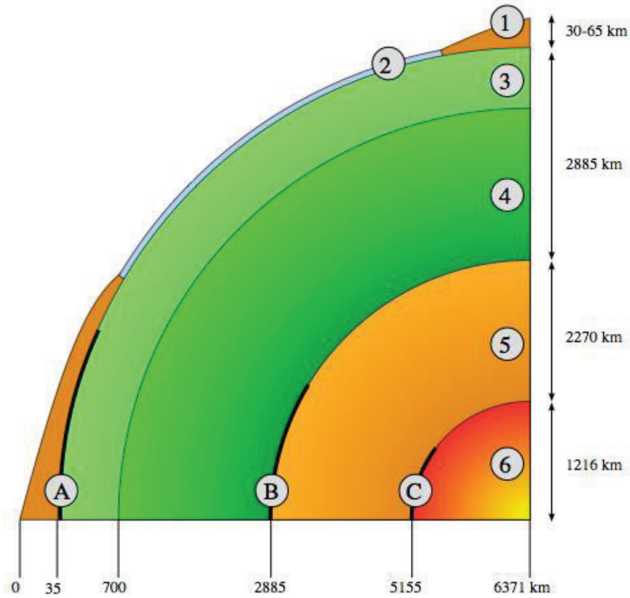


Figure 3.5. Diagram of the layers of the Earth's Interior.
1. Continental Crust
2. Oceanic Crust,
3. Upper Mantle,
4. Lower Mantle,
5. Outer Core,
6. Inner Core,
A. Mohorovičić Discontinuity
B. Gutenberg Discontinuity,
C. Lehmann Discontinuity

Project Mohole: Deep Drilling

When the space race was in full force it was a major focus for many countries, but for a group of geologists known as the American Miscellaneous Society there also existed an Earth race, which was focused on drilling deep into the Earth. Their goal was to determine the age of the Earth through examination of older rock samples that were believed to lie below the crust, as well as to determine the age of life and the age of the oceans (Bascom, 1963). There were also many questions regarding the density, composition and rock type beneath the Earth's crust (Bascom, 1963). This was not the first time drilling into the Earth had been proposed; throughout the ages people had hinted that there might be many answers lying below the crust. Even Charles Darwin wanted to have exploratory holes drilled as he suspected that the interior held important information (Bascom, 1963).

Project Mohole was the first ever-floating platform deep sea-drilling project (Bascom, 1963). Its exploratory phase involved several expeditions from 1961-1966 off the coast of Guadalupe Island, Mexico. The team drilled five holes into the seabed, the deepest one made it 607 m into the Earth, however, none of the holes reached the Mohorovičić discontinuity (Bascom, 1963). After this phase of expeditions, a second phase was proposed in which they would drill even deeper. Unfortunately, engineering problems restricted drilling depth and a lack of funding caused the project to be cancelled before they could make it to this phase (Bascom, 1963). Even though the geologists working with Project Mohole did not reach their final goal, the project was not entirely a waste as the core samples obtained from the first phase proved to be very valuable for research. These samples contained rocks from the Miocene-age (20-5 Mya) that had never been observed before this project (Bascom, 1963). Project Mohole paved the way for many expeditions into perhaps one of the least explored regions on Earth: the interior. This project not only attracted lots of attention to the possibility of finding the answers to many questions within the Earth but also was a historical engineering feat. The American Miscellaneous Society initiated a new era of deep sea drilling that provided research opportunities as well as economic incentives when paired with oil exploitation.

Figure 3.6. Picture of Project Mohole deep sea drilling off the coast of Guadalupe, Mexico in the first stage of the expedition.

Current Expeditions and their Applications

Since the revolutionary mission called Project Mohole was dissolved due to lack of funding, there has been an increased drive towards understanding the workings of the inner Earth. The Deep Sea Drilling Project (DSDP) was created in 1974 to investigate seafloor spreading through the drilling and examination of long sediment cores (IODP, 2013a). Over the years the countries involved would meet and plan out the goals of the project for the years to come. This international program was first called the Ocean Drilling Program (ODP) and then in 2004, the Integrated Ocean Drilling Program (IODP) (IODP, 2013a). The IODP is the product of the partnership of 26 nations focused on international marine exploration and research collaboration (IODP, 2013a). They explore the Earth using data retrieved both from the drilling projects as well as sample collection from the deep sea floor (IODP, 2013a). In October 2013, the countries met and renamed the International Ocean Discovery Program: Exploring the Earth Under the Sea (IODP, 2013a).

From 1974 to 2004 the collaboration of these nations collectively drilled approximately 50 boreholes within various sections of the oceanic crust (IODP, 2013b). Initially they experienced the same issues as Project Mohole, technological restrictions prevented them from drilling deep enough into the crust to obtain significant data (Dick et al., 2006). This was attributed to insufficient drill design and poor locational choices. It was eventually found that it was better to drill within "tectonic windows" which are geologic structures formed on thrust systems by erosion or normal faults (Dick et al., 2006). These create an area that has lower elevation than the rest of the sea floor providing an ideal place to avoid drilling through excess crust.

Outcomes of IODP

In the 21st century, major technological advances occurred in the area of deep sea drilling that aided research programs (Dick et al., 2006). Computers allowed for the combination of Global Positioning System and the latest topography of the seafloor to create three-dimensional maps of the features on the floor allowing for better choice of drilling sites (NOAA, 2013). There have also been improvements in drilling equipment, including GPS devices that hold the boat still throughout the drilling process and new drill bits (NOAA, 2013). There is also now a better understanding of seismically active areas to aid in the determination research locations (Dick et al., 2006).

The deepest borehole to date reached a depth of 7 740 m in 2012 as part of the Nankai Trough Seismogenic Zone Experiment, a branch of IODP (IODP, 2013b). The purpose of this hole was to investigate the mechanics of seismological activity along subduction plate boundary faults (Kinoshita et al., 2010). Sensors were placed in evenly dispersed locations within the borehole from the seismic zone to the Earth's crust. The information obtained from sensors and core samples is expected to lead to a better understanding of the mechanisms of plate boundary slips and how they lead to tsunamis (IODP, 2013b). In the future, IOPD aims to connect these sensors within the borehole with the Dense Ocean-floor Network System for Earthquakes and Tsunamis to monitor tsunamis in real time, which would provide more security for those that live in tsunami prone areas (IODP, 2013b). The core samples also provide information for geologists and other researchers about the composition of the Earth at this depth, as well as clues about the mechanisms at work (IODP, 2013b; Dick et al., 2006). Along with the research being done in the Nankai, there are several other missions occurring in 2013 that are studying other aspects of the deep sea and the mechanics of the Earth. For example, through drilling various boreholes at different positions and depths, the South China Sea Expedition is trying to address the opening of the sea; specifically to determine early paleoenvironments and tectonic movements (IODP, 2013b).

Figure 1.4. The Chikyu is the boat used for the deep sea drilling required for the Nankai Trough Seismogenic Zone Experiment. It is equipped with the most modern technology in the field.

Future Goals of IODP

The International Ocean Discovery Program, which began in October of 2013, is planned to continue until 2023 (IODP 2013a). The goal of this program is to take an international, multidisciplinary approach to understand fundamental concepts of the Earth, such as the limits of life within the interior of the Earth and the mechanisms changing the environment on the surface of the Earth (IODP, 2011). IODP will provide research along with core samples for the scientific community; however, they also want to focus on education in the next ten years (IODP, 2011). They intend to provide materials to educational institutions, as well as training and inspiration for the next generation of scientists to pursue careers in geological fields (IODP, 2011). Since there is a limited amount of equipment to accomplish all that is needed there is a peer-review selection process in order to schedule the important drilling expeditions that will be implemented over the next ten years (IODP, 2011). The main goal of the International Ocean Discovery Program is to gain a much more complete understanding of the composition of the interior of the Earth, the mechanisms of the interior processes as well as the history of the Earth itself.

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The Development of Seismology: Ancient Greece to the 20th Century

Imagine being a citizen of Ancient Greece, living peacefully, and happily going about day-to-day activities. All of a sudden the Earth begins to tremble and emits very loud, bizarre noises. It physically cracks and wreaks havoc in the local community. With a very limited scientific background, it would be very easy for one to believe myths about how this earthquake took place. For example, one may believe that it was caused by the movement of four bulls, which hold up the planet (Halacy, 1974). One may also be willing to accept that the most detrimental earthquakes took place when these bulls decided to casually toss the Earth from one pair of horns to another. Now return back to present-day. Though this idea may seem foolish now, some early Greek philosophers had accepted this as truth. In addition, in other places around the world, many primitive people attributed earthquakes to the restlessness of some underground creature. For instance, in Japan it was initially a giant spider, then later a catfish. In India it was a large mole, and among many North American Indians, earthquakes were due to the movement of a giant tortoise (Leet, 1938).

Figure 3.8: A map of the Aeolian Islands off the coast of Sicily. The red triangles indicate eruptions within the last century, while the green triangles indicate no eruptions within the last century.

The study of seismology, derived from the Greek *seismos*, which means earthquake, has been an area of interest since the time of the Ancient Greeks (Leet, 1938). As described above, many primitive theories about earthquake formation were mythical in nature. Leet suggests that the reason for this is because in those days theories about the underlying processes of natural disasters were shaped heavily by culture and beliefs. Though there was no method of scientific observation during that period, Greek and Roman philosophers pioneered the way for a more scientific approach to seismology (Leet, 1938). Specifically, Aristotle and Seneca were extremely influential in their times, and proposed theories that were held up until the end of the Middle Ages. Leet claims that these theories were based primarily on what Aristotle could visually observe as well as what had taken place in the past. Using the work from these philosophers as a basic foundation, scientists born after the 1500s, such as Kepler, Michell, and Mallet (discussed later), continued to develop theories relating to seismology.

The Influence of Aristotle

The published works of Aristotle (384 BCE–322BCE) are believed to be the earliest known reports of earthquake theory (Missiakoulis, 2008). When developing his theory, Aristotle trusted heavily on his observations and prior knowledge, and did not place as much emphasis on the need for quantitative measurements (Hine, 2002). His account of the formation of earthquakes revolves around the movement of wind. He claimed that the expulsion of wind from deep within the Earth results in an earthquake that runs across its surface (Aristotle, 340BCE). He proposed that wind was created both inside and on the surface of the Earth due to the evaporation of wet moisture. This moisture is created by rainfall, and the sun and internal heat from the Earth is responsible for its evaporation (Lagios, 2010). Wind was believed to be the most powerful natural force in existence, so Aristotle concluded that it must be the underlying cause of earthquakes (Aristotle, 340BCE). To support his claims, Aristotle provided details of a specific earthquake that took place in Vulcano, one of the Aeolian Islands off the coast of Sicily (see Figure 3.8). He writes that in this region, as well as in many others, earthquakes have occurred and not ceased until the wind rose up to the surface like a hurricane (p. 367a22). Specific to the island of Vulcano, the earth cracked open with a loud noise and released a large amount of wind, covering the nearby city with ash.

Alongside the study of specific events that had previously taken place, Aristotle used his observations of the world as he knew it to sculpt his theory of earthquake formation. He wrote that the majority of earthquakes, especially the most disastrous ones, occur in calm weather (Aristotle, 340BCE). According to Missiakoulis (2008), his thought behind this logic is that the movement of wind, being continuous in nature, tends to flow either into the Earth or out from it. In other words, when the wind is blowing inwards and thus allowing for calm weather, the Earth will shake. On the other hand, if the wind is blowing outwards there will be winds on the Earth's surface, but no earthquake will be formed. Aristotle also noted that earthquakes could occur when there are some winds present since when the wind blows, one gust rushes inside the Earth and so the wind on the Earth's surface will be complemented by an earthquake (Aristotle, 340BCE). Despite this, these earthquakes are typically not as strong since the wind is divided, resulting in a distribution of energy. By acknowledging that earthquakes can occur in the presence of wind, Aristotle demonstrated that his proposed theory takes into account many factors, and this illustrates an approach from multiple perspectives. This likely made it easier for his arguments to be accepted among the people of his time, continuing until the end of the Middle Ages (Oeser, 1992).

Aristotle further mentioned that earthquakes are more likely to be formed in areas where the ground is permeable, as wind can easily be absorbed in these locations (Missiakoulis, 2008). Moreover, he wrote that earthquakes are more common in spring and autumn, as well as during periods of rain and drought, since these times produce the most amount of wind (Aristotle, 340BCE).

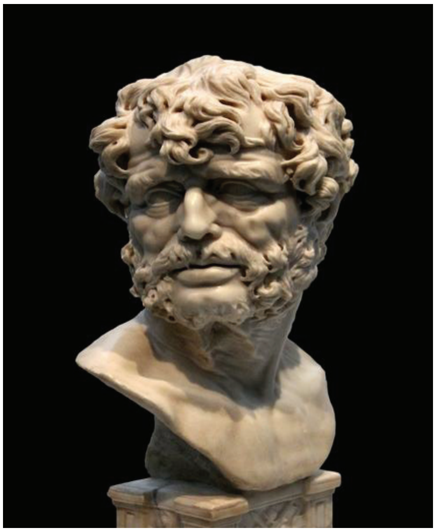

Figure 3.9: A marble bust of Seneca, created by an anonymous sculptor from the 17th century.

In general, as previously stated, Aristotle's theory is based on what he could interpret from past events, as well as what he could visually observe (Hine, 2002). He considered specific facts about earthquakes that took place in the past, such as at Hellespont and Achaea, in supporting his theory. Some historians such as Hine, criticized Aristotle because he never collected all of the facts together and made judgments based on them as a whole; he neglected detailed accounts of phenomena if they did not fit with his claim. Despite these accusations, the authority of Aristotle was so strong that his ideas on seismology remained relatively unchanged and accepted as truth until the end of the Middle Ages (16th century; Oeser, 1992). The only alternative explanation of earthquake formation was from Christian authors, who wrote that God is the ultimate supernatural cause of earthquakes, with Aristotle's theory being a secondary cause. Overall, although Aristotle used empirical facts to make his theoretical claims, Hine believes that Aristotelians in the Middle Ages did not conduct empirical research; they simply commented on or added minor details to the original works of Aristotle.

Seneca: The Roman Voice

Compared to Aristotle, who came up with a novel theory of earthquake formation, Seneca (4BCE–65CE) essentially modified Aristotle's works (Oeser, 1992). Nonetheless, the reports of Seneca are still vital when addressing the formation of earthquake theories over time. Seneca (see Figure 3.9) described a theory that was still supported by many philosophers after the Middle Ages, including Kepler. He considered the Earth to be analogous to a living being; just like a living being has arteries and veins, the Earth has canals with air and water (Williams, 2006). In normal conditions these canals allow for free movement, but in cases of disease and old age they are blocked and constricted.

Similarly, wind is met with obstacles when moving through the Earth, and this in turn results in strong earthquakes (Oeser, 1992).

The Dawn of a New Age: Johannes Kepler

Aristotle's dominant theory finally came to an end when individuals such as Johannes Kepler (1571-1630) began to speculate about other possible explanations for earthquake formation (Oeser, 1992). Though Kepler (see Figure 3.10) retained the metaphor used by Aristotle and Seneca of the Earth being a living being, Kepler explained earthquake formation in a very different manner. He connected the metaphor to an idea that was already disregarded by Aristotle. This is the concept that earthquakes are related to the constellation of planets and the presence of comets. He omitted the idea that earthquakes are directly caused by comet because he did not believe that they could come so close to the Earth as to collide with it. Furthermore, he rejected the notion, similar to Aristotle, that the heat from a comet generates winds in the Earth and then produces an underground wind resulting in an earthquake.

Figure 3.10: A portrait of Johannes Kepler, drawn by an unknown artist in 1610.

Rather than looking at comets in this manner, Kepler considered the reaction of the Earth's *soul* to such a strange phenomenon in the sky (Field, 1984). Just like a dog is scared during a thunderstorm, the soul of the Earth is scared when a comet can be seen. In turn, the Earth's moist vapours cause rain and when these vapours dry, the force of the comet hits the dry vapours and results in the production of sulphur and fire, eventually leading to the formation of earthquakes.

John Michell: The Father of Modern Seismology

John Michell (1724-1793) was the first scientist to propose that earthquakes are associated with wave motion in the Earth, and that seismic shocks take the form of waves (Bullen et al., 1947; Keller, 1998). In addition, he made a connection between the faulting of sediments and earthquakes, explaining faulting in terms of the propagation of waves. The introduction of these ideas was a turning point in the way earthquake formation was viewed by scientists around the world (McCormmach, 2012). In 1760, Michell published 'Conjectures Concerning the Cause, and Observations upon the Phenomena, of Earthquakes' which Hardin (2006) considers to be one of the most sophisticated proposals on seismology in 18th century. Additionally, in his paper Michell criticized early philosophers of seismology such as Aristotle and Seneca, claiming that they neglected to pay close attention to details, and simply speculated as to how earthquakes occur (Keller, 1998).

Michell's contribution to seismology was made possible because the Lisbon earthquake of 1755 provided him with enough information to study its formation (Keller, 1998). He noted the direction in which this earthquake travelled, the time at which the tremor was experienced in each nearby region, and the interval of time between a tremor and subsequent waves (Hardin, 2006). By combining these data, Michell was able to locate the epicenter of the Lisbon earthquake, which was between Lisbon and Oporto (in Portugal), and approximately one to three miles underground.

Michell observed that most earthquakes tend to occur in the same regions, particularly in volcanic areas (Hardin, 2006). Overall, many historians like McCormmach (2012) believe that Michell enlightened the world with a new perspective on seismology, and it is important to note that many aspects of his paper, such as the description of various geological events and locating the epicenter of an earthquake, are still commonly accepted today.

Robert Mallet: The Critic

Robert Mallet (1810-1881) coined the term 'seismology' in 1858 by joining two ancient Greek words; *seismos*, which means 'earthquake', and *logia*, which means 'a study of' (Elnashai, 2002; Johnson, 1997).

Mallet was very different from the other scientists who contributed to seismology before him (Johnson, 1997). One of his major accomplishments is that he proposed a new definition of 'earthquake' from an entirely different perspective. He defined it as "a wave of elastic compression, produced either by [1] the sudden flexure and constraint… or by [2] the sudden relief of constraint by withdrawal of the force, or by [3] their giving way, and becoming fractured" (Musson, 2013). Of the three potential theories of earthquake formation proposed by Mallet in his definition, the first two are now known to be incorrect. Nonetheless, Musson explains that the third theory Mallet included in his definition is currently accepted, as his use of the phrase 'becoming fractured' is interpreted as 'faulting' in modern terminology.

Mallet attempted to analyze the nature of earthquake motion, which had not been successfully completed in the past by others (Ferrari et al., 2005). He expanded upon John Michell's idea of considering earthquake motion to be wave-like by suggesting that there are three kinds of waves that can result from an earthquake. These include earthquake cotidal lines (waves travelling through the Earth's crust), great sea waves (waves travelling across the water), and aerial sound waves (waves travelling through the air).

Mallet reviewed work by many philosophers in the past who studied earthquakes such as Aristotle, Seneca, and Michell (Ferrari et al., 2005). Although he identified flaws in Michell's theories, much of Mallet's works are either based on or expanded from Michell's papers. Mallet believed that by publishing his works on seismology, he was forming a 'true science of seismology' that is absolutely correct and distinct from other theories in the past (Dean, 1991).

Throughout his study of earthquake processes, Mallet contemplated how to improve the measuring devices for earthquakes (Elnashai, 2002). He eventually proposed and designed an apparatus for monitoring and recording earthquakes, now called a seismogram. He stated that it should be able to record following; onset time, vertical and horizontal amplitudes, and the direction of earthquake motion (Musson, 2013). In fact, his paper 'On the Dynamics of Earthquakes', presented in 1847, included a blueprint for a seismograph that was used as a basis for the development of seismographs in areas frequently exposed to earthquakes such as Italy, California, and Japan (Elnashai, 2002). However, when the first model was built, it was much less accurate and sophisticated than Mallet had intended (Musson, 2013). In Musson's opinion, although it was widely believed that many of Mallet's works were truly remarkable, he was not able to effectively apply his theories to creating seismograms for detecting earthquakes.

The 20th Century: A Turning Point

One of the most prosperous periods in the development of seismology was the 20th century. Some historians such as Ben-Menahem (1995) even argue that the history or development of seismology did not begin until the end of the 19th century. Over the course of the past 100 years, the field of seismology has developed at a rate higher than ever before. This growth can be divided into four main stages (Ben-Menahem, 1995; Howell, 1990).

The first major stage in the growth of seismology was after the catastrophic San Francisco earthquake in April of 1906 (Howell, 1990). The study of this earthquake resulted in the formulation of the elastic-rebound theory in 1911 by Harry Fielding Reid (see Figure 3.11). The elastic-rebound theory explains how earthquakes occur in two steps; first, energy slowly accumulates due to the strain of the rocks, and second, when this energy accumulation exceeds the level the rocks can tolerate, a sudden release of fault slip strain causes an earthquake (Segall, 1997).

Figure 3.11: Harry F. Reid proposed the elastic-rebound theory for the first time in history.

The second major development was the development of the high-speed digital computer between 1950 and 1955 (Ben-Menahem, 1995). The ability to perform rapid calculations decreased the time required to process large amounts of data, to evaluate integrals and sums, and to solve various equations efficiently. This allowed for quick and accurate calculations of dispersion curves and other seismological equations, whereas in the past these calculations were difficult to perform and required a lot of time (Howell, 1990). Also, the development of new computer programs enabled users to graph the surface-wave dispersion for the first time ever, allowing them depict the inside of the Earth with multiple layers. In particular, they discovered the boundaries between both continental and oceanic crusts, and the mantle system (Dorman et al., 1960).

The third growth phase arose from the creation of a world data center, National Earthquake Information Center (NEIC), currently located in Golden, Colorado (Howell, 1990). This endeavour was taken on by the Advanced Research Projects Agency (ARPA) of the United States Air Force, and according to Howell (1990), it promoted seismology to be viewed as one of the most important fields in scientific research. Since the creation of the NEIC, over hundreds of standardized seismogram sets were sent to this central hub, and any interested scientist could view these seismograms. Thus, rather than contacting each observatory individually and waiting long periods of time to obtain seismograms, seismic records can now be accessed simply by contacting the NEIC.

Figure 3.12: Harry H. Hess played an active role in the development of the theory of plate tectonics.

The last major development in seismology was the acceptance of the theory of plate tectonics, proposed by Robert S. Dietz in 1961 and Harry H. Hess (see Figure 3.12) in 1962 (Howell, 1990). In essence, this theory depicted the Earth as a model of a heat engine containing hot liquids, which helped clarify exactly where and when earthquakes can occur. Though there were similar theories proposed by other seismologists before the time of Dietz and Hess, new evidence discovered in the middle of the 20th century further supported Dietz and Hess' theory, and so this spurred agreement among seismologists across the globe to accept their theory. To further demonstrate the validity of their theory, Dietz and Hess found that the faulting structure and type of faulting resulting from the seismic energy of most earthquakes matched what was predicted by their plate tectonic theory (Dorman et al., 1960).

Eventually, with the introduction of new technologies such as computers, many previously believed theories, like that of Aristotle, were disregarded and the current thinking of the formation of earthquakes came about (Ben-Menahem, 1995). Thus, rather than relying on visual observation and past events to deduce a plausible explanation for earthquakes, there is now a primary dependence on technology to illustrate the subterranean processes taking place.

Current Applications of Seismology: Geophysical Exploration

Since the beginning of the 18th century, seismology has developed such that the prediction and study of earthquakes is better than ever before (Howell, 1990). However, the current field of seismology does not only involve the analysis of earthquakes; it can now be applied to various other fields of science. Geophysical exploration is one of the most pronounced applications of seismology as it draws attention from not only seismologists, but also scientists from many other fields. Geophysics is the field of study that integrates the principles of physics and seismology to explore subterranean structures (Wightman et al., 2003). Since the 1930s, methods derived from geophysics, such as reflection seismology, have been utilized in investigating sedimentary basins for mineral and hydrocarbon exploration (Milkereit et al., 2003).

Before discussing the applications of seismology, it is necessary to understand how they work. It is known that each underground layer of the Earth has different composition and density (Aminzadeh et al., 1984). One method of measuring these characteristics is to transmit seismic wave signals into the rock layers. By measuring the time taken for these signals to pass through various layers, it is possible to provide estimates of the depth of the reflecting boundary and the wave velocity. This is most accurately done by using samples of geophone arrays (Aminzadeh et al., 1984). By recording the time taken for each seismic signal to be released and detected, one can draw a seismic cross-section that illustrates the amplitude of signal reflectance, and the position or depth of each subsurface layer.

Given this background knowledge, there is a wide range of geophysical applications of seismology that can be considered (Wightman et al., 2003). These include mineral and hydrocarbon exploration, mapping environmental contaminants or subsurface conditions for engineering projects, cavity detection, detection of unexploded ordnance, and archaeological or forensic investigations. Of these numerous applications, the most common one is the detection and mapping of minerals, particularly hydrocarbon resources (see Figure 3.13).

Figure 3.13: The pumpjack that is located south of Midland, Texas for lifting crude oil out from the oil well.

From Wightman's perspective, the multiple advantages of geophysical exploration demonstrate why it is one of the most important fields that extended from seismology. Geophysical exploration is considered to be a non-destructive form of investigation, as it does not involve drilling or digging out earth and disrupting ecosystems. It provides information for geotechnical borings (sedimentological logs), which are required for the construction of transportation infrastructure such as roads. Furthermore, Wightman (2013) emphasizes in his study that geophysical exploration is very efficient since it requires little cost, a short amount of time, and can cover large regions.

There are various methods involved in geophysical exploration (Palmason, 1975). One example is the use of a Thermal Gradient Survey to determine the presence of subsurface heat flows. An area with a low thermal gradient indicates there is a lower likelihood of the presence of magma and thus this area can be used for drilling boreholes. This technique is also applied to detect rocks or other layers that may hinder obtaining subsurface data (Irvine et al., 1990). Another method involved in geophysical exploration is an Electrical Resistivity Survey (ERS) (Palmason, 1975). This is one of the most commonly used techniques, as it searches for geothermal reservoirs by detecting the properties that resistivity depends on, namely porosity, salinity, and temperature of the fluids between and within sedimentary layers. In general, ERS is very efficient in identifying sedimentological stratigrpahies, which are useful in the discovery of groundwater reservoirs. Despite this, the ERS method is not always accurate (Paterson, 1987). As a result, a more precise method has been introduced, called Airborne Electromagnetic Method (AEM). AEM was initially invented to search for subsurface metallic substances but it is now applied for detecting groundwater locations. It is also used to identify subsurface structures to depths of at least 200 metres. Furthermore, AEM allows for the discovery of mineral and ore deposits such as gold or quartz (Irvine et al., 1990).

As illustrated throughout this chapter, the development of seismology has been a long and eventful journey. Many scientists have contributed to shaping seismology into what it is today, and humans are now more prepared for an earthquake than ever before. When comparing the views of seismology of early philosophers such as Aristotle and Seneca to scientists such as Dietz and Hess, it is evident that there was a major change in perspective and approach towards the scientific explanations of earthquakes. Moreover, in modern times the field of seismology has expanded its applications to other areas of interest such as geophysical exploration. This allows humans to search for subterranean resources in an environmentally friendly manner. Despite all of the advances in the field of seismology, it is still a relatively new area of science that demands further research and study.

The Development of Volcanology: Ancient Mythology to the 1700s

From ancient civilizations to modern volcanologists, volcanoes and the fire within them have captivated the attention of humans throughout history. Spanning several centuries and empires, ideas regarding these devastating landforms have certainly evolved, and will continue to change over time. The field of volcanology encompasses many aspects of volcanoes, and was primarily concerned with geomorphology and geography during its youth. As the branch of science became more established, shifts in the perspective of the scientific community grew to include the study of volcanic rocks in order to uncover the geohistory of volcanic regions.

Ancient civilizations

For centuries, people in ancient civilizations believed that volcanoes were home to temperamental and capricious deities, and would offer sacrifices to appease them. From the Pre-Classical period to the 13^{th} century, Mayans, Aztecs and Incas provided human offerings, and Nicaraguans held the belief that the volcano Coseguina could only be mollified if a child was thrown into the crater every quarter century. In central Africa, people living near the volcanoes Nyamuragira and Nyaragongo would sacrifice ten warriors each year. In fact, it was only until recently that people in Java, Indonesia sacrificed humans to the Bromo volcano. To this day, they continue to offer live chickens annually as sacrifices. Skeptics of these traditional ceremonies were often countered with the general belief that without the sacrifice, the eruption could have been worse (Sigurdsson et al., 1999).

To explain the formation and activity of volcanoes, primordial people often associated them with myths and legends. 17^{th} to 20^{th} century Aztec mythology weaves an enchanting love story between the gods Popocatepetl and Iztaccihuatl. On his way to reclaim his beloved Iztaccihuatl following a war victory, the enemies of Popocatepetl spread word that he had been killed. This news reached Iztaccihuatl before Popocatepetl did, and she died from grief. Popocatepetl constructed two mountains, placing Iztaccihuatl's body on one, and stands eternally at the other with her funeral torch in hand (Chaney, 2011).

Volcanic eruptions are also deeply intertwined with Greek mythology. Ancient Greeks in 470 BCE believed that volcanic activity was the movement of Titans, giants confined to the depths of the Earth. Of these monsters, Typhon, the firstborn of Gaia and Zeus, had arms that spanned a hundred leagues, eyes that flashed with fire, and a mouth from which hurtling rocks would come. To end his terror, Zeus imprisoned Typhon underneath Mt. Etna. Whenever Typhon stirs in his prison, Etna rumbles and the Earth shakes, and eruptions and smoke envelop the sky (Binney, 2006).

Early philosophers

In 5^{th} century BCE, the Greek philosopher Anaxagoras proposed that eruptions were a result of great winds stored within the Earth. These pent-up winds were forced through

Figure 3.14 Active stratovolcano Mt. Etna overlooking Catania, Italy.

narrow channels and emerged from openings on the Earth's crust. Friction between the air and rock propagated immense heat, which led to the melting of rock and magma formation (Sigurdsson et al., 1999). Aristotle (384-322 BCE) furthered this idea, and also related it to earthquakes (see more in pp.62-68). He believed that the Earth possessed an internal fire. The heat acted on moisture and trapped air, which served as the driving force behind these great winds. The extent of the force behind these great winds then led to volcanic eruptions and earthquakes. He compares this to the internal wind in the human body that becomes pent up and can cause shudders. These ideas were based on observed phenomena including the fiery rush of hot gas through the crater and the glow of magma, which resembled fire. As heat was viewed as a type of motion, this served as sufficient evidence for this set of theories (Firestone, 2006).

Strabo (63 BCE-21 CE) hypothesized that volcanoes that were closed over imprisoned wind and fire, while open volcanoes were vents that allowed for the escape of fire, ignited matter, and water. General acceptance of the association between volcanoes and earthquakes also contributed to his hypothesis that volcanic eruptions would result in less earthquakes as the wind and fire were no longer confined within the Earth (Firestone, 2006).

While Roman philosophers initially accepted the Greek theories of eruption, they eventually introduced their own interpretation. Lucius Annaeus Seneca (2 BCE-65 CE) suggested that heat from volcanoes arises from the combustion of sulphur, bitumen, and other combustibles. He claimed that water gains heat from ground rich in sulphur, and extends this process to explain volcanic eruptions. When the great winds rushed through subterranean cavities containing sulphur and combustibles, heat due to friction would set the fuels ablaze. This explanation became very popular, and was universally accepted throughout the Middle Ages (Sigurdsson et al., 1999).

Pliny the Younger and Mt. Vesuvius

Pliny the Younger was a distinguished Roman senator born into a wealthy family in Bithynia-Pontus of Northern Italy. Orphaned at a young age, he was adopted by his uncle, Pliny the Elder, and was a remarkable student that began practicing law at eighteen (Dill, 2005). Over his lifetime he wrote letters to significant figures in Roman society, which have allowed historians a glimpse of life during the Roman Empire (Radice, 1960; Isager, 2013). These letters recorded observations of government corruption, public unrest, and pivotal events, and were addressed to senators, magistrates, as well as the Roman emperor Trajan (Isager, 2013). Two letters of particular importance were addressed to Senator Tacitus. These documented the eruption of the composite volcano Mt. Vesuvius in 79 CE, which famously buried Pompeii and Herculaneum (Leach, 1990). This eruption is still regarded as one of the most violent and destructive in Earth's history, and claimed the lives of many civilians, including Pliny the Elder (Dill, 2005). In these letters, Pliny the Younger took detailed observations of lava, pyroclastic debris, and gaseous plumes during the eruption.

Figure 3.15 Statue that was previously buried by volcanic ash from the eruption of Mt. Vesuvius in 79 CE.

A long, dark cloud of heated ash rose from the central vent of the volcano, branching into the sky, then dropping onto the surrounding cities and harbour (Firestone, 2006). Rocks showered onto Pompeii and Herculaneum, while large sheets of flames grew and spilled out onto the sides of Vesuvius. Black ash poured down for two days, and a few episodes of tremors rocked the Earth (Radice, 1960). This description was the first detailed account in the history of volcanology, and has led to the classification of similar eruptions as Plinian eruptions and ignited the classification of other types of volcanic eruptions. These are violent eruptions associated with composite volcanoes, releasing a column of ash and gas up to 50 kilometres high, which collapses into a cauliflower-shaped cloud. Composite volcanoes are composed of alternating layers of cooled lava from previous flows. Lava escapes through multiple fissures branching off the volcano's central vent and from afar, appears as sheets of flames on the sides of the volcano (Sigurdsson et al., 1999). Due to its high silica content, this lava is felsic, viscous, and cools to form intrusive igneous rocks containing siliceous glasses such as rhyolite and andesite (Firestone, 2006). The details in Pliny the Younger's letters set a foundation for future studies and expeditions on the morphology and characteristics of volcanoes. From this depiction, historians were also able to recognize the role of Vesuvius in the burial of Pompeii (Isager, 2013).

Neptunists and Volcanoes

Throughout the 18th and 19th century, two groups with opposing theories on the Earth's processes were engaged in a passionate debate (Lyell, 1853).

The Neptunists (see more in pp.4-9), led by American geologist Abraham Werner (1750-1817), placed emphasis on rocks as being formed by floods during the Earth's formation. They believed that heat was not a major contributor in Earth processes and geologic features. In particular, Werner compared the formation of basaltic rock to the precipitation of crystals from aqueous solutions. As basalt has a crystalline composition, he argued that it must have originated through a similar process. Werner and the Neptunists believed that there was no relation between volcanoes and basalt, and that volcanoes were coal deposits that spontaneously combusted with minimal exposure to heat (Firestone, 2006). However upon heating glass slags, Clement Grignon (1745-1820) observed that they would recrystallize as they cooled, which contradicted Werner's ideas that basalt was a product of water deposition. Grignon recognized similarities between the glass slags and crystals formed by volcanoes, and theorized that the cooling of lava was the process behind the formation of basalt (The Geologic Society of London, 2007). This drove the progressive replacement of Neptunist theories with Plutonist ideas throughout the rest of the century (Leddra, 2010).

Plutonism and Volcanoes

While Neptunism maintained that rocks were born from deposition in shallow water, Plutonism (see more in pp.4-9) asserted that heat generated by the Earth's interior was the

Figure 3.16 Basalt rocks in Lassen Volcanic National Park in northeastern California, United States.

driving force behind rock formation (Leddra, 2010). The principal figure behind Plutonism was the Scottish geologist James Hutton (1726-1797). Devoted to fieldwork and the examination of strata, Hutton observed layers resembling basalt in the midst of layers of sedimentary rock. Recognizing that these layers were not volcanic but were indeed igneous, he was able to conclude that these layers formed through the solidification of magma. This demonstrated the intrusion of magma in layered strata (Sigurdsson et al., 1999). Hutton's theory was met with opposition, as it was argued that melting and solidifying crystalline rocks such as granite could only cool into amorphous glass. Therefore, it was unlikely that this process would be able to yield basalt or volcanic rocks (Firestone, 2006). To test the claim that rocks such as basalt originated from magma, Scottish geologist and chemist Sir James Hall (1761-1832) conducted a series of experiments, similar to those of Grignon. Upon converting melted rock to glass then allowing it to cool slowly, Hall produced crystalline rocks with similar texture and resemblance to the original rock samples. These results demonstrated that melted basalt precipitated silicate crystals during cooling, and were further solidified by chemist Robert Kennedy's analysis that the composition of the melts was the same as the original samples. These experiments were an intrinsic component of establishing the origin of basalt, and dispute the Neptunist theory that igneous rocks were derived from an aqueous origin (Sigurdsson et al., 1999). Hutton's doctrine of uniformitarianism also stated that changes in the Earth's crust are due solely to natural processes rather than great cataclysms. Though he was a great supporter of Hutton, Charles Lyell (1797-1875) was aware of the importance of cataclysms, such as volcanic eruptions and earthquakes, as earth processes (Firestone, 2006).

Desmarest and Geohistory

French geologist Nicholas Desmarest (1726-1815) noted that the recrystallization of basaltic deposits as a result of lava flows results in hexagonal columnar structures. This is illustrated by the hexagonal columns of basalt at Giant's Causeway in Ireland, which were remnants from ancient lava flows that had cooled and recrystallized (Rudwick, 2007). In 1771, Desmarest mapped out the distribution of basalt deposits in Auvergne, France and found that they correlated with regions of past and present volcanic activity. In addition, he noted that while basalt was present within valleys, it was also found on hilltops and plateaus (Wood and Ellyard, 2005; Rudwick, 2007).

Figure 3.17 Hexagonal column structures of basalt in Giant's Causeway, Ireland.

This observation allowed him to classify these deposits into modern and ancient lava flows. Modern lava flows formed structures within a weathered crater that was previously a volcanic cone, while ancient lava flows formed freestanding hexagonal prims without craters and were often found on hilltops. Desmarest further divided the two types of lava flows into historical epochs, which he used to investigate the region's geohistory (Rudwick, 2007). His technique, which he referred to as an *analytical route*, proceeds backwards from the present to the past. For example, ancient lava flows contain basalt embedded with gravel and sand, indicating that following the eruption, other processes have occurred and have led to debris accumulation. Basalt with jagged surfaces has not yet been subjected to erosional processes, which suggests that it was formed during a younger epoch. Using these clues, Desmarest was able to determine that certain lava flows were older and younger than each other, and concluded that volcanoes did not erupt simultaneously (Rudwick, 2007). This *analytical route* to understanding the geohistory of volcanic eruptions provided a basis for future studies on past Earth processes (Wood and Ellyard, 2005). Desmarest's contributions served an important role in the history of volcanology, opening up a window for the study of igneous rocks and lava flows in correlation with geologic time (Leddra, 2010).

Evolution of Theory

Volcanology has come a long way from the legends and human sacrifices of ancient civilizations. From the beliefs of early philosophers, the contributions of Pliny the Younger, the great debate of Neptunists and Plutonists, and the work of Desmarest, it is clear that scientific theory has evolved throughout the centuries. Inherently plastic, the field of volcanology will continue to change as new evidence is introduced and new theories are developed.

Protecting Cities and Harbours from Lava Flows

The devastation inflicted by past eruptions has fuelled the development of protective strategies in order to minimize damage. Modern volcanology is an integrated field that uses studies such as seismology and geohistory to predict eruptions and even divert lava flows. The source of inspiration for many volcanologists in modern history was the eruption of Mt. Pelee in 1902.

Figure 3.18 The remains of St. Pierre, Martinique following the eruption of Mt. Pelee in 1902.

Eruption of Mt. Pelee

Towering over St. Pierre, Martinique is the island arc stratovolcano Mt. Pelee. On April 23, 1902, minor explosions occurred at the volcano's summit and St. Pierre was hit by tremors, showered with ash, and surrounded by clouds of sulphurous gas. The crater rim gave way, unleashing torrents of scalding water from the crater lake which mixed with pyroclastic debris to create a lahar that destroyed everything in its path. Despite public fears, civic leaders assured that St. Pierre was safe, and troops were deployed to turn back refugees. On May 8, Mt. Pelee erupted and decimated St. Pierre less than a minute later. The blast left the city in ruins and destroyed twenty ships offshore. Of St. Pierre's population of 28 000, there are only two known survivors (Camp, 2000). Fascinated by the eruption, American volcanologist Frank Perret built an observatory at Mt. Pelee. Amidst new eruptive activity in 1929, Perret remained in St. Pierre and contributed detailed accounts of eruptions and their aftermath (Smith, 2011). As his interpretations of the safety of Mt. Pelee and Montserrat were proved accurate, Perret was also reputed as a forecaster of volcanic events (Giblin, 1950).

Jaggar and Aerial Bombing

Having also visited the site of destruction from Mt. Pelee, Thomas Jaggar (1871-1953) vowed to devote his life to volcanology so that "no more shall the cities be destroyed" (Bolt, A. et al., 1975, pp.330). He strongly believed that experimentation was intrinsic to the development of earth science, and was himself a great field scientist

(Camp, 2000). Financially supported by Lorrin A. Thurston, Jaggar opened the first volcano observatory in the United States at Kilauea, Hawaii (Richardson, 2011). He developed important ideas on the protection of harbors and cities from eruptions, and became the first to employ aerial bombing as a means of deflecting or stopping a lava flow (Apple, 2005).

The people of Hilo, Hawaii first considered the use of explosives to alter the path of lava. Together with Ruy Finch, Jaggar was actively involved in dropping aerial bombs on lava flows to protect Hilo and its harbor in 1935 and 1942. Aerial bombing of a Mauna Loa pahoehoe flow has also been recognized to have slowed and stopped the advance of lava (Apple, 2005). Aerial bombs were also used to destroy the solidified roof of a slag tunnel in order to cool liquid lava and to expel its stream through a different course (Jaggar, 1945).

Chouet and Predicting Eruptions

In addition to locating regions of past and present volcanism, seismology has also facilitated the prediction of eruptions. Bernard Chouet (1945-present) is a Swiss geophysicist that was interested in studying seismic waves produced by volcanoes (Firestone, 2006). Chouet studied volcano-tectonic events and long-period events, two types of seismic waves that volcanoes generated prior to an eruption. Volcano-tectonic events are more common, and appear as brief, short signals with high frequencies. Conversely, long-period events are less common, produce waves with a lower frequency and last for a minute (LeVay, 2006). Prior to Chouet's work, a large emphasis was placed on studying volcano-tectonic events instead of long-period events in order to predict volcanic activity (Sigurdsson et al., 1999).

Chouet decided to take a musical approach in studying these seismic waves, and related them to the harmonics of acoustic sound waves in fluids. He described long-period events as a result of magma pushing through existing cracks within the rock but remaining confined, thereby producing a low-frequency acoustic wave. Chouet believed that long-period events indicated that the volcano was progressively increasing in heat and pressure, as the rising magma is confined by rock (Chouet, 2003; Chouet, 1996). Once the pressure was great enough to remove the overlying rock, an eruption would occur. In examining past eruptions of volcanoes in Columbia and Alaska, he found evidence that long-period events preceded these eruptions. The occurrence of these events had increased, and were happening every two minutes leading up the eruptions (Chouet, 1996). As such, Chouet then used this idea to predict the eruption of the Redoubt Volcano in Alaska on June 1, 1991. The town was evacuated, and affected by an eruption just two hours later, precisely as Chouet had predicted (Firestone, 2006).

By studying the past, volcanologists have gained an understanding of the causes behind eruptions and have used this knowledge to predict future volcanic events. Not only have these advancements protected cities, but they have also saved countless lives. While the havoc wreaked by Mt. Pelee in 1902 can never be undone, it served as a catalyst for developments in the conceptualization and implementation of protective strategies for cities and harbours from volcanic events. From using aerial bombs to divert lava flows to seismology as an indicator for volcanic activity, the contributions from dedicated volcanologists have broadened the field of modern volcanology and its protective applications.

Figure 3.19 Aerial view of the Halema'uma'u plume from The Hawaiian Volcano Observatory at Kilauea, Hawaii.

The Debate over Snowball Earth

The Earth experienced several severe glaciation events between c. 570 - 750 Mya, and some scientists believe that at this time the oceans froze all the way to the equator (Hoffman et al., 1998). The idea that the Earth was once covered entirely by ice during the Neoproterozoic Era is known as the Snowball Earth theory. Snowball Earth is a topic of academic debate with many controvercies in the supporting evidence as our knowledge of the Precambrian period is relatively incomplete. To prove Snowball Earth, supporters believed they needed to present strong evidence that glaciation occurred in the tropics since it was once believed to only reach mid latitudes (Hoffman et al., 1998).

Figure 3.20. Sir Douglas Mawson, who spent most of his life exploring glaciers and glacial deposits in Southern Australia and Antarctica.

Evidence to Support Snowball Earth

In the late 1940s, Sir Douglas Mawson (1882-1958) proposed that glacial deposits discovered in Southern Australia indicated that glaciation had extended to lower latitudes than was believed to be possible and that global glaciation had occurred (see Figure 3.20) (Mawson, 1949). During this time one of Mawson's students, Reg Sprigg (1919-1994), was studying fossils of multicellular organisms, called Ediacara biota, found in younger rocks in the same region. This relationship lead Mawson to also suggest that the end of the period of severe glaciation resulted in the evolution of multicellular organisms (Palmer, 2005). Mawson's ideas were eventually dismissed when it was realized in the 1960s that the continents were not fixed. This meant that the Neoproterozoic glacial deposits in Australia could be explained by the changing position of the continents (UCMP, 2013).

In 1959, a geologist named Brian Harland (1917-2003) and a colleague examined the accumulating evidence related to the Neoproterozoic glaciations, and postulated that there were two periods of global glaciation (Harland, 1964). One of the main lines of evidence he used to support the Snowball Earth hypothesis was that ancient glacial till (tillite) of Neoproterozoic age was widespread throughout the continents. These deposits can only be formed by glaciers; however many geologists believed that these tillites had been deposited when the continents were located near the poles (Harland and Bidgood, 1959). To verify the location of the continents at the time of this extensive ice age, Harland decided to use paleomagnetic evidence. The tillites were not suitable for paleomagnetic studies, but the paleomagnetic signature of surrounding sediments was useful (Harland, 1964). The mean direction of the paleomagnetic field was used as a measure of the true magnetic field during the time of rock formation. Based on his paleomagnetic data, Harland demonstrated that Neoproterozoic tillites in Greenland and northern Norway had been deposited when the continent was in tropical latitudes (Harland and Bidgood, 1959).

By the 1960s, the world was at the height of the Cold War, and the fallout of nuclear attack became the focus of many scientists (Budyko, 1990). It was known that a series of explosions could release enough dust into the atmosphere to potentially block out the sun. The Soviet Union was interested in calculating the severity of a man-made ice age, and a climatologist named Mikhail Budyko (1920-2001) was given the task. Budyko compiled statistics and research relevant to the creation of ice sheets and created an equation to describe the formation of an ice age (Budyko, 1990).

Budyko focused on the knowledge that the Earth's surface temperature is dependent on the amount of incoming and outgoing solar radiation. A portion of the incoming radiation is reflected back into space and is referred to as the albedo. Increasing albedo has a positive feedback because when the amount of ice on the Earth increases, more light is reflected and the surface temperature decreases (Ramstein et al., 2004). Conversely, when the amount of ice decreases, a smaller fraction of radiation is reflected and the temperature increases. The Budyko model predicts that a decrease in radiation of one percent would cause the mean temperature of the Earth to drop by five degrees (Budyko, 1969). Budyko also found that his calculations apply to a critical latitude that is so severely affected by these predicted changes, that they could decrease global temperatures sufficiently to allow glaciation to encompass the entire Earth. However, this equation alone could not prove the Snowball Earth hypothesis as it also can be used to argue against the hypothesis. Conditions leading to ice covering the entire Earth could not have been reversed according to the theoretical formula, as the albedo effect would reflect too much of the sun's radiation to warm the Earth (Budkyo, 1969). This would have caused life to die out and the Earth to freeze permanently.

Many geologists did not believe that the Earth was entirely covered by ice and supporters of the hypothesis needed more concrete evidence. A geologist named Joseph Kirschvink (1953-present) presented data that he believed would end the debate. Kirschvink, a professor at the California Institute of Technology, originally thought that the idea of a Snowball Earth was absurd, but as evidence began to accumulate his curiosity took over (Kirschvink, 1992). He used sophisticated equipment to confirm Harland's findings, that glacial tillites had been deposited while the continents were near the equator. Kirschvink continued his work and coined the term 'Snowball Earth' (Kirschvink, 1992). He eventually realized what Budyko had missed. Budyko's formula only considers incoming and outgoing radiation, but there is a force on Earth that has the potential to greatly impact climate; volcanic activity (Kirschvink et al., 2000). Active volcanism releases carbon dioxide (CO_2) into the atmosphere, which can build up over millions of years. In combination with decreased weathering, this leads to less CO_2 being deposited in carbon sinks and could result in the end of a Snowball Earth through an induced greenhouse effect (Kirschvink et al., 2000).

Another interesting contribution by Kirschvink was the interpretation of banded iron formations as support for Snowball Earth conditions (see Figure 3.21). During a period of extensive glaciation, the ocean would quickly become anoxic and rich in iron (Kirschvink et al., 2000). Melting of the glaciers would have produced cyanobacteria blooms and therefore, an increase in oxygen levels. This would lead to the oxidative precipitation of iron that had accumulated in the ocean (Kirschvink et al., 2000).

Figure 3.21. Banded iron formation with alternating bands of black iron oxides and cherts as described by Kirschvink.

In 1998, a paper was published by a geologist named Paul Hoffman and his colleagues presenting evidence to support the hypothesis that Snowball Earth conditions ended through rapid global warming (Hoffman et al., 1998). Hoffman is a professor at Harvard University and has spent time in Namibia examining Neoproterozoic glacial deposits. He was puzzled by the carbonate deposits that were found directly above the glacial tillites. Carbonate deposits are usually formed in warm, shallow seas, so it was very odd to find them in close proximity to glacial deposits (Stanley, 2009). A colleague of Hoffman's, Daniel Schrag, is a geochemist who proposed that the carbonate deposits, called cap carbonates, could indicate the intense climate change that was taking place at the time. If Snowball Earth had ended abruptly as described by Kirschvink et al. (2000), the CO_2 level would have been as high as 350 times our current level of atmospheric CO_2 (Hoffman, 1998). The extreme greenhouse effect would result in the rapid precipitation of calcium carbonate. Another interesting observation about these cap carbonates is that they have negative carbon isotope anomalies that are consistent with decreased levels of photosynthesis (Hoffman, 1998; McKay, 2000).

How Would Life Have Survived?

Chris McKay is a NASA scientist who was interested in extremophiles and by extension determining whether photosynthesis would have been possible during a Snowball Earth. McKay proposed that modern Antarctic lakes could be used as an analogue for the conditions that would have been present on Snowball Earth. He found that photosynthesis was possible on the basis of three factors. First, the tropics would still be exposed to direct solar radiation and therefore, the thickness of the ice in this region would be limited, as the freezing rate would balance the sublimation rate (McKay, 2000). Second, the ice layers would have been formed through slow freezing of water, which results in clear ice as impurities are excluded. Thirdly, extremophiles continue to survive in harsh environments under metres of ice in Antarctica to this day.

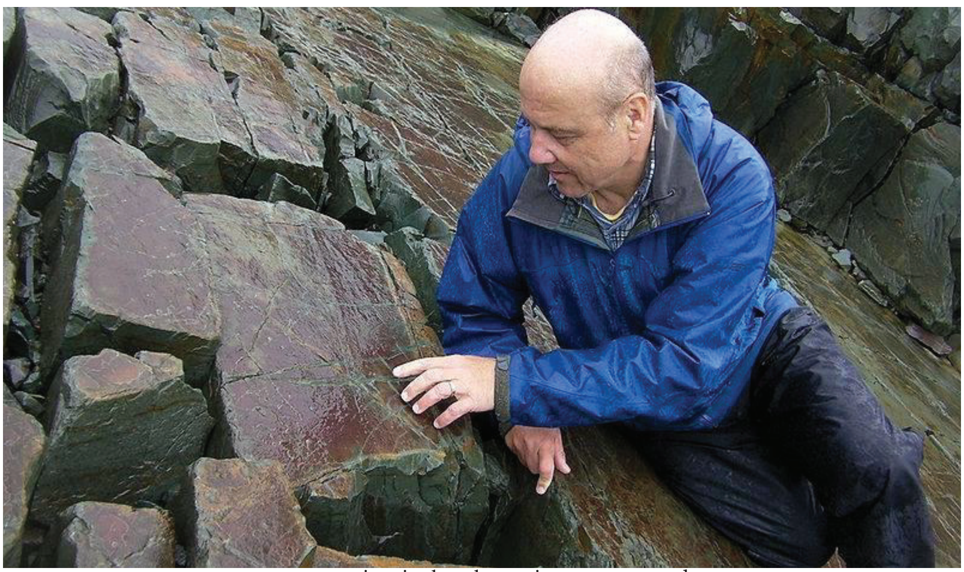

Figure 3.22. Guy Narbonne examining the fossils of Ediacara biota at Mistaken Point, Newfoundland.

The Snowball Earth hypothesis received further support from a Canadian professor currently at Queen's University named Guy Narbonne (Narbonne and Gehling, 2003). He presented evidence to support Mawson's hypothesis that multicellular organisms appeared immediately after the massive glaciation period. Mawson's student, Reg Sprigg, was the first scientist to realize the significance of the Ediacaran fossils as complex organisms in Australia, but those fossils were not old enough to be associated with Snowball Earth. However, the Mistaken Point fossils in Newfoundland are the oldest known Ediacaran fossils and can be linked to Snowball Earth as they lie directly above a glacial deposit dated to the estimated time of Snowball Earth (see Figure 3.22).

Competing Theories

While the Snowball Earth hypothesis has a lot of evidence supporting it, debates are still taking place on whether or not it occurred. While it is widely accepted that there was a major ice age at this time, there are many geologists who do not believe that the Earth was completely covered with ice. This is due to recent findings contributing to the main opposing hypothesis; the "Slushball Earth" hypothesis. Some of the other competing theories are the "Zipper-Rift" and "High Tilt" hypotheses (Zalasiewicz and Williams, 2012).

During the Neoproterozoic Ice Age, some scientists believe that the Earth was largely covered in ice; however, some seaways remained unfrozen, allowing the continuous action of some hydrologic cycles. Another process that this partial freezing permits is the constant exchange of carbon between the Earth and the atmosphere. This is supported by the fact that many models of possible climate during the Neoproterozoic Era suggest that there are some parts of the world that would have had temperatures above 0˚C (Micheels and Montenari, 2008). Also, if the Earth had been completely covered in ice, only a small movement of the glaciers would have been possible. This is a particularly weak spot for the Snowball Earth hypothesis as there is evidence that some Neoproterozoic glacial deposits contain deformed structures caused by glacier movement as well as striated clasts (Hoffman and Schrag, 2002).

This evidence supports the Slushball Earth hypothesis; a term coined by Schrag and Hoffman in 2001 to explain the conditions of a slightly modified Snowball Earth. Climate models created by William Hyde et al. (2000) along with other models created by Thomas Crowley et al. (2001) proposed that there was an area of open water during the

Neoproterozoic Era while the rest of the world was covered by ice. The first climate model suggests that there was a decrease in ^{13}C isotopes that would only have occurred if there was a land mass which contained a small population of organisms, but was not entirely covered by ice. This model takes into consideration many factors, including possible fluctuations in solar radiation, the rotation of the Earth, and heat transfer changes through the ocean glaciers (Hyde et al., 2000). The second climate model suggests that the aforementioned landmasses would have to be a great distance from major glaciers in order to be ice-free. If this model is correct it implies that deglaciation with some open water would require an atmospheric CO_2 level of two magnitudes less than the atmospheric CO_2 level required to melt the glaciers of a Snowball Earth (Crowley et al., 2001; Hyde et al., 2001). Their argument is that when CO_2 levels rise, a major glaciation with open water would not start to disintegrate until a threshold is reached, at which point melting would occur quite rapidly (Hyde et al., 2001). This would also produce cap carbonates, making these common to both scenarios.

Life surviving beyond this major glaciation period is more reasonable with the Slushball Earth hypothesis than the Snowball Earth hypothesis. The very extreme temperatures of a Snowball Earth provide a much harsher environment for the metazoan organisms to survive. It would be very difficult for life to have survived on Earth if it were completely covered in ice, making the possibility of life succeeding the Neoproterozoic Era implausible. The Slushball Earth hypothesis better supports the continuation of life on Earth (Hyde et al., 2001).

The Zipper-Rift hypothesis was created by a professor at the University of Toronto, Nick Eyles, with the help of Nicole Januszczak in 2004 as an alternative hypothesis to that of the Snowball Earth (Zalasiewicz and Williams, 2012). The Zipper-Rift hypothesis is based on the breaking up of the supercontinent Rodinia and its effects. These effects include: rifting as the supercontinent split apart, the localized climate changes caused by rifting, and the resulting rift basins that formed and allowed accumulation of glacigenic sediments (Eyles and Januszczak, 2004). When Rodinia split into different continents, extremely long (over 20 000 km) rift margins were created around their perimeter. These rift margins allowed for the deposition of sediments that are produced in a tectonically active environment. These were deposited in a "zipper" pattern, repeating back and forth from c. 740 Mya to 610 Mya. Some of these diachronous deposits are indicative of glaciation, but not all (see Figure 3.23). When mapped they show when and where sporadic glaciation occurred (Eyles and Januszczak, 2004).

Figure 3.23. Rock formation with interbedded diamictites and cap carbonates in Namibia.

Many Neoproterozoic glacial sediments were originally thought to be tillites (Hoffman et al. 1998), but in fact consisted of diamictites and conglomerates. The assumption of a glacial origin for these deposits has proven to be incorrect as deposits with these characteristics are not unique to glacial environments, and could have been the result of rapid, high energy mass flows such as turbidites. The sedimentary evidence for synchronous, globally severe glacial conditions during the Neoproterozoic appears to be lacking (Eyles and Januszczak, 2004).

The High Tilt Earth hypothesis (sometimes referred to as HOLIST, which stands for High Obliquity, Low-latitude Ice, STrong seasonality) takes a different perspective on the glacial periods during the Neoproterozoic Era (Williams, 2008; Zalasiewicz and Williams, 2012). This hypothesis was created by George Williams in 2008 and focuses on the idea of ice specifically at the equator caused by changes in the Earth's tilt. He proposed that the Earth's tilt was over 54° during this time, whereas it usually ranges from 21.5° to 24.5° over 41,000 years (Schieber, 2007). This would cause the Earth to be colder at the equator than at the poles, accounting for these high seasonal changes and equatorial glaciation (Williams, 2008). A weak point in the Snowball Earth hypothesis is that it focuses on glaciers at the equator as proof for global glaciation, but that is not necessarily true.

Figure 3.24. Graded diamictites, possibly formed from high energy mass flows, found in the Paleo Proterozoic Gowganda Formation in Elliott Lake, Ontario.

In summary, there are four major competing theories about the Ice Age(s) of the Neoproterozoic Era: Snowball Earth, Slushball Earth, Zipper-Rift, and High Tilt (Zalasiewicz and Williams, 2012). These were developed by geologists in an attempt to explain the conditions of Earth's climate at this time, since little relevant information is definitive. As evidence is found, ideas are created and modified to predict future climate change through these four theories. The Snowball Earth hypothesis believes that the Earth was encased entirely in ice approximately 570-750 Mya. Brian Harland was the first geologist to propose the idea in 1959, while the term was coined by Joseph Kirschvink in 1992. The main opposing hypothesis to Snowball Earth is the Slushball Earth hypothesis which was the name created by Schrag and Hoffman, for an idea that Hyde et al. presented in 2000 and 2001. The Slushball Earth hypothesis states that the Earth was mainly covered in ice, except for patches of unfrozen water at the equator (Hyde et al., 2001).

The Zipper-Rift hypothesis was proposed by Eyles and Januszczak in 2004, and states that sediments were deposited in a repetitive, 'zipper-like' pattern as rift basins opened and were filled during the break up of Rodinia. According to this hypothesis, not all deposits interpreted as 'tillites' are of glacial origin. There is evidence that these sediments were instead deposited from high energy mass flows such as turbidites (see Figure 3.24). In 2008 George Williams created another hypothesis, called High Tilt Earth. This hypothesis attempts to explain why it appears the Earth experienced glaciation at equatorial latitudes. Williams explains that if the Earth had a higher tilt, locations at the equator would have been colder and therefore, more susceptible to glaciation (Williams, 2008). The debate over Snowball Earth continues to this day and as more evidence comes to light, hypotheses and opinions will continue to be shaped and change. It is clear that there was a major glaciation event during the Neoproterozoic Era. The severity of this event, however, will continue to be researched to predict future climate change and understand its effects on life.

Is Snowball Earth Possible in the Future?

Climate change has been a popular topic in the last twenty years, but there is still a lot of ambiguity related to how it actually takes place. Geological records are the only source of information about past climate change, but these geological records do not implicate a mechanism for how this change has occurred (Stanley, 2009).

What Could Have Caused Snowball Earth?

The severe glaciations of the Neoproterozoic Era are believed to be the result of the runaway albedo feedback during the break-up of Rodinia (Ramstein et al., 2004). As

Rodinia began to break up there was an increase in weathering from the tectonic uplift of the continents. When the continents separated, large basaltic provinces formed, which were more susceptible to weathering. The smaller plates experienced more precipitation and therefore had more runoff (Ramstein et al., 2004). This effect increased silicate weathering, which lead to higher drawdown of atmospheric CO_2. The greenhouse effect that is involved in warming the planet depends on CO_2 in the atmosphere. When levels decreased, less radiation was reflected back to Earth, through the atmosphere, paving the way for a runaway albedo effect and another Snowball Earth (Ramstein et al., 2004).

Another hypothesis for how Snowball Earth was created relates to the position of the continents after the break-up of Rodinia. Schrag hypothesized that if the continents were lined up in equatorial positions, as is indicated by paleomagnetic evidence, this could have played a large role in initiating Snowball Earth conditions (Halverson, 2002). Continents are more reflective than the ocean, and since the majority of incoming light hits the equator, this arrangement of the continents could have helped the planet to cool. Another, more abstract, idea pertaining to the possible recurrence of Snowball Earth, is that a major event such as the impact of an asteroid or a series of severe volcanic events could initiate conditions which may lead to Snowball Earth.

It is also interesting to note that most of the larger land masses today are located near the poles. Another supercontinent is anticipated to form in the next 250 million years called Pangaea Ultima, and the break-up of this continent is predicted to have a major effect on climate (Williams and Nield, 2007). If the continents were to line up again at the equator, which is believed to happen after the breakup of supercontinents, then a Snowball Earth could occur in the future. The exception to this rule comes from Pangaea which broke up relatively quickly compared to Rodinia and as a result, did not experience a lot of glaciation (Walker, 2003).

Climate Models

It is important to continue to try to decipher the past in order to predict future climate change. One strategy is to use climate models to simulate the effects of various factors on global heating and cooling (Ramstein et al., 2004). Climate models are important as they allow us to study the interactions between the Earth, the atmosphere, and the biosphere to predict future changes. Researchers such as Budyko (1969) and Hoffman et al. (1998) originally analyzed the conditions necessary for Snowball Earth using one-dimensional energy balance models. This method is problematic because these simplified models focus on major factors such as solar luminosity and CO_2 concentrations while neglecting other factors that play a role in glaciation (Jerkins, 2004). These other factors include: atmospheric thermodynamics, cloud cover, the locations of the continents, and the hydrologic cycle; all known to play a large role in climate change. Computer models, called global climate models (GCM), are now available and account for many of these factors (see Figure 3.25). GCMs have been used to both prove and disprove the possibility of a Snowball Earth because the results of these models can be manipulated based on the parameters used. For instance, GCMs that use a slab ocean with no heat transport supports conditions for both a Snowball and Slushball Earth; however use of dynamic ocean processes do not yield these results (Jenkins, 2003). As technology advances, more complex models can be used to predict climate change, however, they are limited to the knowledge available at the time. Future glaciations are inevitable, but whether or not Snowball Earth will occur will remain a mystery.

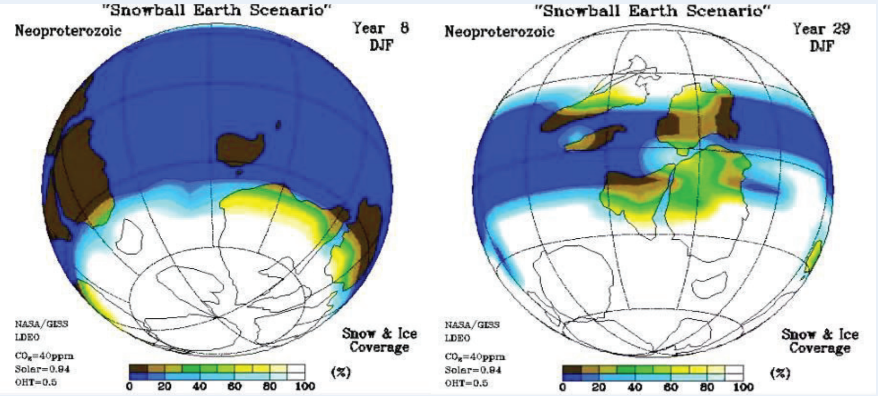

Figure 3.25. An example of a GCM created by Chandel and Sohl to show the spread of low latitude ice sheets from Year 5 to Year 29, initiating Snowball Earth.

An ammonite preserved through replacement fossilization

"Why has not anyone seen that fossils alone gave birth to a theory about the formation of the Earth, that without them, no one would have ever dreamed that there were successive epochs in the formation of the globe."

GEORGES CUVIER

Chapter 4: Fossilization

The word "fossil" comes from the Latin term *fossilis*, meaning "obtained by digging". In ancient China, bones that were found were believed to belong to dragons and were used in sacred rituals (McDaniel et al., 2013). Discoveries and contributions by Xenophanes of Colophon, Shen Kuo and Leonardo da Vinci, emphasized the importance of the observation and classification of natural phenomena.

Many scholars in the 18th century believed that fossils were remnants of the biblical flood (Rudwick, 1985). With the beginning of the Age of Enlightenment, the theories pertaining to the origin of the fossils received increased scrutiny. Martin Lister and John Ray focused specifically on ammonites, which Robert Hooke later believed to be of organic origin. Scientists began to question why fossilized species were only observed in specific sections of the geologic record. Biostratigraphy, the classification of different rock strata based on their fossils, came into existence and lead to the idea of extinction which would provide a framework for many important discoveries in the field of biology (McDaniel et al., 2013).

The 20th century brought improvements in radiometric dating and the geologic time scale. Plate tectonics theory followed, which helped to cement the research done on the expansion of life across the globe.

The tools and techniques involved in fossil studies have also advanced. Aristotle, Albert of Saxony, and many others derived well-supported hypotheses from the direct observation of fossil specimens (Murphy and Kiran, 2012). Early paleontologists had few tools and methods available to them, but figures such as Henry de la Beche began to document their protocols for use by others and fossil studies began to take on a modern standardization. This chapter aims to inform the reader of the continuing study of fossils which is important in understanding evolution and human origin, the relative age of geological features, the understanding of environmental processes, and the ability to predict future environmental events.

Fossils and the Flood: Christianity's Influence on Early Geological Knowledge Regarding Fossils

Figure 4.2. Artist's rendition of the Great Flood.

Often high in the mountains and far from the sea, there existed stony objects that mysteriously resembled shells and marine creatures. While humans had been aware of these objects, now known as fossils, since at least the beginning of recorded history, the discovery of their true origin did not come about until much later in time. Although theories regarding the nature of fossils had been developed earlier, it was the progression of ideas throughout the 18th century in particular that lead to the rationale accepted by modern scientists. Specifically, it was the European naturalists who were responsible for the development of these theories, as the rest of the world at this time was not participating in high-level scientific debate. Interestingly, their theories lead to one of the most notorious cases of the conflict between geology and religion, namely the attempts to interpret certain physical features as evidence of the biblical Flood (see Figure 4.2) (Rudwick, 2009).

The Problem with Organic Fossils

Preceding any theories involving the biblical Deluge were ideas surrounding the inorganic nature of fossils. In the 16th century, many naturalists believed that fossils were jokes of nature created for a variety of mysterious reasons. One such justification was that God had created features in rocks with some resemblance to extant life when he was practicing the creation of the organic world (Young, 1982). Another attributed fossils to vapors being emitted from rocks and a belief that rocks had plastic properties. At this time, fossils were considered to be any dug up objects ranging from what are considered to be true fossils today, to minerals, crystals, ores, and so on. This broad definition made it difficult for scholars to pinpoint their origin (Young, 1982). Philosophical ideas such as Neo-Platonism, which held that there was no sharp distinction between living and non-living things, as well as Aristotelianism, which stressed the importance of exhalation in terrestrial phenomena, also acted as barriers to the realization of the organic origin of fossils (Young, 1982).

Even as the ideas of Neo-Platonism and Aristotelianism lost their persuasiveness in the 17th century, two major obstacles faced naturalists in accepting that fossils were, in fact, organic. The first of these issues was that fossils did not entirely resemble extant organisms. Extinction was not something the Christian naturalists would be willing to accept at the time due to their belief in the concept of the *plentitude of creation*. Their perception was that God, having pronounced his creation to be very good, could not allow any of his creatures to vanish from the Earth (Young & Stearley, 2008a). However, this obstacle could be circumvented by explaining that fossils may have been remnants of organisms that humanity had yet to discover (Young & Stearley, 2008a).

What proved to be the most difficult problem, though, was the position in which most fossils were found. Often they were located at great distances from the ocean, high in the mountains, and embedded within hard rock. As this time period preceded theories regarding plate tectonics and mountain formation, naturalists were in need of an explanation to describe how fossils, especially those of marine origin, came to be at these locations. Even with the realization that some fossils showed tremendous similarities in form to living organisms, their organic nature could not be accepted unless accompanied with an explanation for how they came to be positioned above sea level and embedded in rocks. This issue produced a divide in the scientific community, with some naturalists accepting fossils as organic and others refuting this theory.

The Rise of Diluvialism

There were some individuals, such as the Christian author Tertullian (160-225) in the second century who suggested that the Flood had carried marine creatures onto mountaintops. However, it was not until the work of Niels Stensen (1638-1686), a Danish naturalist, at the end of the 17th century, that this traditional belief received any scientific confirmation (Cohn, 1996). Stensen, known to the English-speaking world as Steno, brought these ideas into worldview in his essay entitled *Prodromus,* or "Forerunner". Within this work he distinguished between inorganic materials, namely crystals, and fossils, which he believed to be of organic nature (Rudwick, 1976a). Thus, he narrowed the definition of the word "fossils", making their organic nature easier to accept. In addition, his essay presented the idea of stratification for the first time, as he established that sediment was deposited as a succession of individual layers in which each layer hardened before deposition of the layer above (Young & Stearley, 2008a). As an accompaniment to this definition he also developed the first classification of strata. He considered the lower, crystalline rocks that he observed in mountains to be primary rocks, and classified the stratified, fossiliferous strata above these as secondary rocks (Young & Stearley, 2008a). He also stated that fossils would have been lodged within sediment as the Flood deposited it layer by layer, thereby providing an explanation for how fossils came to be embedded in rocks (Cohn, 1996).

Steno's diluvial theory was also able to provide a rationalization for the position of fossils. As with many other naturalists at the time, Steno was greatly influenced by the work of René Descartes (1596-1650), who had developed a mechanistic cosmology (Rudwick, 1976a). Steno accepted the Cartesian concept regarding the natural development of the Earth. This involved the belief in an ancient Earth that had originally been a sphere of water surrounded by a smooth, solidified crust (Cohn, 1996). When this crust collapsed irregularly into the subterranean fluid, it formed oceans, continents, tilted strata, and mountains (Rudwick, 1976a). In Steno's attempt to reconcile Cartesian theory with scripture, he also used it to propose a natural cause of the Flood. In his opinion the Deluge was triggered by the crustal collapse, which caused flooding of the subterranean waters onto the crust (Cohn, 1996). With Descartes theory Steno was able to justify the production of mountains as well as the Flood, which allowed for the deposition of fossils onto these mountains.

While Steno's theories were in part based on his observations of the natural world, his work was also influenced by his religion because he felt the need to reconcile his observations with scripture. However, in his mind this was no forced reconciliation, but an amalgamation of what he and his contemporaries believed to be two equally valid sources of information- the Bible and nature (Rudwick, 1976a). Steno was the first to develop ideas related to stratigraphy and the geological significance of the Flood. As a result, he was able to provide a complete explanation for the organic theory of fossils. As such, he was the first proponent of diluvialism and the significance of his work can be seen by its resonance throughout the 18th century.

Woodward's Influences

While Steno brought diluvialism into the realm of scientific thought, it was his successors in the 18th century that took off with the idea. Notably, while many of Steno's publications were forgotten throughout the 18th century, his ideas managed to live on as a result of plagiarism, most of which can be attributed to the English naturalist John Woodward (1665-1728) (Rudwick, 1976a). Woodward's Flood theory was perhaps the most radical, and he too included some concepts regarding stratification. He believed that the Flood had completely dissolved the Earth's crust such that it combined together in a thick slurry (Rudwick, 1976a). As the floodwaters disappeared, he stated that the materials suspended in the water, which included the bodies of plants and animals, settled out more or less deeply according to their specific gravity. According to Woodward, all fossils were originally deposited horizontally until some time near the end of the Flood in which heat from within the Earth caused some strata to rise and other strata to sink, forming mountains and valleys (Cohn, 1996).

Like Steno, this concept was developed as the result of scientific observation and religion. Due to his familiarity with the work of Newton (1642-1727), he believed that solid bodies were cohesive due to gravity. He reasoned that if gravity were halted, all earth material would dissolve. Due to his religious beliefs, he considered it plausible that God would have governed this suspension at the time of the Flood (Rudwick, 1976a). This theory was developed so that he could explain both the order of strata and fossils that he observed (he noticed that heavier types of rocks and fossils were located beneath other layers of sediment). His theory was not based on overly accurate observations, as he did not make careful enough measurements to realize that rock layers were not laid down in order of decreasing specific gravity (Young & Stearley, 2008a). However, since his theory allowed for the acceptance of the organic nature of a wide range of fossils found in a variety of strata, he motivated other naturalists to carefully describe and document fossil remains.

Figure 4.3. Scheuchzer's Homo diluvii testis, the fossilized skeleton that was misinterpreted to be that of a human, specifically a victim of the Great Flood, for decades.

Scheuchzer's *Homo diluvii testis*

Following the presentation of Woodward's theory, the description and documentation of fossils and their organic interpretation became motivated primarily by the desire to prove the reality of the Flood (Rudwick, 1976a). This becomes evident in the work of the Swiss naturalist Johann Jakob Scheuchzer (1672-1733). Scheuchzer had originally believed fossils to be of an inorganic nature until he was converted after reading one of Woodward's essays. From there, Scheuchzer became the leading advocate of diluvialism (Cohn, 1996). Scheuchzer's leadership in this field can be attributed to his efforts to find the fossil remains of an antediluvian human. In 1725 Scheuchzer misinterpreted a large fossilized skeleton as being human, which he even gave a scientific fossil name: *Homo diluvii testis,* "Man who witnessed the Flood" (see figure 4.3). His discovery caused a sensation and it was widely accepted that this skeleton was indeed the remains of a Flood victim. It was not until nearly sixty years later that his error was detected (Cohn, 1996).

Due to the work of Steno, Woodward, and Scheuchzer it became accepted that fossils were the remains of living creatures whose deposition and position could be attributed to the Flood (Cohn, 1996). However, due to stratigraphic investigation carried out by succeeding naturalists, this idea became hard to sustain.

The Fall of Diluvialism from a Fossil Perspective

Woodward and Steno's theories promoted the organic interpretation of fossils, but they also focused attention on the diluvial origin of fossiliferous strata as they suggested that they were deposited in sequence at the time of the Deluge. As a result, in the mid- 18th century, a classification of rocks was developed by a variety of naturalists that was essentially an extension of Steno's thoughts (Rudwick, 1976a). The unfossiliferous, ore-bearing strata seen in the outcropping of mountain regions were called "Primary" and were believed to have resulted from the original consolidation of the Earth's crust. The stratified rocks containing fossils on top of this layer, typically seen in the outcropping of hills, were termed "Secondary". Notably, many attributed the deposition of these secondary rocks to the Deluge. Succeeding these layers were irregular superficial deposits termed "Tertiary", which were mostly unconsolidated and considered to be the product of the recent post-diluvial period (Rudwick, 1976a).

Moving into the late 18th and beginnings of the 19th century, William Smith (1769-1839), a British engineer, was responsible for conducting one of the most accurate investigations of the secondary rocks of England (Young & Stearley, 2008b). He discovered the connection between types of fossils and the regularity of strata, and published volumes and maps outlining the characteristics of these strata. He was a very practical geologist and did not propose theories for how the strata had been laid down; rather he simply described his observations (Young & Stearley, 2008b). With the knowledge of his work, other geologists began experiencing difficultly reconciling the strata with the biblical Flood. Firstly, his observation that fossil remains were restricted to certain strata did not agree with Flood theory because a violent flood would have produced a more chaotic and mixed array of fossils (see Figure 4.4). Also, the sheer thickness of the secondary strata made it seem unlikely that it could have been produced by the Deluge, as its deposition would have most likely taken place over a long period of time (Young & Stearley, 2008b).

While William Smith was able to spread his knowledge throughout England, his low social position and lack of leisure from practical work prevented him from publishing his findings in a way that was accessible to the international scientific community (Rudwick, 1976b). In France several years later, Georges Cuvier (1769-1832), a renowned anatomist with an interest in the earth sciences, came to similar conclusions while studying the stratigraphy of the Paris region. He observed that the basin contained alternating layers of limestones, which contained marine fossils, and layers of gypsum-bearing mudstones containing the remains of land flora and fauna (Rudwick, 2008). These observations lead Cuvier to conclude, independent of William Smith in England, that groups of strata could be characterized by the wholly unique fossils embedded within them (Young & Stearley, 2008b). Cuvier also had difficulty reconciling his observations regarding the distribution of fossils with the action of a single universal flood. He observed the thickness of the marine deposited strata and the detailed preservation of fossils within them, which lead him to propose that they would have had to have been deposited in a tranquil ocean over a long period of time (Turner, 1832).

Additionally, since the fauna within one group of strata would appear to have been replaced by wholly new faunas in successively younger rock strata, Cuvier was able to use his observations to scientifically assert, for the first time, the concept of extinction (Young & Stearley, 2008b). This more successfully and thoroughly solved one of the problems associated with the organic nature of fossils discussed earlier, however, it could still not account for the position of fossils. This problem, accompanied by Cuvier's observations of the interchanging terrestrial and marine strata in Paris, lead to the development of the theory of catastrophism. He proposed the idea that the globe had experienced a series of "revolutions" or catastrophes, many of which he believed could be connected to some type of flooding (Young & Stearley, 2008b). Cuvier never explicitly stated that Noah's Flood was not one of these revolutions, however, he did mention that no human fossils were ever found. This indicated that humans did not exist at the time of the flood; therefore the type of flood that he considered being involved in the revolutions did not seem to be analogous to the Flood described in Genesis (Rudwick, 2008). Cuvier was also the one who pointed out the mistake of Scheuchzer, as he analyzed the *Homo diluvii testis* fossil only to find that it was, in fact, a giant salamander (Young & Stearley, 2008b).

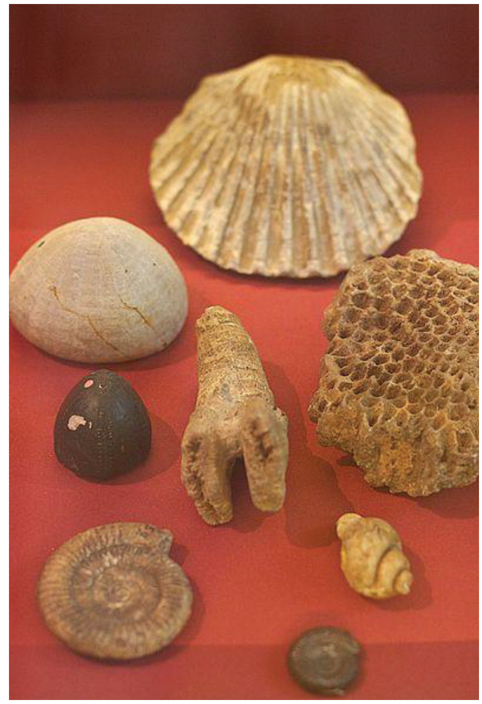

Figure 4.4. Fossils collected by William Smith as he postulated the relationship between fossil type and the regularity of strata.

The reason Cuvier never explicitly stated whether or not the biblical Deluge could have been one of the revolutions he hypothesized, likely had to do with the fact that he kept his religious beliefs separate from his scientific work. Although a strongly religious man, he did not attempt to use his physical observations to explain his beliefs. He was known to have never come to a conclusion without having sufficient information to back it up (Rudwick, 2008).

While neither of them was entirely in agreement with modern geological concepts, the stratigraphic observations of Smith and Cuvier gradually carried attention away from the Flood and provided more scientifically based theories for the nature of fossils. It is important to note that the concept of diluvialism lived on for sometime after the discoveries of Smith and Cuvier. Specifically, some scientists attributed gravel deposits across Europe as having a diluvial origin (Rudwick, 2009). However, Louis Agassiz (1807-1873) who was a student of Cuvier later proved that it was the activity of glaciers that resulted in these and other formations in the area (Rudwick, 2008). As for the position of fossils, this problem was eventually correctly accounted for, as Cuvier's proposed revolutions did not provide an accurate solution. The clarification of this issue began in the 19th century when Charles Lyell (1797-1875) suggested that active processes such as volcanism and earthquakes lead to the gradual elevation of strata (Rudwick, 1976c). In subsequent centuries, as the antiquity of the Earth became known and theories involving plate tectonics were developed, human understanding regarding the deposition of fossiliferous strata continued to grow. As a result, it required the contributions of many more individuals and an even greater amount of time to acquire the understanding of fossils that scientists possess in modern times.

While diluvialism turned out to be incorrect, it allowed for one important truth to be discovered- fossils were organic formations. The incorporation of religion into science allowed naturalists in the 18th century to accept this fact when they did not possess enough observational evidence to substantiate it. As a result, the realization that fossils were organic forms lead to many other valuable scientific contributions. While the case of faith and science discussed here could be used as evidence for those wishing to disprove religion, another interpretation exists. Interestingly, the men who contributed to the invalidation of diluvial theory were very religious individuals. However, it is important to point out that they separated their scientific and religious ideas. They based their theories solely on their observations, and did not try to reconcile them with the Bible or use the Bible as a source of scientific fact. This exemplifies the learning process that took place throughout the 18th century, which revealed that science and religion could exist in harmony as long as nature and the Bible remained as two distinct entities for sourcing information.

Paleoenvironmental Reconstruction through the Analysis of Fossilized Plants

Like Cuvier and the many scholars that came before him, scientists today attempt to reconstruct paleoevironments by analyzing fossils. Plant fossils in particular are the type of fossils that have recently become popular in these reconstructions. There are many different methods that are used to do this, some requiring intricate analysis of fossils through the use of microscopes, and others requiring the identification of nearest living relatives for comparison. These techniques have evolved from the 16th century due to the progression of technology and advancement of knowledge through the ages. Cuvier, for example, noticed marine deposited strata with shell-like fossils around Paris, and implied the presence of a deep marine environment; however, nowadays there is a lot more information that can be extrapolated from a fossil- especially that of a plant. Plant fossils provide important details of their surroundings at the time in which they lived. Specifically, the imprints of leaves are studied to gain paleoenvironmental information (see Figure 4.5).

One basic technique that is used is to identify a modern plant that most closely resembles the fossil in question (Seyfullah, 2012). The climate in which the analogue lives can then be used to identify the type of climate the ancestor existed in. An example of this is the discovery of *Nyssa* (tupelo) fossils in the Rhine area of Germany. These plants existed there in the Miocene era, but no common ancestors survive in Germany today. Instead, the closest relative was found in hot, humid areas of the Mississippi. It can now be inferred that in the Miocene era, the Rhine area of Germany was hot and humid as well (Seyfullah, 2012).

If no relative of the plant can be found, a more complex analysis can be done (Seyfullah, 2012). The Climate Leaf Analysis Multivariate Program (CLAMP) involves the statistical analysis of the features of modern day plants to determine the reason for their appearance. For example, statistical analysis has shown that leaves with smooth edges dominate in warmer climates, whereas leaves with jagged edges dominate in cooler climates (Seyfullah, 2012). Many analyses have been done on all different features of plants. In this way, by identifying features on a fossil plant, the environment in which it lived can be extrapolated. This technique is not perfect, and can result in many uncertainties. The analyst must also be objective in their enquiry, as any prior knowledge of the fossil can influence their examination (Seyfullah, 2012).

Other parts of the leaf of a plant that can be used to identify its environment are the cuticle and stomata, specifically their densities (Seyfullah, 2012). These cannot be studied without the use of a microscope. Plants that have a thicker waxed surface called a cuticle are known to live in environments with less water, whereas plants with thinner cuticles are found in environments where water is more abundant. Stomata indicate carbon dioxide levels, with high CO_2 levels being indicated by fewer stomata, and windy conditions with many stomata. Heightened CO_2 levels generally indicate a warmer climate (Seyfullah, 2012).

Radiocarbon dating may be used to determine the type of plant that lived in a region at a certain time. By identifying the carbon the plants used for photosynthesis, the environment in which they lived can be determined (O'Leary, 1988). This method is based on the decay of certain elements found in fossils, in this case carbon. The most stable isotope in the atmosphere is ^{12}C, however ^{13}C and ^{14}C are also present. The ratio of these isotopes in the atmosphere and in living plants is generally the same. Once the plant dies and ceases to intake carbon, the radioactive ^{14}C decays with a half-life of 5730 years (Plummer et al., 2007). The carbon isotope composition of plant material can be used to determine when the plant died and what the ratio of carbon isotopes in the atmosphere was at that time, as well as what type of plant it was. C_3, C_4 and CAM plants live in different environments and each intake a different ratio of these isotopes (O'Leary, 1988).

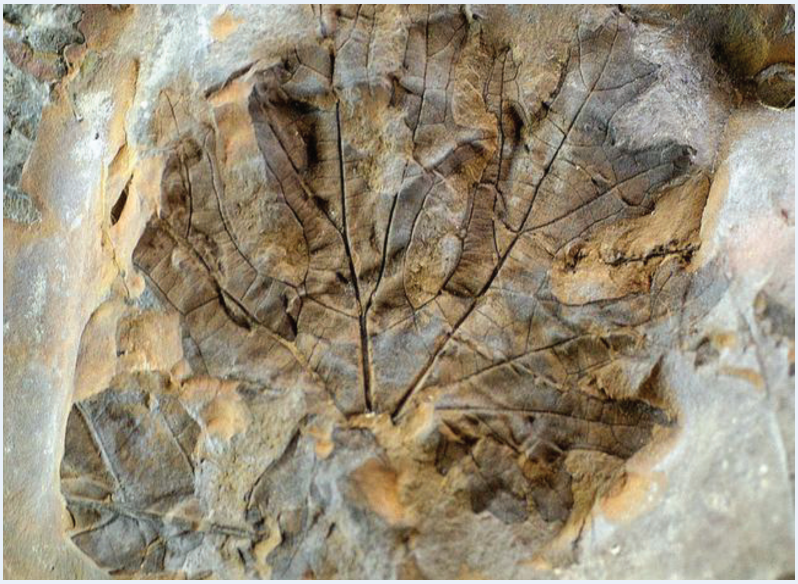

Figure 4.5. Angiosperm leaf from Alberta from which characteristics can be identified and used to find a modern day analogue to reconstruct the environment this leaf could have been in.

A less common method of determining climate from plant material is the analysis of fossil wood, for the simple reason that it is not a very common fossil to find (Seyfullah, 2012). If the horizontal cross section of a tree is preserved in the fossil record, the rings can be analysed. Because trees have constantly replicating cells that form rings as they divide, the conditions under which they have replicated can be seen. This is especially useful in annual climate analysis because it does not exclusively provide a broad-spectrum analysis like the other techniques. A thick ring indicates that the tree underwent optimal growth conditions with appropriate temperature and weather, whereas thin rings indicate abnormal temperatures that are not ideal for growth (Seyfullah, 2012).

The techniques for determining paleoenvironments have changed dramatically throughout the years. From the development of theories in the 16th century, to applying these theories with the help advanced analytical techniques, scientists today are able to create an accurate reconstruction of past environments using fossil materials.

Evolution of Fossil Excavation in North America

The fossilized remains of biota have been investigated for hundreds of years, with contributions from notable philosophers such as Anaximander (7th century BCE), Aristotle (4th century BCE), and Aristotle's student, Theophrastus (Marsh, 1879). Paleontology is defined as the study of fossils, a term first used in the early 1800s (Plummer et al., 2007; Wolfram, 2013). As Othniel Charles Marsh stated in an 1879 publication, much of the earliest paleontological work was not based on well-defined or described practices (Marsh, 1879). It was not until the 19th century that there was an emergence of standardized descriptions and protocols for paleontological practices. The earliest recording of such information is said to be made by George Cuvier in his 1804 publication, *Description des os du megatherium* where he carefully describes removing a marsupial skeleton from a basin with a fine pointed steel tool (Whybrow, 1985).

Although the 1800s saw an initiation of standardized documentation, there were still lackluster recordings of the paleontological process. In the 19th century, North American geologists found themselves entangled within serious conflicts with the Aboriginal peoples (Fenton, 1933). These conflicts greatly slowed work and made expeditions dangerous as scientists were prone to frequent attacks by Aboriginal peoples on their native lands. In addition to the direct physical dangers, the collected materials and excavation sites were often sabotaged by the natives as well. To protect themselves, the American scientists often brought guns and ammunition as a means of defense (Fenton, 1933). These precautions were a response to the political instabilities that existed but limited the materials and equipment that could be brought for the actual paleontological work itself. Fortunately, these ethnic conflicts were eventually reduced, if not eradicated, by the late 19th century (Fenton, 1933). This allowed paleontologists to completely focus on their excavations and properly record their work. ethnic conflicts were eventually reduced, if not eradicated, by the late 19th century (Fenton, 1933). This now allowed for paleontologists to completely focus on their excavations and properly record their work.

Henry de la Beche

Although the 19th century lacked an adequate community of paleontologists, some individuals presented the public with their findings. One individual was Henry de la Beche (see Figure 4.6), a cadet in the Royal Military College in England until he was expelled from the institution in 1811 (Whybrow, 1985). After being thrown from the institution, de la Beche worked on palaeontological studies by collecting, describing samples, and collaborating with other prominent figures including Mary Anning (Whybrow, 1985). His efforts played an important role in various advancements in geology including the collection of a plesiosaur (Whybrow, 1985) and the development of mountain building theories (Gerstner, 1975). In 1836, de la Beche also produced an early and complete field guide for collectors that was titled "How to Observe - Geology" (Whybrow, 1985).

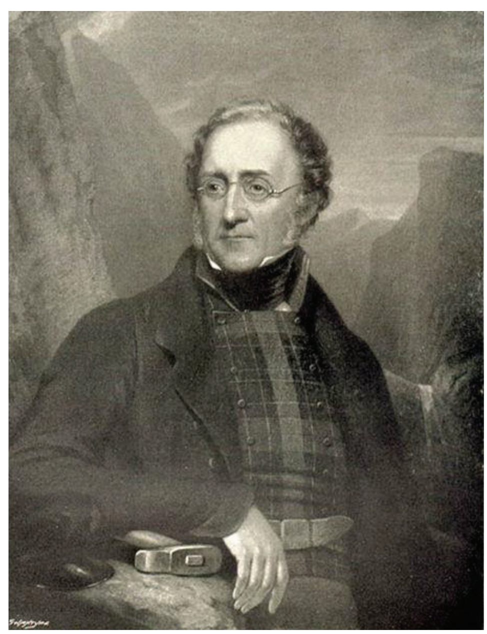

Figure 4.6. Henry de la Beche, made significant contributions to the paleontology community, making one of the first efforts in standardizing and describing the collection process in detail.

In this book, as well as in other publications, he describes numerous geological techniques that may be used at excavation sites. De la Beche describes differentiating between siliceous sandstones and limestones by means of applying a small amount of muriatic acid to the stone (de la Beche, 1836). He also outlined clear methods of fossil collection and isolation, the important details of which were reiterated for decades. He insisted that fieldworkers should record the particular details of their excavation process in their field books. Specifically, he advocated the documentation of events for each individual specimen collected. De la Beche also noted the effectiveness of strengthening specimens with encased plastering during excavation. The sample, now embedded in plaster, was easier to remove (Whybrow, 1985). Such attention to recording one's work, and using careful innovative protocols, is repeatedly reiterated throughout his many publications. With these clear efforts for improvement, De la Beche paved the way for future standardizing procedures in the field of paleontology.

The 20th Century

By the turn of the century, the appearance of the Second Jurassic Dinosaur Rush led to the development of further improved paleontological methods (Brinkman, 2009). With the frenzy of excavations and collecting during this period, monographs and articles show the evident advancements in paleontological work. Museums in New York, Pittsburgh, and Chicago amassed large collections of bones and produced many dinosaur skeletons to be mounted for public viewing. With this growth of fossils to showcase, there also came a demand for standardizing efficient protocols for paleontologists to follow (Brinkman, 2009).

The efficacy of these early methods of documentation was insufficient to obtain adequate results during the Second Jurassic Dinosaur Rush. With the demand for improved techniques, the paleontology community began to share and publish their best methodologies for work (see Figure 4.7). This ultimately led to the standardization and improvement of paleontological fieldwork and preparation (Brinkman, 2009).

Developments in Field Collection Technique

By the first quarter of the 20th century, better techniques were introduced to alleviate prior issues and were described in more detail. At this time, fossils were isolated through the removal of surrounding rock by progressively more cautious techniques (Fenton, 1933).

A fossil's surrounding matrix, known as overburden, was removed using picks and shovels. If a large amount of overburden existed around a durable fossil, dynamite and horses could be used to assist in the matrix removal (Fenton, 1933). Once the large sections of unwanted material were cleared out, any leftover matrix could be picked away with a trowel, a scraper, and a camel hairbrush. The boundaries of the fossil would be defined and then trenches would be dug around the specimen (Fenton, 1933). After cutting underneath the specimen, the isolated portion of rock, with the fossil still partially embedded, would be removed. This was preferably done with a block and tackle, as opposed to manually lifting, to reduce the strenuous efforts of the workers. At this point in the process, the specimen was then packaged within various mediums, as well as physically encased for further protection (Fenton, 1933).

Despite these known procedures, the excavation of delicate

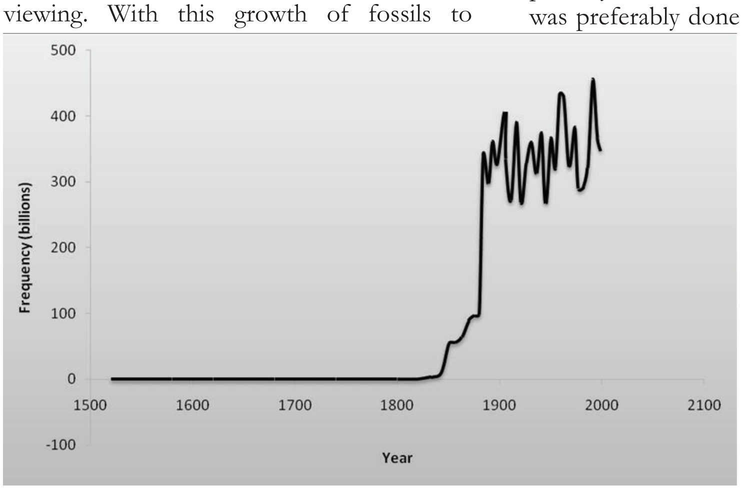

Figure 4.7. The line-graph (left) displays the number of recorded instances of the use of the word "paleontology" in billions for various years and shows the rapid development of the field towards the 21st century. The raw data were obtained from Wolfram Alpha (Wolfram, 2013).

fossils often resulted in the crumbling and fragmentation of the specimen (Hermann, 1909). It was not uncommon for the brittle fossils to develop severely challenging breaks, from which the resulting fragments were near impossible to reassemble (Brinkman, 2009). This was a significant implication for the individuals responsible for preparing the samples in laboratories. These workers often dreaded the condition of severely broken specimens brought from the field and urged for better technique and caution. Hermann, who at the time was working in the American Museum of Natural History, provided methods to alleviate some of these inefficiencies and published his findings, a benefit for the many people collecting specimens (Hermann, 1909).

Figure 4.8. Elmer Riggs (above) beside a specimen that underwent the bandaging process in the field. This bandaging helped strengthen any fossils during the vigorous excavation procedures (Hermann, 1909).

Hermann noted various ways of strengthening brittle fossils. Arabic gum was used to strengthen softer bones, a practice that was also used in the 19th century. However, this method was soon recognized to be flawed (Hermann, 1908). Although it was effective in strengthening very porous bones, thicker bones did not allow the gum to fully penetrate the outer layers. This ultimately led to the insufficient strengthening of the fossils and a need for improved materials and methods (Hermann, 1909). Hermann found shellac to be superior to gum arabic due to its waterproofing and penetrating characteristics. The application of shellac proved an effective and efficient solution on many excavation trips (Hermann, 1909).

Having been treated, these fossils were then covered in a layer of burlap, rice paper, or tissue paper and any cracks were mended and reinforced. The unit was then cast in a hard outer layer in a fashion similar to that of papier-mâché (see Figure 4.8). As well, they often used wire, wood, or iron splints to add strength where it was needed before the sample was transported (Fenton, 1933). This process was referred to as 'bandaging' and was useful in preventing the breakage and fragmentation of fossil samples in transport (Hermann, 1909).

At the labs receiving the raw collections, the fragments of fossils were reassembled and strengthened with brass or steel (Fenton, 1933). These standardized methods provided paleontologists with a basis for the development of other practices for fossil preparation.

Developments in Fossil Preparation

When brought back to the laboratory, it was the preparator's job to isolate, assemble, and repair the collected specimens for display in the particular museum (Hermann, 1909). The 20th century saw the growth of large, well-funded, urban museums which ultimately helped the modernization and improvement of preparator technique (Brinkman, 2009). Establishments such as the American Museum of Natural History in New York, the Carnegie Museum in Pittsburgh, and the Field Columbian Museum in Chicago all experienced growth in their respective paleontology departments. This was greatly facilitated by the creation of dedicated laboratory spaces (Brinkman, 2009).

As collecting continued at an astonishing rate, the existing lab spaces became overburdened with the sheer volume of samples (see Figure 4.9). An example of this can be seen in the American Museum of Natural History in New York (Brinkman, 2009). The Department of Vertebrate Paleontology storerooms had insufficient quarters for lab work to be comfortably and efficiently done. Fossils were placed in trays, which were then stacked on top of each other without any racks. This meant that accessing fossils required un-piling and re-piling specific trays to obtain the sought fossil (Brinkman, 2009). Similarly, the tables with oversized specimens also required further stacking due to inadequate floor space. Along with boxes that were stacked in an equally inconvenient manner, there was a definite lack of lab space for the preparators to work (Brinkman, 2009).

Figure 4.9. Elmer Riggs (left) beside the vast amount of specimens being brought into the lab space, showing how cluttered it was during this time period (Fenton, 1933).

Other museums saw similar spatial issues. Individuals like William J. Holland of Pittsburgh's Carnegie Museum did not take these issues passively and requested more space for their preparatory work (Brinkman, 2009). Holland was able to get the Committee on Buildings to provide a new larger space for the lab and storeroom. Eventually, the museum management saw that with a growing demand for fossil exhibitions, there also was a need for the expansion of lab spaces (Brinkman, 2009).

As collectors continued to scavenge the United States, amassing large collections of fossils in need of processing, there soon became a bottleneck with the preparators being overwhelmed with samples (Brinkman, 2009). Their work included removing excess matrix from the bones so they could repair and piece the collection together for public displays (Hermann, 1909). The bottleneck in their process was caused by the inefficient equipment that was used in the lab (Brinkman, 2009). Using chisels and awls, the repetitive tapping and chipping away of the excess matrix was quite tedious for the preparator. Often, workers would experience pain and exhaustion, and the specimens themselves would undergo breakage (Brinkman, 2009). Even though shellac was used to strengthen fossils, there was a definite need for the development of newer, faster, and more accurate techniques to improve efficiency and reduce the frequency of mishaps.

Some individuals investigated the use of technologies used in other fields of work. Hermann looked into the dental industry for inspiration and started using electric dental lathes and engines in his work (Brinkman, 2009). John Bell Hatcher of the Carnegie Museum similarly found improvements by using electric mallets and lathes (Brinkman, 2009). Eventually, by sharing and accumulating knowledge on the subject, the paleontology community was well informed of developments in the techniques used. For example, Elmer Riggs (see Figure 4.9) of Chicago's Field Columbian Museum created a device which became highly sought after for its speed and ergonomic characteristics (Whybrow, 1985).

Attempting to improve the original hand tools of preparators, Riggs developed the pneumatic hammer in 1903 (Whybrow, 1985). Through modifying and experimenting with prototypes, he produced a pneumatic tool that used hammers or drilling tips to easily chip away the matrix. The device consisted of a pneumatic engine, pressurized tank, piping, and a pressure gauge (Brinkman, 2009). It was capable of producing a hammering action at greater than 3000 strokes per minute, but did leave much room for improvement in its design (Brinkman, 2009). The papers and lectures about this new form of preparatory equipment proved a convincing advertisement to others in the field. Riggs was eventually able to implement his pneumatic system into other paleontology laboratories to help increase their productivity (Whybrow, 1985).

In addition to these mechanical advancements, improved chemical methods also aided the excavations. Chemicals in early paleontology were not limited to strengthening the fossil material itself, but were also used in creative ways to isolate the fossil structures. A rather intricate technique was introduced in 1928 by John Walton to transfer fossilized plant materials contained in coal to a cellulose film that could be mounted onto a microscope slide for analysis (Davies, 1947; Walton, 1928). Walton showed that since hydrochloric acid degrades the carbonate of coal balls faster than the fossilized plant materials, it could be used to reveal a section of fossil in relief. This protruding section of fossil is then coated in a cellulose solution which is then allowed to dry. The section of plant fossil then becomes embedded in the cellulose film. Pulling the film away from the coal surface draws the plant material along with it (Walton, 1928). By grinding the surface down and repeating the procedure, thin sections throughout the entire fossil could be made and preserved. The sections could also be mounted between a cover slip and slide in Canada balsam. Before the introduction of this method, researchers would shave or grind off a thin section at a time and examine the remaining face on the coal ball or photograph the face for documentation (Davies, 1947). This method was important because it provided a means to section the samples, and also to preserve the physical information.

The Second Jurassic Dinosaur Rush marked a significant period for the development of paleontological technology and practices due to the introduction and communication of innovative methods. With the spike in the number of collected fossils, this particular community was forced to improve the overall process of fossil excavation and they did so with success.

In the years to follow, with more information being published regarding specimen collection, techniques became further refined and specialized for different scenarios. Henry de la Beche initially stated that it is preferable to avoid cleaning the fossil samples on the spot unless they are very large and would thus be too difficult to transport (Davies, 1947). In addition, the practice of carefully notating samples and recording information regarding their collection became the norm. The ways in which fossil extraction was conducted became very diverse, as evident in the 1947 monograph titled "An Introduction to Paleontology." Within this work, methods for removing fossils from hard and friable rock are discussed at length. Professor A. Morley Davies, the author, described that while strong fossils may be removed from hard rock by simply impacting the surrounding rock with a hammer, the fossil is often too delicate and requires more care. For fragile fossils in hard rock, or where the rock was otherwise too tightly bound to the surrounding matrix, it was common to heat the sample and then rapidly cool it by immersing it in cold water to break the matrix. The use of chemical treatment also began to gain popularity and was described by Davies for the removal of matrix surrounding a fossil. His text suggests that various acids may be used, but for calcium rich fossils it is advisable to use a caustic substance instead, such as potash. These methods have developed considerably since their introduction and their application has been refined over time.

Digging into the Code of Life: DNA Preserved in Amber

Amber has been recognized as the product of a plant secretion since 77 CE, when Pliny recognized its origin and wrote about it in his work "Historia Naturalis" (Langenheim, 1990). The mineral (see Figure 4.10) is produced through the fossilization of resins produced from trees, which may be either comprised of terpenoids or phenolic compounds depending on the species that produced it (Grimaldi, 2009). These compounds are produced within ducts or in surface glands, which can then be fossilized through polymerization of diterpenoids followed by the gradual crosslinking and isomerization of the contained molecules, allowing the resins to resist chemical breakdown (Langenheim, 1990). Small amounts of other compounds within the resin, such as gas bubbles, can become trapped and preserved within the fossilized resin. More impressively, biologic tissues from flowers and insects have also been preserved due to inert dehydration and embalming from the resins (Langenheim, 1990). These high quality preserved remains introduce new possibilities for fossil investigations.

In the early 1990s, at the start of the Human Genome Project, researchers were making efforts at sequencing more than just the human genome: they had begun efforts in the isolation and amplification of ancient DNA. Amber acted as a well-suited medium for preserving the nucleic acid polymers, and presented itself as the optimal candidate for the endeavor. An early attempt was made by DeSalle et al., (1992) and reported having extracted a 25 million year old DNA sample. Their study started with a sample of amber containing *M. electrodominicus* which was dissected with a sterile razor to remove small soft segments contained within the hardened mineral. The DNA was found to be highly degraded and in general, isolated fragments were less than two-hundred and fifty base pairs in length (DeSalle et al., 1992). Though the results were limited, it was still sufficient for comparison with extant, similar species and showed how much the genetic composition of the extant and fossilized specimens were related. However, the researchers also admit that contamination is difficult to negate, and that these contaminant sequences are also amplified during the DNA amplification (PCR) process (Ross, 1997).

Much skepticism has been raised around several of the experiments making claim to have isolated genetic material from ancient specimens. An example of such a case is the report published in 1994 by Woodward and co-workers that made claim to have isolated 9 fragments of mitochondrial DNA of roughly one-hundred and seventy base pairs long from a bone roughly eighty-million years old (Austin et al., 1997). The bone was found at a coal seam which was likely deposited in a coastal deltaic environment, where it would have been buried roughly 3 kilometers underground and subjected to over ninety degree Celcius temperatures. These conditions would have made the preservation of DNA essentially impossible, leaving great skepticism around the discovery. It has instead been suggested that what had actually been found was a contaminant of mammalian origin, specifically a human pseudogene sequence (Austin et al., 1997). The fossilization conditions of the specimen plays a vital role in what information can be preserved.

Figure 4.10. Insects, such as the one pictured here, have been found preserved within amber on many occasions. The soft tissues of the biological inclusions are impressively preserved due to the inert environment the fossilizing lignans provide (Langenheim, 1990).

DNA has been shown to rapidly degrade, especially in the presence of water, which brought much skepticism to the authenticity of the retrieved fragments. The dehydration properties of the resin fossilization process help in preserving such delicate biomolecular compounds, giving possibility for the isolation of authentic, ancient, DNA (Ross, 1997). This requires great care on the researchers behalf and the use of negative controls (PCR of contaminants) to identify artifactual sequences. The strict requirements are necessary because PCR will favourably produce better quality DNA, so the newer contaminant DNA sequences are amplified more readily than the damaged sequences of the specimen (Austin et al., 1997). While the research is still in its infancy, the application of biochemical techniques has shown great potential in expanding the capabilities of palaeontology.

The tools of paleontology have become increasingly sophisticated over the years. A more diverse toolbox for the paleontologist has not only improved the efficiency and accuracy of paleontology, but has expanded the niche of the field itself. From early examiners, who developed treatments to strengthen fragile fossils, to the modern researchers who have shown the possibility of extracting DNA from fossilized insects, paleontology has become the foundation of understanding the origin and evolution of life on Earth.

The Role of Fossil Location in the Development of Plate Tectonics Theory

The beginning of the Renaissance in the 14th century marked incredible expansion and development of many different areas of art and science, including the study of fossils (Kemp, 2006). Fossils were commonly recognized as evidence of life forms that had lived thousands of years ago, but they were thought to be remnants of creatures that were left behind after the Great Flood of the Bible. The famous artist and inventor Leonardo da Vinci (1452-1519) questioned this view. While living in Milan as a court artist to Ludovico Sforza, da Vinci was conveniently close to the Alps and went on frequent walks (Jones and Dhaliwal, 2011b). In a personal journal, he wrote about exploring a mountain cave which contained massive fossil bones (Jones and Dhaliwal, 2011a). While he was living in Milan, peasants brought da Vinci a sack full of seashells they had found in the mountains. This struck a chord with da Vinci and sparked his interest in the movement of rocks (Kemp, 2006). He posed the question: "Why are the bones of great fishes and oysters and corals and other diverse shells and gastropods found on top of high mountains on the coast as well as in shallow seas?" (Jones and Dhaliwal, 2011a).

At this time, da Vinci generated his 'living earth theory'; he postulated that the earth is analogous to a living organism, with the rocks as its bones and water as the blood (Kemp, 2006; Jones and Dhaliwal, 2011b). This brought about his discovery of the rock cycle, which included the formation of rocks, the reformation due to heat and stress, and the eventual erosion of the material (da Vinci, 1519). Centuries later, da Vinci's recognition that fossils tell the true story of the Earth would be rediscovered by science and this insight would overturn religious views of creation. It can then be said that it was Leonardo da Vinci who struck the first blow against Biblical views of nature (Jones and Dhaliwal, 2011b).

Before the rediscovery of da Vinci's work, Biblical forces were credited with the creation of many strange specimens found on earth. In the year 1666, strangely-shaped stones from Malta were brought to the attention of the Danish geologist and neuroanatomist Niels Stensen, better known today as Nicolas Steno (1638-1686). These stones, called *glossopetrae melitenses* (tongue stones from Malta) were believed to be the tongues of snakes that had been turned into stone by Saint Paul (Perrini, Lanzino and Parenti, 2010). Some of Steno's contemporaries rejected the theory that supernatural forces were involved, and believed that the earth had simply produced the stones in mimicry of snakes' tongues; others argued that the *glossopetrae* had an organic origin (Hsu, 2009). Steno noticed that the *glossopetrae* looked remarkably similar to the teeth of a shark captured near Leghorn (see Figure 4.11). He published his findings in his report *Canis carchariae dissectum caput* (The head of a shark dissected), and proposed that the *glossopetrae* were shark's teeth that had turned to stone through

Figure 4.11. Sketch of a dried shark's head by Steno. Steno noticed the similarity of the teeth of this shark to the glossopetrae *and suggested they had an organic origin.*

natural processes (Perrini, Lanzino and Parenti, 2010).

In the year 1669, Steno was employed by the Grand Duke of Tuscany as curator of the Duke's collection of mineral and fossil samples. In his role as curator, Steno travelled from Pisa to Volterra and finally to the islands of Elba (Thomsen, 2009). There, he collected samples and made observations on the local geography (Thomsen, 2009). The observations he made during his travels added more evidence to support his theory on the formation of fossils such as the *glossopetrae*, and in 1669 Steno published *Prodromus to a Dissertation on Solids Naturally Contained Within Solids* (Thomsen, 2009). He argued that fossils were originally fragments of organisms which had gradually been replaced by stone, maintaining the form of the fossilized organism (Steno and Winter, 1968). He also described principles for the relative dating of rock layers, including the principles of original horizontality, original continuity, and superposition, which are still used today. Using these principles, Steno was able to work out the stratigraphic history of Tuscany and determined that the area had fallen below sea level at least twice (Steno and Winter, 1968).

Steno's work suggested as da Vinci's had, that slow natural processes rather than acts of God were responsible for the formation of fossils and landforms. For this suggestion, Steno would certainly have faced persecution from the Catholic Church, except that he was a devout Catholic and was protected by the powerful Grand Duke of Tuscany (Steno and Winter, 1968). Fortunately for his contemporaries, Steno's ideas were allowed to be communicated, and eventually formed the foundation of paleontology.

The Theory of Uniformitarianism

During a time in which catastrophism was rampant and the Earth was believed to be 6 000 years old, the Scottish farmer and naturalist James Hutton (1726-1797) observed the cycling of rocks and created the theory of Uniformitarianism (Hutton, 1785). Catastrophism focused on geologic changes due to sudden and violent events such as massive floods and earthquakes, which would cause mass extinctions. Hutton, however, described an earth very different to the Biblical norm of his time; he observed the continuous cycle of rocks and soil, which are transported, deposited, compacted, heated, and eroded into sediment in a continuous cycle (Mathez, 2000). He hypothesized that the cycling of materials due to geologic forces in the present day reflects geologic processes which operated in the past (Hutton, 1785). Therefore, by examining the processes at work in the present, estimates can be made on the deposition rates of strata. Once these strata were examined, it was soon evident that the Earth was much older than the Biblical age of 6 000 years (Mathez, 2000). Hutton used multiple sources of evidence in order to substantiate this claim.

In particular, Hutton paid attention to the formation of strata. He did so by looking to the past strata as well as those forming currently. In his observations, he noted multiple layers of fossil evidence of marine organisms now located inland (Hutton, 1785). This confirmed da Vinci's observation that the Biblical flood would not have produced multiple layers of marine fossil-ridden strata (Jones and Dhaliwal, 2011b); therefore, another process had to be in play. This was when Hutton formulated the idea of his version of the rock cycle (Hutton, 1785; Mathez, 2000).

Unfortunately, Hutton had difficulty communicating his ideas, and could not hold his own in scientific debates (Hutton and Playfair, 1970). His theories may not have received much attention, if not for his close friendship with John Playfair (1748-1819), a well-known Scottish mathematician and geologist (Playfair, 1956). After Hutton's death in 1797, Playfair illustrated and continued to defend Hutton's theories. In 1802, Playfair published his book *Illustrations of the Huttonian Theory of the Earth*, in which he clarified and provided new evidence for Hutton's concept of Uniformitarianism (Playfair, 1956). This publication proved to be highly influential, and allowed other scientists to access and build on Hutton's ideas. In particular, Charles Darwin used Hutton's ideas of strata deposition and uniformitarianism in the development of his theory of evolution. Thanks to Playfair, Hutton is now widely considered to be the founder of modern geology (Mathez, 2000). Another influential scientist who expanded upon Hutton's theories was the British geologist Charles Lyell (1797-1875). Lyell's 1830 book *Principles of Geology* struck the final blow against Catastrophism, providing conclusive evidence that continuous processes were largely responsible for moulding the earth (Lyell, 1970). One of the most famous examples from *Principles of Geology* is the Macellum of Pozzuoli, also called the Temple of Serapis (see Figure 4.12). The Macellum is the remains of the marketplace in the Roman town of Pozzuoli, including three large, upright columns. These columns displayed borings left by marine bivalve mussels, indicating to Lyell that the sea level had changed at least twice (had risen and fallen) since the Macellum was built (Lyell, 1970). However, this sea level change could not have occurred due to a catastrophic earthquake, as such an event would have knocked over the columns. Lyell concluded that gradual movement of the earth's crust was responsible for changes in sea level (Lyell, 1970). This conclusion paved the way for the development of the theory of continental drift.

Developing the Theory of Continental Drift

Eduard Suess (1831-1914) proposed a mechanism to explain the movement of the Earth's crust observed by Lyell. He proposed that the Earth was analogous to a drying apple: the planet originally had a continuous continental crust which then broke apart as a volume reduction occurred in the interior (Oreskes, 2003). Suess's theory not only provided a potential driving force behind crustal movement; it also proposed that the Earth's crust was broken into sections that moved against one another.

Suess used his theory to explain some baffling observations about the global distribution of fossils. Since the 19th century, geologists had recognized that there were similarities in fossils found in vastly different areas of the world. This uniformity of fossil-containing strata was observed by Suess, who proposed that the southern continents had once been combined in a single supercontinent, which he called Gondwanaland (Wegener, 1966; Oreskes, 2003). Gondwanaland connects the similar fossils found in parts of India, Africa, and South America (Wegener, 1966). Darwin's theory of evolution caused a complication: if animals had evolved independently in different areas and environments, then why did these fossils show similarities? Suess answered with his theory of Gondwanaland (Oreskes, 2003). Gondwanaland was a continuous continent which allowed for the migration of the organisms rather than the same evolution of each organism, independently, thousands of miles apart (Wegener, 1966). His theory was widely argued and discussed, which resulted in a varying acceptance of the theory in Europe (Oreskes, 2003).

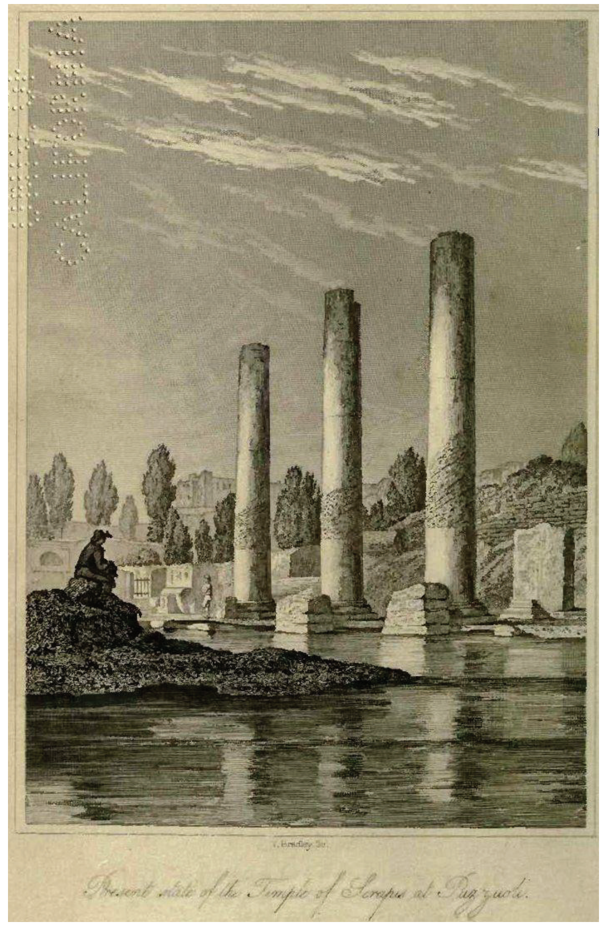

Figure 4.12. Drawing of the Pillars of Pozzuoli from Principles of Geology. *Markings on the pillars from bivalve mussels indicated to Lyell that the pillars had at one point fallen below sea level.*

While Suess's theory of Gondwanaland was supported by fossil evidence, little was found to support his 'drying apple' theory. An alternate mechanism for continental movement was proposed by the German meteorologist Alfred Wegener (1880-1930). While studying the fossil deposits that led to Suess's proposal of Gondwanaland, Wegener came upon a compendium of information describing the similarities of faunal fossils of Paleozoic strata in Africa and Brazil

(Wegener, 1966). These similarities were first believed to be caused by a land bridge between the two continents. Wegener dismissed this at the time because he regarded it as improbable and the theory lacked concrete evidence (Schwarzbach, 1980; Wegener, 1966). The fossil evidence, however, puzzled Wegener, and he instead thought of another possibility: if the earth's crust can move vertically, why could it then not move laterally as well? Expanding upon this concept, Wegener proposed his theory of continental drift.

In 1910 Wegener stated:

"Doesn't the east coast of South America fit exactly against the west coast of Africa, as if it had once been joined? The fit is even better if you look at a map of the floor of the Atlantic and compare the edges of the drop-off in the ocean basin rather than the current edges of the continents" (Schwarzbach, 1980).

Along with this evidence, Wegener expanded on the fossils that Suess studied and found that all the existing continents could be aligned according to similarities in the fossil record (see Figure 4.13) into a supercontinent which he named Pangaea, meaning 'all earth' (Schwarzbach, 1980; Oreskes, 2003). Wegener's research focused more closely on the paleoclimatology of geographical locations and how these lined up in Pangaea (Schwarzbach, 1980). Fossils in Wegener's mind were a by-product of the climate and acted as 'climate witnesses'. Continental drift would explain paleoclimate changes due to the movement of the continents through different climate zones; as well, ocean circulation was altered by the changing orientation of landmasses (Schwarzbach, 1980; Oreskes, 2003). The interactions of the rifts and the drifting continents offer a mechanism for the origin of mountains, volcanoes, and earthquakes.

Unfortunately, continental drift was not accepted at first. It was widely discussed in the 1920s and early 1930s, and largely rejected because Wegener could not propose an adequate mechanism (Oreskes, 2003). Wegener was arguably misguided in his view of the separation of the continents. He believed that the mid-Atlantic ridge, which is an active site of sea floor spreading, to be 'dead' or inactive (Schwarzbach, 1980). He also believed that the ocean floor was the oldest rock material and the continents were the newest. After Wegener's death, a South African geologist Alexander du Toit continued to advocate for continental drift theory, but it seemed as if he was one of only a few (Schwarzbach, 1980; Wegener, 1966). In fact, it took until the 1960s when the theory was used as the cornerstone of plate tectonics for it to become widely accepted (Oreskes, 2003). At this time, it was determined that convection currents in the earth's mantle were the cause of continental drift and therefore, plate tectonics.

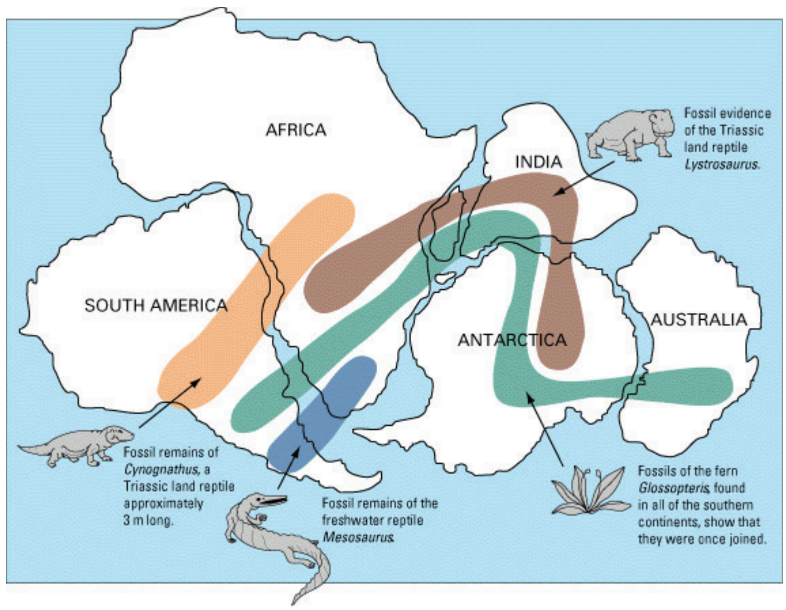

Figure 4.13. Distribution of fossils across the supercontinent of Gondwana. The fossil evidence spanning the continents was used by Wegener to support his theory of continental drift.

Though Wegener's theory was not entirely correct, his assumptions of continental drift were correct as it did, in fact, occur, just not for the reasons he claimed. His hypothesis opened a new door in the theory of the formation of the Earth as it is today. With the emergence of plate tectonics in the 1960s, Wegener's theory gained a solid mechanism to support the hypothesis alongside the fossil and paleoclimatological evidence (Oreskes, 2003). Today, Wegener is recognized as the 'father of continental drift', and his theory forms the basis of much of our understanding of the processes that shape the Earth's crust (Schwarzbach, 1980).

Pangaea Ultima: the Next Supercontinent

Wegener's study of the fossil record led him to propose the existence of the ancient supercontinent of Pangaea, and his theory of continental drift explains the breakup of the supercontinent. However, Pangaea was not the first supercontinent to exist in the history of the Earth: evidence from the geological record shows that supercontinents have formed approximately every 500-700 million years throughout the history of the Earth (Williams & Nield, 2007). This led to the proposal of a 'supercontinent cycle' in which the continents, driven by convection currents in the mantle, continuously break up and reform. The breakup of Pangaea occurred about 200 million years ago; therefore, a new supercontinent is predicted to form in the next 250-500 million years (Nield, 2007). Several different geologists and geophysicists have tried to predict the shape of this new supercontinent, with differing results (see Figure 4.14).

Chris Hartnady of the University of Cape Town proposes the formation of a future supercontinent which Paul Hoffman of Harvard University has dubbed 'Amasia' (Williams & Nield, 2007). Hartnady's theory is based on extrapolating the current movement of tectonic plates into the future, including the spreading of the Atlantic and the subduction of the Pacific oceanic crust (Broad, 2007; Williams & Nield, 2007). He predicts that the Atlantic will continue to widen, causing the Americas to swing clockwise about a pivot in north-eastern Siberia, which he believes will then fuse with the eastern margin of the future supercontinent. Australia will continue on its current northward path. Africa will stay in approximately the same position, moving only slightly north to close the Mediterranean Sea. Antarctica will remain situated at the South Pole and will not join Amasia. Antarctica is situated well away from any subduction zones and therefore has no reason to move (Williams & Nield, 2007).

Roy Livermore at Cambridge University disagrees with Hartnady's prediction that Antarctica will not move: he postulates the formation of a new subduction zone that will drag Antarctica northwards (Nield, 2007). In addition, he extrapolates the activity of the East African Rift into the future, predicting that the rift will propel East Africa and Madagascar across the Indian Ocean to collide with Asia. Livermore has named the resulting supercontinent 'Novopangaea'. Unlike Amasia, all of the continents would participate in the formation of Novopangaea, including Antarctica (Nield, 2007). Although Livermore has little evidence for the formation of a new subduction zone to move Antarctica north, he holds to his theory, pointing out that "the beauty of all this is that no one will ever be able to prove me wrong" (Nield, 2007).

In spite of the differences in their theories, Hartnady and Livermore both agree that the next supercontinent will form following the closing of the Pacific Ocean and the widening of the Atlantic. Christopher Scotese of the University of Texas, however, has come up with a completely different theory. His predictions are based on examination of past cycles of formation and breakup of supercontinents, not on the current understanding of the mechanisms of tectonic change. Scotese argues that these mechanisms are too imprecise to project hundreds of millions of years into the future (Broad, 2007). He agrees with Hartnady and Livermore that for the next 50 million years, Africa will continue north, closing the Mediterranean Sea and driving up the Himalayan mountain range. Australia will rotate and collide with South China and Borneo. After 200 million years, however, Scotese's predictions diverge (Broad, 2007; Williams & Nield, 2007).

Scotese claims that subduction will start on the western boundary of the Atlantic plate due to the spreading of a smaller, existing subduction zone, possibly the Puerto Rico trench in the Caribbean (Broad, 2007; Williams & Nield, 2007). The trench would spread along the American coast as a result of what Scotese believes to be stress changes on the planet. The stress would cause the existing trench to tear. Scotese claims a subduction zone will result on either the eastern or western side of the Atlantic plate from planetary stress. Either way, this will signal the demolition of the Atlantic Ocean and the start of the next supercontinent, with the collision of the Americas with Europe and Africa (Williams & Nield, 2007). The continents would essentially re-form Pangaea. Originally, this supercontinent was called Pangaea Ultima; however, the use of the word 'ultima' implies that this supercontinent would be the final one, which is not the case. Therefore, the name was changed to Pangaea Proxima, meaning 'next Pangaea' (Broad, 2007).

Finally, a team of researchers led by Masaki Yoshida and M. Santosh have rejected the formation of all three different potential supercontinents (Yoshida and Santosh, 2011). They argue that a more complete understanding of convection currents in the mantle, which regulate plate tectonics, is the best way to predict the movement of the continents. Yoshida and Santosh used a numerical model to predict how conditions in the mantle will change over the next 250 million years (Yoshida and Santosh, 2011). Their results indicate that the large mantle plumes currently located in the South Pacific, between the American and Asian continental masses, will remain stable for the next few hundred million years. These plumes will prevent the Pacific Ocean from closing entirely, posing a challenge to the theories of Amasia and Novopangaea. In addition, there is a high probability that any subduction in the Atlantic would spread laterally, preventing the formation of Pangaea Proxima (Yoshida and Santosh, 2011). Instead, Yoshida and Santosh have proposed a different theory: Australia, Eurasia, North America, and Africa will all move northward and collide, creating a supercontinent in the northern hemisphere. South America and Antarctica will remain in their current positions (Yoshida and Santosh, 2011).

Of all the proposed future supercontinents, Scotese's theory is the most well-known. Perhaps because it is the most surprising given current evidence. Scotese stated:

"It's all pretty much fantasy to start with. But it's a fun exercise to think about what might happen. And you can only do it if you have a really clear idea of why things happen in the first place" (Williams & Nield, 2007). Whatever the future configuration of the continents, it is almost certain that humans won't be there to witness it for themselves. So for the time being we as a species expand hypotheses to take a guess at the future that has yet to come; to fill in the gaps of a fantasy we will never witness.

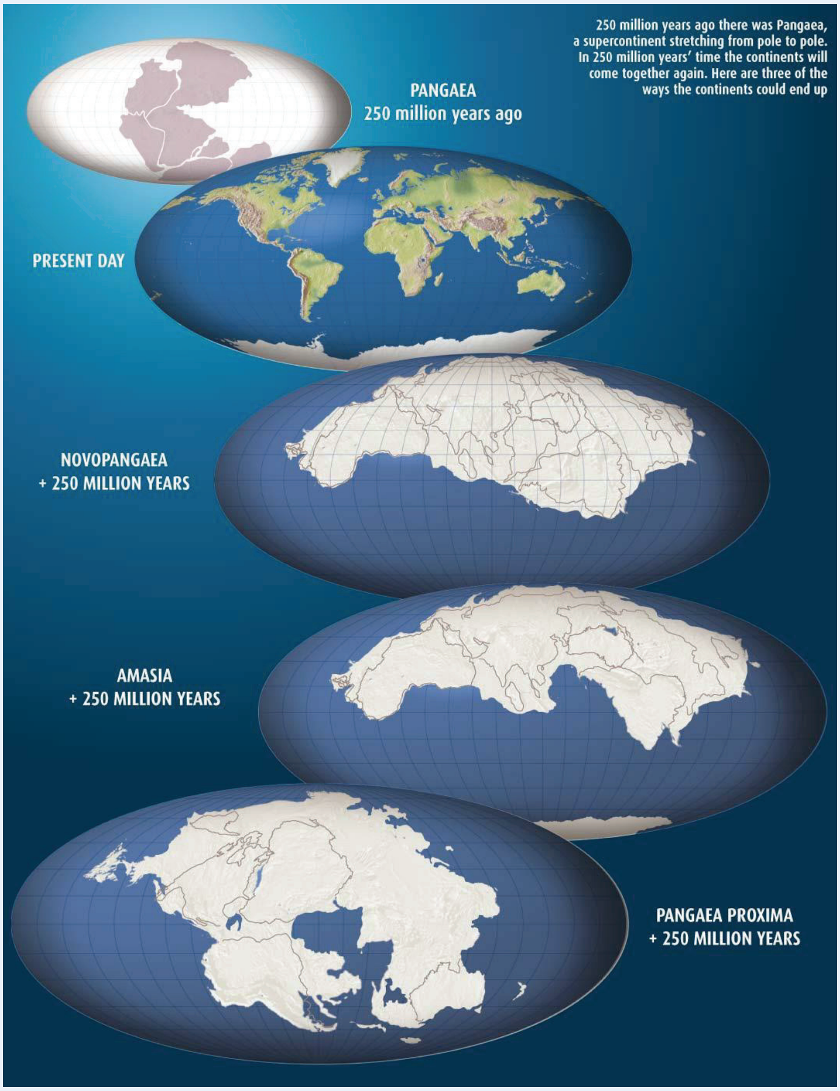

Figure 4.14. Predictions of continental positions 250 million years into the future. Three different proposed supercontinents are shown here: Amasia, Novopangaea, and Pangaea Proxima.

Biostratigraphy in the 19th Century: Early Ideas on Fossil Succession and Extinction

Biostratigraphy, the identification and comparison of rock layers based on the fossils they contain, has been integral in the progression of ideas on species succession through time. The study was first used by the geologist William Smith (1769-1839). Smith, born in Oxfordshire, started working as a land surveyor, and eventually became involved in underground surveying in coal-mining areas. This prompted Smith to start thinking about the succession of strata. Smith was hired to survey routes for canals designed to bring coal from land to the sea. During these excavations, Smith had the opportunity to observe the succession of strata on different routes. In the 1790s Smith began to map the Bath strata, similarily to a topographic map, and included their thicknesses and dips. By 1795 he had created the local *Order of Strata*, where he identified the strata around the city of Bath. At this time, his order was not finished due to unconformities in the local area. He also noted that fossils within the strata could be used as an identifying feature. Smith was able to separate strata based solely on the fossil content. Certain strata had previously been thought of as belonging to the same layer due to similar physical appearances. His map served to help locate coal and other valuable substances in the rock layers. Shortly thereafter, Smith compiled the first fossil collection based on stratigraphic succession (Phillips, 1844).

Figure 4.15. The first geologic map of England, published by William Smith in 1812.

In 1803, Smith moved his office to London, and brought his impressive fossil collection with him so it could be properly displayed. While there, he continued to improve and add to his list of England's ordered strata. During this time, a few of his supporters attempted to help him publish his work, including the geologic map that he was working on. The Geological Society of London was founded in 1807, and they competed with Smith to produce the first geologic map of England. However, in 1812, Smith became the first successful person to publish a geologic map (see Figure 4.15). This development led to the public's eventual acknowledgement of the value and importance of Smith's biostratigraphic work (Phillips, 1844).

Geologic Revolutions and the Extinction of Species

Smith's revolutionary work with the strata of England prompted analogous studies in other areas throughout Europe. Some of the most extensive work was done in the Paris Basin by two French geologists: Georges Cuvier (1769-1832) and Alexandre Brongniart (1770-1847). By studying the fossils in successive layers of the Basin, the two were able to form hypotheses on the succession of fossilized species (Cullen, 2006). Cuvier received his education in a wide variety of topics, which prompted him to approach problems from multiple perspectives (Rudwick, 1997). By the time the French Revolution was over in 1795, Cuvier had already read and reviewed many scientific papers on his passion: the history of the Earth. As a result, his talent was soon noticed by patrons who were trying to construct a new network of promising scientists. He was given a position at the Muséum National d'Histoire Naturelle in Paris where he began to conduct his research (Rudwick, 1997). Cuvier outlived all of his children and, as a result, became less connected with religion while he was interpreting his research (see pages 82-87).

Unlike other scientists at the time, Cuvier looked at fossils of terrestrial species rather than the abundant marine ones. In doing so, he could directly compare the fossil assemblages to modern terrestrial organisms (see Figure 4.16). Cuvier, being very well educated in the principles of comparative anatomy, was able to observe that the fossilized bones of these terrestrial organisms became less related to extant species in successively older strata (Rudwick, 1997).

Cuvier was an advocate of species stability throughout time so he did not believe that the species were evolving or transforming. Instead, he proposed that species went extinct, and, as they did, new species were created (Appel, 1987). In this way, the archetypes for the species were the only things he believed were changing with time (Rudwick, 1997). To disprove the theory of species transformation Cuvier compared the anatomy of mummified cats in Egypt to modern cats and found them to be exactly the same. He concluded that since species did not change during that length of time, then species were inherently stable (Rudwick, 1997).

Cuvier's examination of fossils integrated the important studies of mineralogy and natural science. This gave him an edge over other scientists studying the history of the earth and allowed him to come up with theories based on evidence from both the fossil and rock record (Rudwick, 1997). Cuvier believed that current geologic processes were too feeble to cause the massive beds and erosional surfaces that he could see in the rock record (Rudwick, 1997). He proposed in his essay, *Theory of the Earth* (1813), that major geologic revolutions were the cause of the numerous secondary features now visible in the rock record. Only through powerful and sudden geologic changes could structures like tilted beds and massive volcanic deposits form (Appel, 1987). The revolutions Cuvier proposed are now referred to as catastrophes and the scientists that followed his line of thinking are called catastrophists (Appel, 1987).

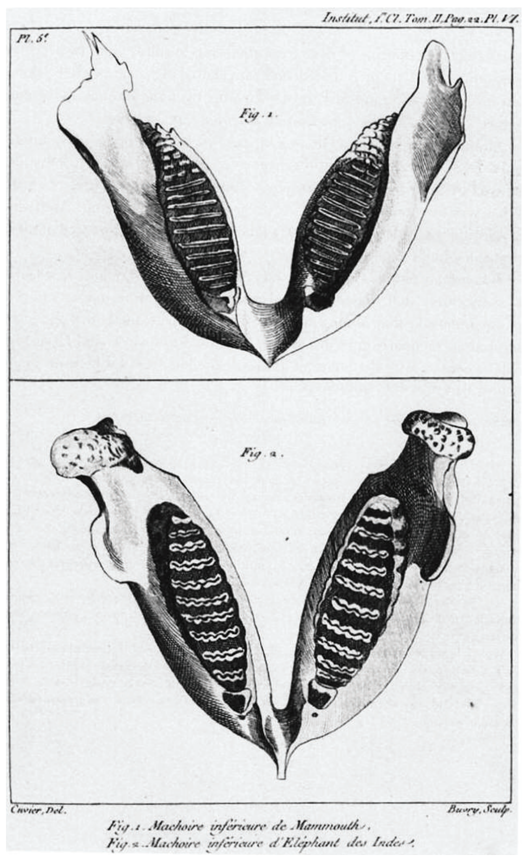

Figure 4.16. Cuvier's use of comparative anatomy to identify similarities between the teeth of modern elephants and mammoths.

To support his new theory, Cuvier turned to the fossils he had been studying. He noticed that some of the terrestrial organisms were buried alongside marine sediment (Rudwick, 1997). To him this suggested that there had been a massive flood that caused a mass extinction of terrestrial organisms. Later on, he decided that instead of a flood, the transition from marine to terrestrial environments was caused by an almost instantaneous ocean-continent switch (Rudwick, 1997). He believed that the uplifting of the crust from this process would have been sufficient to cause the deformations seen in the strata (Rudwick, 1997). This revolution also explained why earlier fossils of humans were not seen. According to Cuvier, since what are currently oceans used to be continents, any fossils of humans before the catastrophe would have been buried under the ocean. He believed that the most recent revolution happened only a few thousand years ago and humans were able to start developing civilizations after it occurred (Rudwick, 1997). Later on, Brongniart discovered numerous instances in the rock record where terrestrial and marine sediments switched. Cuvier theorized that there must have been multiple revolutions in the history of the Earth and that they occurred even before life was present (Rudwick, 1997).

Another French geologist, Alcide d'Orbigny (1802-1857), helped to further justify Cuvier's theory of geologic revolutions (Vénec-Peyré, 2004). D'Orbigny's career choice was largely motivated by his father, an amateur naturalist, who pushed d'Orbigny to observe and study the wonders of nature. D'Orbigny spent part of his career studying the invertebrates of the Paris Basin, classifying both macroscopic and microscopic species (Vénec-Peyré, 2004). At the age of 24 d'Orbigny was given the privilege to complete scientific research in South America. On this journey, he made observations on everything he came across, from the interactions of novel species to the ruins of ancient human civilizations. The shear amount of information d'Orbigny was able to collect in his relatively short lifespan is truly one of his most remarkable feats. This extensive collection was partly due to the lessons he received as a child on the importance of observation (Vénec-Peyré, 2004). In addition to being a renowned scientist, d'Orbigny was also an accomplished artist. This skill helped him to clearly convey his findings to the rest of the scientific community upon his return. Using biostratigraphy, d'Orbigny classified 27 different stratigraphic periods based on the fossils they contained. He believed that the layers of strata were periods of stability and the unconformities that separated each layer marked the occurrence of a revolution (Vénec-Peyré, 2004). Like Cuvier, he believed these revolutions caused mass extinctions of species and led to the creation of new species. Unlike Charles Darwin, who would soon begin his own journey to South America, d'Orbigny was unable to recognize that the species he identified had evolved over time (Vénec-Peyré, 2004).

The Uniformitarian View on Fossil Succession

An opposing theory to catastrophism that became popular in the 19th century was uniformitarianism. The idea behind uniformitarianism was originally proposed by James Hutton (1726-1797) in his book "Theory of the Earth", published in 1788 (Wyllie, 1998). Contrary to the popular belief that the age of the Earth was a few thousand years, Hutton believed that the Earth's history stretched back a seemingly infinite amount of time (Wyllie, 1998). His reasoning behind this theory was that the geologic processes that were occurring in the present were the same as those occurring in the past. Consequently, the slow processes that occur in the present indicate that it must have taken a very long time to produce currently observed geologic structures (Wyllie, 1998). Unfortunately Hutton was not able to successfully convince people (see pages 94-99) (Wyllie, 1998). It was not until Hutton's death in 1797 that Charles Lyell (1797-1875), the geologist who would successfully spread Hutton's ideas, was born (see Figure 4.17).

Lyell was born in Scotland to a botanist father. His interest in natural history at a young age would influence his future career

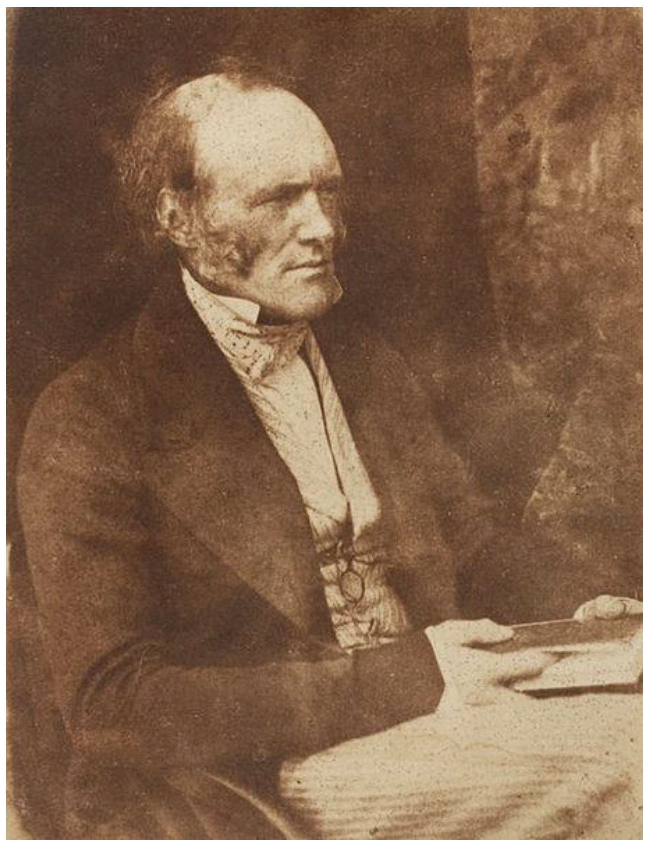

Figure 4.17. Portrait of Charles Lyell; the 19th century geologist that popularized uniformitarianism.

choice. Lyell attended Oxford University where he initially studied law before his childhood passion drew him to geology (Baker, 1998). It was in school where he was first introduced to Hutton's theories. Being a former student of law, Lyell liked the idea of order in geology and thought the idea of catastrophic geologic events shaping the

Earth was erroneous (Baker, 1998). Lyell was also a fan of the Newtonian philosophy, which uses the concepts of *vera causa*. *Vera causa* is a method of scientific thinking that looks for causes of natural phenomena in events that are presently known to exist. Uniformitarianism follows *vera causa* by looking for explanations of geologic events in the most logical processes occurring today (Baker, 1998).

In addition to popularizing uniformitarianism, Lyell helped to classify distinct periods in Earth's history based on the fossils contained in the rock record. In this way, he utilized biostratigraphy to develop a standard for rock layers that could be used to compare strata in multiple locations throughout Europe (Berggren, 1998). Lyell liked the idea that fossils in strata acted as a natural chronometer. The epochs he proposed fell within the Cenozoic era and included, from oldest to youngest, the Eocene, Miocene, Pliocene, and Pleistocene. He used the percentage of extant mollusc species found in the rocks to differentiate between the successive epochs (Berggren, 1998). Lyell did not envision a great importance for his epochs and believed that they should be subject to change as more evidence was found. In fact, the boundaries for each epoch were not determined until later because Lyell believed his epochs were merely snapshots of a uniform process rather than periods defined by precise geologic events. Remarkably, the epochs he proposed are still widely used today with only minor modifications (Berggren, 1998).

Lyell's views on extinction and fossil succession reflected his views on geologic succession. He read Cuvier's work on the fossils of the Paris Basin and was intrigued by his idea of extinction. What he did not agree with was that catastrophic events caused these supposed extinctions (Hallam, 1998). He believed in a more gradual process whereby species would go extinct after regular time intervals and be replaced by new ones. Lyell did not like the idea of fossil succession leading to increasingly complex organisms and argued that the incomplete fossil collection at the time was not enough to show that species were becoming more complex (Hallam, 1998). Jean-Baptiste Lamarck (1744-1829), a French naturalist, postulated that species were in a constant flux, which allowed them to slowly become more complex with time (Corsi, 1988). If Lamarck's theory was true, it would mean that biostratigraphy would not be an appropriate method to relate similar geologic layers because Lamarck believed that the least complex organisms were being spontaneously produced all the time. He believed that these organisms would then continually acquire new characteristics to evolve into increasingly complex species. As a result, a specific fossil type would not necessarily represent a specific time period in the rock record because the same species could evolve at different times in Earth's history (Corsi, 1988). Lyell firmly believed that species were stable. Consequently, he could not bring himself to believe Lamarck's idea of evolution even though it required the long timescales of the uniformitarian theory (Hallam, 1998).

In 1832, at the time of the first edition of his book, *Principles of Geology*, Lyell's views on extinction and fossil succession were more popular than those of Lamarck. As more evidence for evolution was unearthed, the scientific community began to change their beliefs to correspond with the theory of fossil progression. With time, Lyell was convinced as well and had to completely alter chapters of his book (Hallam, 1998). To understand how hard this was for Lyell, one must realize that he switched over to a theory that he had completely renounced in previous versions of his book. This was especially hard due to his older age. For Lyell, a change in beliefs meant abandoning part of his life's work. Fortunately, Lyell was still able to integrate aspects of uniformitarianism into this new belief (Hallam, 1998).

Implication of Early Ideas

The work and theories compiled by Lyell helped solidify the theory evolution by natural selection when Charles Darwin eventually proposed it. The long timescales associated with uniformitarianism allowed for an appropriate means of evolutionary change (Hallam, 1998). In time, Cuvier's theories on revolutions would also be used again to explain massive extinction events seen in the geologic record (Rudwick, 1997). From a modern viewpoint, both the principles from uniformitarianism and catastrophism are used to help explain the history of the Earth. Though the same processes that occur today have caused many of the noticeable geologic structures on the Earth, the past must also be examined for processes that have led to relatively fast paced changes (Cullen, 2006). The work done by scientists in the 19th century utilizing the novel study of biostratigraphy was paramount in leading to much of what is known today about evolution and extinction. Though the theories may have not been completely correct, the ideas behind them were the product of well thought out explanations of observed evidence. These theories are the driving force of science that allow for future individuals to build upon existing ideas and knowledge.

Understanding Mass Extinctions

Although the exact causes of the five major mass extinctions are still uncertain, several theories have evolved over time and become accepted as the likely causes. The five mass extinctions include the end Ordovician (440 mya), late Devonian (365 mya), end Permian (250 mya), end Triassic (200 mya), and end Cretaceous (65 mya) (Jablonski, 1994). The best studied are the end Permian, also known as the Great Dying, and the end Cretaceous, which was responsible for the extinction of the dinosaurs. The most widely accepted theories to explain the mass extinctions include impact events from meteorites, sea-level changes, low oxygen levels, climate change, and volcanic activity (Hallam, 2004).

Modern Interpretation of Geologic Features as Causes of Mass Extinctions

Georges Cuvier was the first to raise the idea of catastrophism as the cause of mass extinctions. However, in his time many disregarded this theory, and it was not until recently that it became generally accepted that catastrophes probably were the cause (Hallam, 2004). The method of examining stratigraphic layers to determine what events took place is important when studying the causes of mass extinctions.

The extinction event at the Cretaceous Paleogene (K-Pg) boundary is one of the most extensively studied because it is the most recent and is responsible for the loss of the dinosaurs. One theory to explain this mass extinction is the asteroid impact hypothesis, which was originally proposed by Walter and Luis Alvarez in the 1970s, and thus is commonly known as the Alvarez Hypothesis. A thin clay layer was discovered at the K-Pg boundary layers in the Umbrian Apennines of Gubbio, Italy (Figure 4.18). To find the cause of the mass extinction at this boundary, Alvarez consulted his father, Luis, who suggested that they test the iridium levels in the clay layer and compare them to other layers above and below. This method is used to determine the presence of meteorite ejecta since the ejecta contain higher levels of iridium than the Earth's crust. Indeed, higher levels of iridium were found in this clay layer, indicating the possibility of an impact event (Hallam, 2004).

Figure 4.18. The sedimentary layers that represent the boundary between the Cretaceous and Paleogene periods. The lighter-coloured clay layer has an abnormally high iridium content. This sample was taken from the Umbrian Apennines of Gubbio, Italy.

Potential Triggers for the Late Cretaceous Mass Extinction

The cause of the late Cretaceous extinction event was heavily debated up until the 1980's when the 200-km-diameter Chicxulub crater was discovered in Yucatan, Mexico (see Figure 4.19). Before this discovery, most paleontologists agreed that there was a significant biotic event near the K-Pg boundary due to the discovery of an abnormal amount of iridium in the K-Pg clay layer. However, it was not until the

Chicxulub crater was found that the rest of the scientific community was convinced that an extraterrestrial event could be responsible (Kiessling, 2002).

While it is generally agreed that an impact event was the cause of the K-Pg extinction, the mechanism behind the impact's effects is still unknown. One theory suggests that upon collision, gases from carbonate- and sulfate-rich rocks were released, causing harmful environmental effects. This would have resulted in a climatic catastrophe, including darkness and global cooling (Shulte et al., 2010).

Another theory to explain the K-Pg extinction is the production of the Deccan flood basalts in India, which also occurred at this time. Similar to the impact theory, this event would have resulted in the mass extinction of life forms through the release of sulfur and carbon dioxide during extensive and prolonged volcanic eruptions. (Shulte et al., 2010).

Evidence in Support of the Chicxulub Impact Event at the Cretaceous-Paleogene Boundary

In order to determine which of these events is most likely responsible for the K-Pg extinction, geologists have studied the sedimentary layers corresponding to the late Cretaceous and early Paleogene periods. The ejecta pattern in the sediments supports the impact theory because the thickness of the ejecta layer decreases as the distance of the K-Pg boundary site from the Chicxulub crater increases. Sites within a 500-km-radius of the Chicxulub crater contain impact deposits between 1 to 80 m thick, while cores taken near the crater rim contain breccia deposits >100 m thick. Boundary sites that lie between 500 and 1000 km away from the crater have conglomerate deposits, ranging from cm- to m-thick layers, which signify high-energy sediment transport. At distances of 1000 to 5000 km away from the impact site, the stratum contains a 2- to 10-cm-thick spherule layer, which is covered by a thinner layer rich in shocked minerals. This layer is indicative of a high-energy impact event. Finally, sites greater than 5000 km away from the crater contain a 2- to 5-mm-thick red clay layer with deposits of ejecta material (Shulte et al., 2010). Additionally, the ejecta deposits found in the boundary sites contain silica, limestone, dolomite and granite, which match the sediments found in the Chicxulub target rocks. Further evidence can be found in both the sediments and shocked grains that have sphericity indicative of a high-energy event. Sediment types found near the crater also suggest that the impact event triggered mass flows and tsunamis in the Yucatan peninsula and surrounding areas (Shulte et al., 2010).

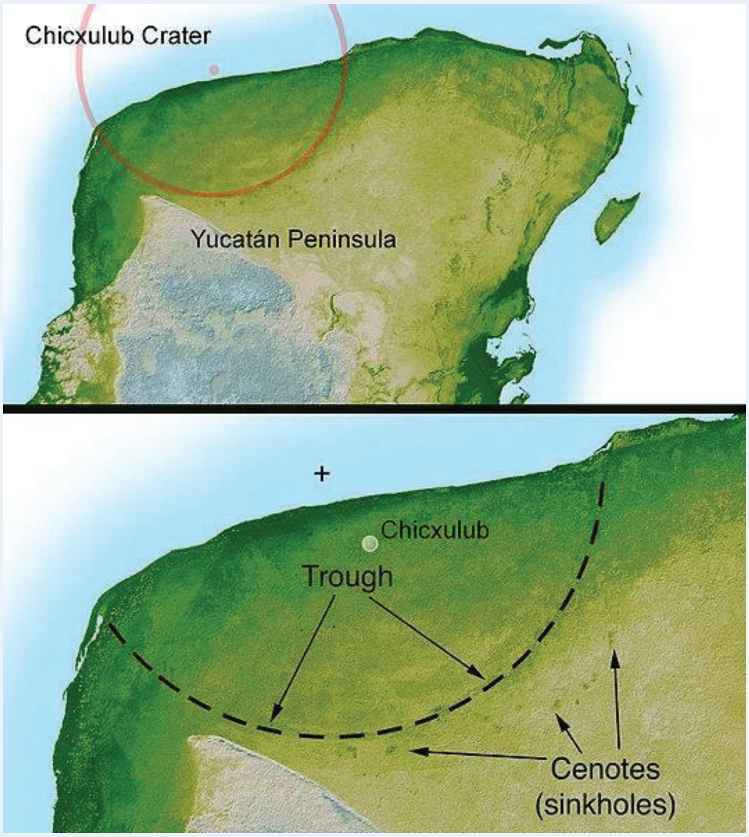

Figure 4.19. The boundary of the Chicxulub crater in the Yucatan Peninsula.

Despite the overwhelming evidence for an impact event, some scientists still argue that the Chicxulub impact event occurred before the K-Pg boundary, and the sedimentary layers previously described were deposited before the mass extinction. They instead believe that the Deccan flood basalt eruptions were responsible for the late Cretaceous mass extinction. However, this belief is not the commonly accepted one due to the high volume of evidence in favor of the Chicxulub impact (Shulte et al., 2010). This debate will only be resolved through more accurate dating of the impact and flood basalts and better understanding of the processes involved in the extinction events.

The Dinosaur Renaissance: Changing Thought about the Warm or Cold-Blooded Nature of Dinosaurs

The existence of dinosaurs has been a popular area for research and debate for centuries. All characteristics of dinosaurs, such as their physical appearances, behavioural tendencies, and evolutionary origins, have been extrapolated from 65 million year old fossils. These ancient preserved bones give paleontologists limited knowledge about the physiology of dinosaurs given the age of the fossils and the fact that in many cases, the fossil record was incomplete. The limitations inherent in these discoveries have yielded a large array of different opinions from reputable scientists including Georges Cuvier, Gideon Mantell, and Richard Owen. One of the main areas of debate was whether these ancient beasts were cold-blooded like modern reptiles or warm-blooded like modern birds. The innovative and influential research conducted by John Ostrom and Robert T. Bakker have helped shape what is now widely accepted to be the most realistic possibility for the blood temperature of dinosaurs.

Discovering Dinosaurs

Robert Plot (1640-1696) illustrated the first published image of a dinosaur bone in 1676, although unknowingly (see Figure 4.20) (Parsons, 2004). He described the bone in the *Natural History of Oxforshire* as too large to belong to any currently living animal known to man, and therefore classified it as the thighbone of an ancient Roman war elephant. After inspection of a present-day elephant, he concluded that the bones were too dissimilar to have been related (Plot, 1677). Plot's religious background helped him to reclassify the ancient bone, leading him to state in 1677 "It remains, that (notwithstanding their extravagant Magnitude) they must have been the bones of Men or Women" (Plot, 1677). The whereabouts of the bone was lost through time, but Plot's illustration and recordings were so detailed that the bone was much later identified to be the femur of a *Megalosaurus*.

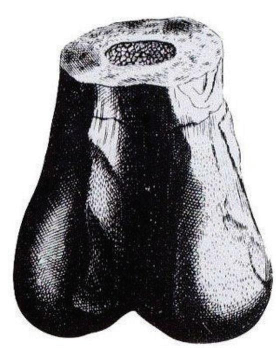

Figure 4.20 The first illustrated dinosaur bone, which at the time was not known to belong to a dinosaur

After Plot's discovery, there were more documented instances of large animal bones being discovered of which people did not know the origins nor how to classify them. It was not until the early 1800s when scientists began to find large numbers of fossilized remains that they began to classify them as something entirely new.

In 1809, William Smith (1769 – 1839) discovered the remnants of what appeared to be a large animal (Norman, 2005). These remnants, which were fascinating to Smith, were collected in Cuckfield, Sussex during his research that ultimately led to the creation of the first geologic map of Britain. The remnants were not classified until the 1970s when David Norman identified them as belonging to an *Iguanodon*. Only one year after Smith's discovery, Georges Cuvier (1769-1832), a French zoologist and naturalist, examined a fossil extracted in Holland, which was claimed by Napoleon's army as a prize in 1795, and suggested it came from a gigantic marine lizard (Norman, 2005). This prediction later proved to be correct and the organism was later classified as a *Mosasaurus*. The discovery of these pre-biblical animals such as the *Iguanodon* and *Mosasaurus* encouraged others to dig for similar large, presumably cold-blooded, reptiles. Gideon Mantell (1790-1852), an English obstetrician and geologist, and his wife Mary Ann became intrigued these finds and were inspired to find more ancient reptile fossils to analyze.

Cuvier and Mantell have since become known as two of the pioneers in the identification and classification of dinosaurs (see Figure 4.21). Richard Owen (1804-1892) also worked in paleontology around the same time as the Mantells and was the first person to draw similarities between these ancient reptiles and present-day mammals (Owen, 1842). He argued that these organisms, because of their dissimilarity to modern reptiles, could be "deemed sufficient ground for establishing a distinct tribe or sub-order [of reptiles], for which I would propose the name of *Dinosauria*" (Owen, 1842). His remarks went largely unnoticed and untrusted until the 1960s when a dinosaur revolution changed scientists' and civilians' perceptions about the presumed reptilian nature of these animals.

Figure 4.21 Portraits of Georges Cuvier (left) and Gideon Mantell (right), two of the most influential people in discovering dinosaurs

Cuvier & Mantell: paving the way for ectothermic beliefs

The persistence of the Mantells led to the finding of very large fossilized teeth. After much debate, Gideon Mantell was unable to determine the origins of the teeth. In order to determine their origin, he reached out to other scientists in the same field for assistance. He sent the teeth to Georges Cuvier, a specialist in comparative anatomy. Cuvier concluded that the teeth must have belonged to a recent animal (Norman, 2005).

It was only by coincidence that Mantell was in the process of observing a modern-day iguana when he realized the similarity between the teeth of the reptile to the specimens found by the Mantells. He aptly called the giant ancient reptile from which this tooth originated an *Iguanodon* and published his conclusions in an illustrated book (Mantell, 1825).

In 1809, Cuvier identified a fossil as belonging to an enormous marine lizard (Norman, 2005), which led to subsequent searches for evidence of ancient large lizards. This finding influenced how other similar fossils were later identified. In addition, Cuvier concluded that dinosaurs were anatomically similar to most living reptiles (Norman, 2005). A decade later, Cuvier travelled to England to examine fossils found by scientists with similar interests as his own (Norman, 2005). Cuvier determined that fossilized bones collected by William Buckland (1784-1856) resembled large land-dwelling, lizard-like bones that he had previously seen in Normandy (Norman, 2005). These fossils came from what was later named *Megalosaurus*.

Mantell and Cuvier, along with most other paleontologists, believed that dinosaurs were ectothermic, (otherwise known as cold-blooded), similar to present-day reptiles. Ectothermic organisms rely on external sources of heat in order to maintain internal temperatures. They depend on their environment for heat to sustain energy levels, and are therefore restricted in their activities. These scientists put forward the theory that dinosaurs were closely related to modern day reptiles known to be sluggish in the morning and require time to spend absorbing heat emitted by the sun in order to perform daily tasks such as foraging. If clouds were to block the sun's rays, the mental and physical abilities of ectotherms are greatly hindered. However, if the sun's rays are much too hot, ectotherms risk overheating (Bakker, 1986).

A number of discoveries supported the theory that dinosaurs were cold-blooded. In the early 1900s, Roy Chapman Andrews (1884-1960) discovered essential artifacts that supported ectothermy (Norman, 2005). He was among the first to discover a dinosaur egg, thought to have been from a *Protoceratops*. This discovery demonstrated that dinosaurs laid eggs with a hard shell, similarly to modern reptiles. Louis Dollo's (1857-1931) identification of a fossilized imprint of scaly-skin constituted further evidence to support the theory that dinosaurs were cold-blooded since present-day reptiles also have scaly skin. Through comparing dinosaurs to reptiles currently living around the world, paleontologists came to the conclusion that dinosaurs were cold-blooded because they had scaly skin, laid shelled eggs, and were therefore sluggish.

John Ostrom's *Deinonychus*

John Ostrom (1928-2005) was an American paleontologist who was a mentor to his student Robert T. Bakker, and inspired him to begin the Dinosaur Renaissance. Ostrom hypothesized that some dinosaurs may have been endotherms as opposed to ectotherms after he discovered *Deinonychus*, meaning "terrible claw", in 1964. By conducting biochemical analysis of a *Deinonychus'* bone structure, Ostrom discovered that these creatures were incredibly active. They were exceptional in both speed and agility due to their bipedalism. Ostrom's studies of *Deinonychus* and the *Pterodactyl* led him to the study of the *Archaeopteryx*, meaning "the first bird". He discovered how closely related *Deinonychus* and *Archaeopteryx* were through studying their hand structures and feathers seen in fossils (see Figure 4.22). Both *Deinonychus* and *Archaeopteryx* had long bony fingers, and a swiveling wrist. Ostrom then went on to study their whole body structures and found they had many nearly identical features, such as their shoulders, hips, thighs, and ankles. Ostrom had discovered the link between dinosaurs and modern day birds and in doing so demonstrated that modern day birds were direct descendants of dinosaurs. Although Ostrom was not intentionally examining these dinosaurs in hopes of showing their warm-blooded nature, his work was critical and inspirational for his mentee (Norman, 2005).

Figure 4.22 A fossilized Archaeopteryx *currently located within the Museum of Natural History, Paris*

Robert T. Bakker and the beginning of the Dinosaur Renaissance

Robert T. Bakker is an American paleontologist born in New Jersey in 1945 (see Figure 4.23). At age ten, Bakker read a magazine article about dinosaurs that included full colour images of several dinosaurs. From this moment on, he decided that he would devote his whole life to researching these creatures. Unlike most children who grow out of their fascinations for dinosaurs, Bakker's fascination persisted and eventually led him to study at Yale University. There, Bakker completed his doctorate with the guidance of John Ostrom.

Ostrom's discovery of *Deinonychus* is thought to be one of the most important fossil finds in history, and it guided Bakker's research in investigating whether dinosaurs were warm or cold-blooded by nature. Bakker, alongside Ostrom, made extremely significant discoveries leading to the belief that dinosaurs were warm-blooded. He presented both his and Ostrom's findings to paleontologists and to the general public through the publication of *Dinosaur Renaissance*, a pivotal article (Bakker, 1975).

Within *Dinosaur Renaissance*, Bakker argues that some dinosaurs were in fact endotherms. Endotherms are warm-blooded organisms that use high amounts of endogenous heat production, mainly ambient heat, in order to maintain a metabolically favourable temperature. As a result, endotherms have the ability to be active more often during the day and live in a larger range of environmental conditions than ectotherms. Endothermy is advantageous as it reduces an individual's vulnerability to the fluctuations of external temperatures. When in cooler climates, endotherms have behavioural mechanisms that aid in heat production. These behaviours include muscular exertion such as shivering. When in warmer climates, other behavioural mechanisms prevent the overheating of

Figure 4.23 Robert T. Bakker, author of The Dinosaur Renaissance*, in his current workplace The Houston Museum of Natural Sciences*

endotherms by increasing heat loss. Panting and sweating increase water evaporation and would release heat from dinosaurs' bodies. Internal homeostatic mechanisms control body temperature allowing for nocturnal activity and increased physical endurance (Bakker, 1975; Bakker, 1986).

The first piece of evidence that Bakker used to substantiate his theory was the fact that ectotherms cannot survive in drastically changing climates. The understanding of plate tectonics at the time was similar to the current understanding and it was known that the range in which ectotherms lived was comparable to the range in which they would have lived many millions of years ago. From the knowledge about the spreading of continental landmasses and their changing geography, Bakker was able to demonstrate where the dinosaurs lived on Earth. He was also able to predict seasonal temperatures from different areas around the world. He used this latitudinal zonation of dinosaurs to show that some geographical areas were more suited to endotherms than ectotherms and vice versa (Bakker, 1975).

Bakker also argued that dinosaurs had high metabolic rates, thus supporting the idea that they were warm-blooded. To determine the metabolic rate, Bakker first looked at dinosaur bones. The microtexture of bones provide much information about the dinosaur. As bones grow, crystals of minerals are added to previously existing minerals. This growth creates a pattern in the bones, which can be seen through examination of thin, cross section slices of bone. The number of crystals and their size is indicative of the growth rate and metabolism of the organism. In the bones of warm-blooded organisms, many channels exist through which blood vessels may travel whereas in cold-blooded organisms bones are dense with parallel layers of fibre with minimal growth. Through the examination of dinosaur bones, Bakker noted the similarity between bones of present-day warm-blooded creatures and those of dinosaurs. The open weave pattern in several dinosaur bones that was very similar to that of warm-blooded modern species supported Bakker's idea that dinosaurs were warm-blooded (Bakker, 1975).

Another piece of evidence that Bakker used to show that dinosaurs were most likely warm-blooded was the predator-prey ratio. From the fossil record, researchers were able to determine the ratio of predators to prey in certain areas. Using knowledge of today's predator-prey ratios of particular species and information about predator metabolism, inferences were made in order to compare dinosaurs to today's predator-prey interactions. For current endothermic species, the maximum predator-prey biomass ratio is about 1-3%, while that of ectotherms is significantly higher (see Figure 4.24). This is because endotherms have a higher cost of energy, which means that a prey population of either endotherms or ectotherms will be able to support a much greater number of ectothermic predators than endothermic ones. From the fossil record, these ratios can be deduced and can show that the predation of dinosaurs was indicative of endothermy (Bakker, 1975).

All of Bakker's research involved comparing modern mammals and reptiles with dinosaurs' remains. Another piece of evidence used by Bakker was the size of the lungs and heart of dinosaurs. Currently, lizards have small chest cavities that hold a small heart and lungs, whereas mammals have a much larger chest cavity. A larger chest cavity is necessary for mammals as they are endotherms and rely on internal regulation of heat, which requires blood to be pumped through their bodies at great rates. Bakker looked at the chest cavities of the remains of several Brontosauri and noted their massive chest cavities. The Brontosauri had incredibly lengthy necks through which blood travelled to reach their brains. In order

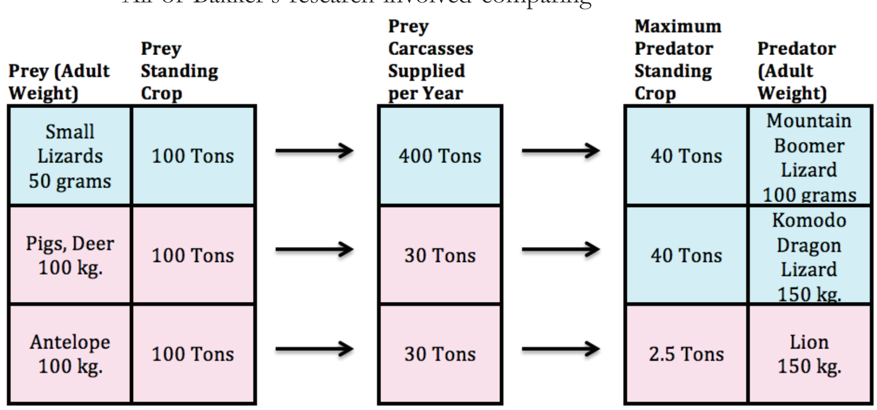

Figure 4.24 Energy flow of ectotherms and endotherms. The blue boxes indicate ectotherms and the pink indicate endotherms. Standing crop is the potential energy contained in the tissues of the organisms averaged over a year

to pump blood a long distance, a large heart and lungs would have been essential. In having a large chest cavity, dinosaurs would have had a distinctive walk. They walked in an upright fashion, similar to modern day mammals, rather than the sprawling form seen in modern day lizards. If dinosaurs had large chest cavities and walked in a sprawling form their chests would have dragged along the ground and a pair of their footprints would have a wide gap between them. Through studying trace fossils of dinosaur footprints, Bakker was able to deduce that dinosaurs walked in a more erect form to allow for their large chest cavities (Bakker, 1986).

Through Bakker's inspired research of dinosaur fossils, he determined that dinosaurs had many features that were more similar to those of mammals alive today than reptiles. He demonstrated that dinosaurs were endothermic because of their high activity levels and metabolic rates, their predator-prey ratios, and the latitudes where evidence of their existence were found. Although it is difficult to prove for certain whether dinosaurs were warm or cold-blooded, Bakker's research and the evidence that he found is undoubtedly suggests his theories are true and has shaped the way many people think about dinosaurs.

The Depiction of Dinosaurs before and after the Dinosaur Renaissance

Trying to recreate 3D, anatomically correct images from fossils that are tens of millions of years old is an extremely difficult task. Many scientists and artists have tried to imagine what these great beasts could have looked like in the flesh and, naturally, there exists a wide range of interpretations based on scientific theory. One of the main events that changed the depiction of dinosaurs from slow, reptile-like animals to fast, smart, bird-like animals occurred when Robert Bakker introduced the concept, through the Dinosaur Renaissance, that dinosaurs were most likely endothermic.

Bakker believed that dinosaurs, in reality, would not have reflected their classical representation, as they were not slow and stupid but fast and intelligent. Bakker avidly wanted the world to believe this depiction and he wanted other depictions of dinosaurs to change to better reflect this (see Figure 4.25). Being endothermic would change how an animal could move and function in their daily life (Bakker, 1986). Instead of relying on the sun and having short bursts of energy, dinosaurs would have been able to make their own energy and move around at faster paces and for longer periods of time, without being weather dependant. Popular media took hold of Bakker's hypothesis when he controversially and stubbornly responded to many of the then-famous palaeontologists who believed that dinosaurs were ectothermic. Bakker did not simply put the idea of endothermic dinosaurs into the world for people to believe as they wished; he forced the idea on people through media appearances and public statements. It seemed as though Bakker's style and attitude was fitting with that of the 1980s, which helped him convince the general population

Figure 4.25 A modern depiction of a bipedal dinosaur with feathers and other bird-like features

of his idea.

Before Bakker suggested that dinosaur were not as slow as was once believed, all depictions of dinosaurs were relatively similar. With so little known about dinosaurs, early depictions of some of the first dinosaurs discovered turned to ancient mythology for inspiration. The similarity between early drawings of dinosaurs and dragons were evident. After all, they were both said to be ferocious, large, and reptilian. Many early illustrations and descriptions of dinosaurs' physical appearances showed quadrupeds with large bodies, small heads, dull colouration, and scaly skin. Many also resembled current crocodiles but were much more terrifying.

The first depiction of a bipedal dinosaur appeared in the book, The Origin of Birds, by Gerhard Heilmann in 1927. This book, which was highly advanced for its time, did not receive much attention until decades later. Heilmann, who illustrated the paper himself, showed dinosaurs as fast moving bipedal animals (Heilmann, 1927), not unlike present day birds, similarly to Bakker's papers decades later. The book was used much later in the ongoing debate of the origin of birds and the evolution of dinosaurs.

The first ever drawing of a feathered dinosaur was in Robert T. Bakker's 1975 journal article, *Dinosaur Renaissance*, which is another reason why this article **is** among his most famous. Now, with the ongoing debate of whether dinosaurs were the ancestors of present-day birds, illustrations of feathered dinosaurs have become even more popular. Additionally, many illustrations no longer show dull-coloured animals but rather vibrantly coloured ones. This shows how Bakker's ideas have been understood and applied by artists and scientists to create more realistic looking dinosaurs.

Along with drawings, there have also been many depictions of dinosaurs in movies. The first movie to feature a dinosaur was a silent film created in 1914 by Winsor McCay. It was a short animation entitled *Gertie the Dinosaur* showing how man could train "Gertie". The audience saw a slow moving dinosaur that, when asked to raise its left leg, takes its time in making a decision as it is unsure of the correct answer. The dinosaur appears to act more like a human toddler than a ferocious beast.

This view of dinosaurs was evident in many other films including *The Lost World* released in 1925, and the 1954 original *Godzilla* (the terrorizing beast was based on a mixture of a *Tyrannosaurus rex*, an *Iguanodon*, a *Stegosaurus*, and a fire-breathing dragon) (Parsons, 2004). After many people accepted Bakker's ideas, he was asked to work closely on the creation of the movie *Jurassic Park* (released in 1993) to ensure that the new depiction of dinosaurs was realistic (Parsons, 2004). This movie highlights the intelligence of lean *Velociraptors* and the speed of the *T-rex*. Suddenly, most people's first thought when encountering a dinosaur would be to run and pray for a miracle, instead of attempting to train it or put it in the circus.

Figure 4.26 A depiction of an Iguanodon *from 1859*

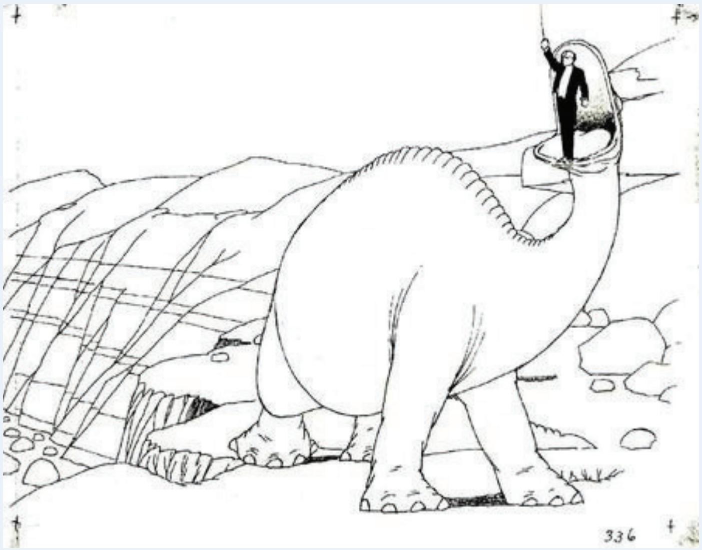

Figure 4.27 Gertie, the first ever animated dinosaur created by Winsor McCay

The world as known in 1812, following the route taken by Captain James Cook on his voyages on the British ship the *Endeavour*

"Do not go where the path may lead, go instead where there is no path and leave a trail."

RALPH WALDO EMERSON

Chapter 5: Exploring the Earth

Human curiosity is never satisfied. To observe this, one need only examine the time period extending from 350 BC all the way to the 20th century, where explorers travelled all over the world for information about our origins and future. In order to communicate their findings these individuals utilized a pivotal tool: maps.

Maps began as very simple drawings on cave walls in ancient civilizations (Harley and Woodward, 1987). Mapping originated through a great interest to explain large unknown spaces, such as the solar system. Constellations were the first tools to be used for navigation and set the stage for many maps to come. Before maps of the world existed, explorers who sailed through the seas to find new lands used the night sky as a compass. By applying the understanding of how to accurately portray the sky, explorers began to create maps depicting the seas they sailed (Rozwadowski, 2005).

The next natural step in the application of maps was to depict distributions of land. One of the largest applications of mapping is using Geographic Information Systems (GIS), which is a tool that manages and analyzes geographic information (Demers, 2000). GIS is extensively used to map out the distribution of disease over a population (Talbert, Richard and Unger, 2008). In the view of modern culture, the most recently created maps are thought to be the most accurate possible (Etherington, 2007). However, this does not mean that future mapping will not unlock new ways of modeling the land and ocean.

This chapter aims to explore the processes driving the creation of maps and exploration of the world. Early explorers introduced in this chapter paved the way for scientists in the current world, allowing them to carry on their work with much greater ease. Without these foundations, modern science would not be at the stage it is today.

The Birth of Cartography: Investigating the Unknown

Cartography, the study of mapmaking, is a field that has evolved significantly through exploration and the expansion of civilizations over the course of history. From a modern perspective, the best map is the most physically accurate, however this has not always been the case. Ancient maps provide information about the distribution of power amongst long gone nations as well as the beliefs held by their people, and even the environme-ntal conditions they endured. The breadth of a map can indicate not only geospatial awareness, but also the way in which civilizations perceived the world around them.

Figure 5.2 British map of Africa from 1813. The coasts have been mapped in detail because of their importance to commerce while the interior remains unexplored.

Innovations in travel and surveying techniques significantly influenced the field of cartography. This holds especially true for inventions that aided in nautical travel. Likewise, as maps became more sophisticated they proved increasingly useful tools for travellers. The Age of Discovery led to highly Eurocentric historical accounts of colonization and gave way to a very technical method of cataloguing geospatial evidence (Lewis and Wigen, 1997). In this way, maps continue to influence our worldview.

Lost in Translation

It is unclear whether historical maps always provide reliable geographical information since cartographic techniques have changed over time. For example, in 1852, measurements of Mount Everest recorded an elevation of 29 002 feet, while later measurements from 1957 found it to be 29 141 feet. This discrepancy could be attributed to either growth of the mountain or error in early measurement techniques (Stillman, 1957).

It is necessary to recognize that accurate geographical representation was not the goal of all maps. The motivation behind a map's creation can significantly impact the map produced. The Desana culture in South America, described the spatial relationship between celestial bodies and geographical landmarks for the purpose of understanding the natural and divine order of the world. As such, the mapping of their surroundings was a by-product of this spiritual exploration (Woodward & Lewis, 1998). Similarly, a mosaic map of the Mediterranean found in Ammaedara, Tunisia from the 4th century CE displays only sites related to the goddess Aphrodite (Talbert & Unger, 2008). In both of these cases, geographical accuracy is of lesser importance than spiritual symbolism. During the Renaissance, however, European cartography was primarily motivated by commercial and military interests. The detailed mapping of coasts was the result of the importance of nautical trade routes, whereas exploring inland areas inhabited by indigenous peoples was assigned less importance. For this reason, the South African coastline appears on European maps as early as the 17th century, while the interior remained uncharted for the following two hundred years (see Figure 5.2) (Etherington, 2007). In other cases, political events sparked exploration. For example, with the expansion of the Ottoman Empire in the 15th century, trade routes previously used by the British between Asia and Europe were no longer accessible. This development provoked a greater interest among European maritime powers in exploring the southern Atlantic and Indian oceans (Etherington, 2007).

Differing ways of conceptualizing space contribute an additional level of complexity to the translation of historical maps. Originally, many measures of distance were based on body parts and therefore differed from person to person (Robinson, 1982). In 1824, the Imperial system in England was standardized with an official yard-length ruler. The metric system was developed beginning in 1790 by a commission of scientists requested by the National Assembly of France during the French Revolution. Due to inconsistencies in measurement between regions, commercial interactions were often unfair, providing the motivation for a universal system of measurement (Hallerberg, 1973). The metre is one ten-millionth of the direct distance from the North Pole to the Equator. While the official metre stick is housed in France, its destruction would not be detrimental due to its clever origin (Robinson, 1982; Stillman, 1957).

Landmarks are a component of historical mapmaking still in use today. Unfortunately, their locations are rarely preserved over time. Regardless, landmarks and their positions on historical maps provide information about the organization of ancient communities. As well, their absence can indicate changes in environmental conditions. For example, maps of ancient Egyptian communities living alongside the Nile River have few landmarks because floods significantly altered the landscape each year (Stillman, 1957).

Innovation and Travel

In the Mediterranean region, it was generally accepted by the 4th century BCE that the Earth was round and therefore innovative techniques were required to accurately map this curvature. Many of these techniques originated in Ancient Greece, a society known for its scientific approach to cartography (Andrews, 2009). In 194 BCE, Eratosthenes of Cyrene created a world map using the first coordinate system composed of parallels and meridians (Bagrow, 1964). In the 2nd century CE Claudius Ptolemy (87-150 CE) further developed this coordinate system in his literary work, *Geographia.* Ptolemy's writings detailed the locations of approximately 8 000 localities. *Geographia* was, unfortunately, not well preserved and no maps have been found to accompany it (Crone, 1968). In spite of this, Ptolemy's meticulous use of the coordinate system allowed cartographers to later derive maps from the text. While remarkably accurate in many regards, Ptolemy distorted several longitudinal measurements (Heidel, 1976). This proved problematic as these errors were perpetuated up to 13 centuries later by European cartographers when his work resurfaced in the 15th century after the fall of Byzantine Empire (Bagrow, 1964; Crone, 1968).

The way that cartographers portrayed geographical information had a significant influence on how expeditions were undertaken. Perhaps the most well-known example of this is Christopher Columbus's famous journey to the Americas in 1492. The significant longitudinal distortion in the East from maps based on Ptolemy's *Geographia*, led Columbus to believe that he could sail directly to India. If, at the time, the maps had not portrayed such a short distance between Europe and India, this voyage may not have been attempted at all.

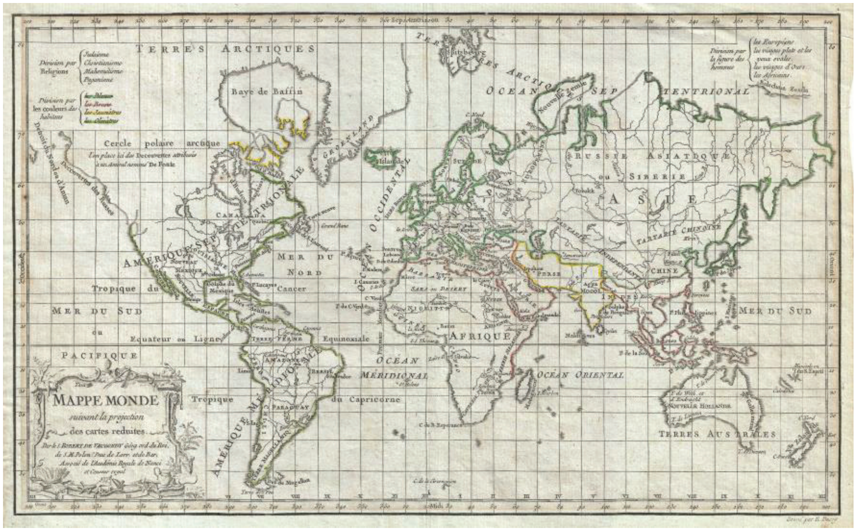

Figure 5.3. Map of the world by Robert de Vaugondy from 1785 with Mercator projection. This projection allows for coordinates to be more easily ascertained, however, places further from the Equator are disproportionately large.

Although the spherical shape of the Earth was known earlier, it was not until 1569, that Gerardus Mercator of Flanders developed the Mercator projection. This provided a solution to the representation of a spherical map in two dimensions and allowed bearings to be plotted as straight lines. While still slightly distorted, it is the basis for most atlases used today (see Figure 5.3) (Bagrow, 1964; Klinghoffer, 2006).

Travel and exploration were instrumental in developing maps of greater accuracy. Ancient itineraries marking out travel routes played an important role in the construction of early maps. The first Greek map in 6th century BCE was based on itineraries created by merchants who travelled along the coast (Crone, 1968; Talbert & Unger, 2008). The exploration required replaced deteriorating agricultural land led early Greek scholars to set the foundation for cartographic studies. Miletus, a city in ancient Greece, became the centre for geographic knowledge in 600 BCE (Heidel, 1976).

Figure 5.4. Map of the world from 1482 based on Ptolemy's Geographia. Faces blowing air represent the four main winds.

In the Achuar culture of Ecuador, travel routes were described using a system of natural landmarks (Woodward & Lewis, 1998). Settlements were located along river banks, so a network of riverine coordinates was established to locate specific places. The direction of river flow was used to orient travellers instead of the more common method of observing the Sun's location in the sky. Large distances were measured by the time necessary for travel, usually in days, while precise distances were reserved for architecture (Woodward & Lewis, 1998).

Over time, innovations in travel led to more numerous and extensive expeditions, and the production of more detailed maps. Ships were instrumental in the exploration of land that was difficult, or impossible, to access by foot. Navigation by sea was initially conducted using charts that referenced coastal landmarks through a process known as "Church Steeple Navigation". In the Northern Hemisphere, the North Star was instrumental in early sea travel as it gave a steady, unchanging focus for sailors without other visual landmarks. On cloudy nights when the stars were not visible, the four main winds, illustrated on maps as faces, provided the only remaining, though unreliable, means of orientation (refer to Figure 5.4) (Stillman, 1957). Dead reckoning, where a captain painstakingly tracks their approximate location over time, was used up to the time of Columbus (1451-1506). Sailors were able to determine their latitudinal location by measuring the angle from the horizon to the North Star using instruments such as the astrolabe, and later the sextant. However, it was only in 1714, with John Harrison's invention of a reliable watch, the chronometer, that sailors could find their precise location. To determine their longitudinal coordinate, they compared the time on the chronometer at noon to the time in Greenwich (Stillman, 1957).

The compass is another invention that revolutionized travel. The compass was invented in Imperial China around the 3rd century BCE. Its initial purpose was for spiritual navigation as opposed to exploration (Nakamura, 1962). Initially, slivers of lodestone (now known as magnetite) were attached to reeds and suspended in water. Although unpredictable, these first compasses allowed merchants to find their way across the deserts of Asia. More advanced compasses were made with lodestone slivers attached to pivots. This increased reliability and made compasses indispensable tools for nautical travel (Stillman, 1957).

Discovering Land and Mapping Cultural Changes

Shifts in cartographic expertise from one culture to another were often fuelled by technological advances and changes in political power. Some of these changes were the results of deliberate political or religious decisions, while others were the result of new geographical discoveries (Barrow, 2003).

Religion and mythology, in particular, played a prominent role in historical cartography.

Islamic nations studied geography using the parts of Ptolemy's work that remained accessible (Talbert & Unger, 2008). Two important cartographers rose to prominence in this period: Ibn Haukal (c. 980), and Al Idrisi. Idrisi, in particular, made significant contributions to the knowledge of Asian geography in 1154 CE (Bagrow, 1964). However in Europe, the Christian Era, spanning from the 11th century CE to the beginning of the Renaissance in the 15th century, marked a halt in cartographic progress (Bagrow, 1964). Many Greek maps were burned or lost and Ptolemy's writings were discarded in favour of older ideas. At this time, world maps, known as *mappae mundi*, were primarily used as tools for religious teachings. They were adorned with depictions of Paradise and Hell, along with an assortment of mythological creatures (refer to Figure 5.5). They portrayed a flat Earth, even though its spherical nature was known (Klinghoffer, 2006; Harley, J.B., Woodward, 1987). Chinese cartography developed separately and remained unaffected by external cultural influences during this period. In fact, most of China had already been mapped before the arrival of the Europeans (Bagrow, 1964).

The translation of Ptolemy's *Geographia* into Latin along with the fall of the Byzantine Empire in the 15th century marked the end of the medieval *mappae mundi* and the dawn of the Golden Age of Cartography. Marco Polo's expeditions in the 1270s and 1280s led to a marked increase in the popularity of sea expeditions. The 15th and 16th centuries saw a rise in the prominence of explorers including Columbus and Cabot. Post-medieval maps generally aimed for maximal accuracy, but large unmapped spaces remained. This period was known as the Age of Discovery as it involved the colonization of much of the world by Europe including, for the first time, the Americas (Bagrow, 1964).

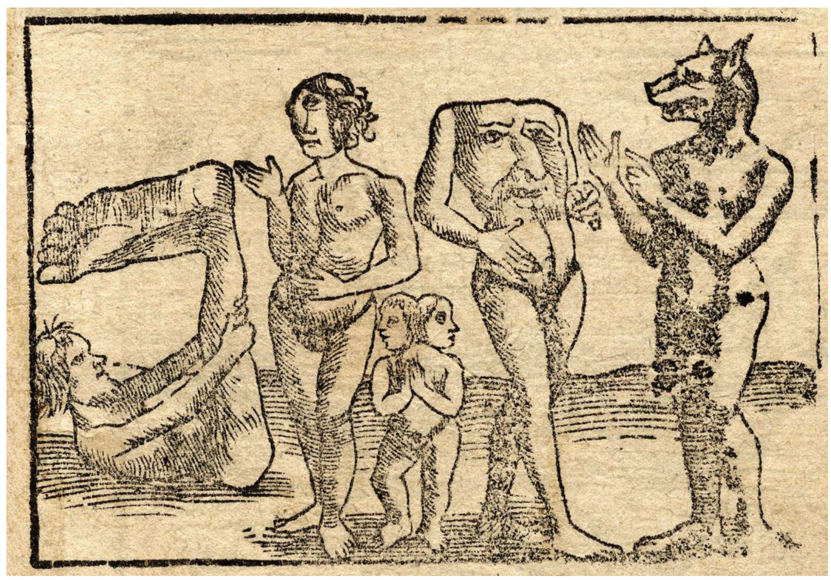

Figure 5.5. Illustration of mythological creatures commonly found on mappae mundi world maps during the Christian Era.

The finding of new landmasses and continents by explorers is often termed "discovery", however native populations already inhabited most of these lands. Unfortunately, due to cultural biases, many maps of indigenous creation were overlooked. An example of this is seen in the change towards European techniques and styles in Chinese cartography post-colonization (Bagrow, 1964). The European maps created during the Age of Discovery show dynamic political boundaries as a result of interactions with other invading and pre-existing cultures. Emma Willard's maps from the 19th century illustrate this concept through the gradual disappearance of North American indigenous groups as the frontier of colonial exploration expanded west (Etherington, 2007). Native peoples were often identified outside of the borders of colonial territories, while those within were erased. One method used to assert power over a colonized territory was to name various landmarks after prominent colonial figureheads. For example, while colonizing India, maps of the Himalayas were made with the tallest peak named after British surveyor General George Everest (1790-1866) (Barrow, 2003).

Although explorers asserted power through the creation of maps, conventions of indigenous cartography were also often incorporated. Explorers charting unknown territory often relied upon native guides, occasionally resulting in a negotiation of power (Etherington, 2007). When the exchange of knowledge was voluntary, indigenous guides strategically chose whether or not to provide accurate geographical data depending on their relationship with the colonizers. For example, as a result of their 16th century alliance with the Aruaca culture, the Spanish were given geographical information about the Rupununi River, an important transportation and commercial route. Lacking native knowledge of the area, this river passage was not included in Dutch, English, or Portuguese maps of the region until the 18th century (Woodward & Lewis, 1998).

Over the course of history, there has been a gradual shift from symbolic maps to maps that strive for geographic accuracy. The maps of the 18th century demonstrate this change with the removal of all decorative features and monsters (Lewis and Wigen, 1997). However, complete accuracy is not always ideal (Klinghoffer, 2006). After all, the Earth is a dynamic place with ever changing geographies and political boundaries. Maps are relevant not only to the field of geography, but also to reflect the development of human history.

Mapping the Cosmos

The study of astronomy has existed since the beginning of the historic record and has been practiced by cultures all over the world. The exploration of space itself, however, has only been a possibility since the 20th century. Much like the exploration of new territories on Earth, the exploration of space has been motivated by scientific curiosity as well as military and commercial interests.

The Space Race

The beginning of space exploration was sparked by the "Space Race" between the United States and the Soviet Union. The competition to lead in the exploration of space closely mirrored political tensions of the Cold War unfolding on Earth (Stares, 1985). The Soviet Union was the first nation to successfully send a man-made object into orbit with the launch of Sputnik 1 on October 4th, 1957. The satellite itself had no useful function; instead its purpose was intimidation in the midst of a potential nuclear crisis (Moltz, 2011). The ability to send an object into space sent a clear signal that the Soviet Union was technologically powerful. The Soviets followed this feat with additional milestones including the launch of the first living being into orbit in 1957, the first human spaceflight in 1961, and the first automated landing on a celestial body in 1966 (Moltz, 2011). It is the American's National Aeronautics and Space Administration (NASA), however, that is credited with the first manned mission to the Moon with the landing of *Apollo 11* on July 20, 1969 (Wilson, 2013).

The International Space Station

With the end of the Cold War, exploration of space shifted from a competitive endeavour by individual countries towards international collaborations. The International Space Station (ISS) represented an unprecedented scientific collaboration between fifteen countries and five space agencies (Catchpole, 2008). The ISS program was created by the merger of three planned space station projects which had not yet been executed: the Russian *Mir-2*, NASA's *Freedom*, and the European Space Agency's *Columbus*. Technology from other countries was also incorporated, such as the *Canadarm* from Canada and the *Kibo* research module from Japan. The ISS was launched in 1998 and assembled in space with the assistance of the *Space Shuttle* which transported the individual modules (Catchpole, 2008). Even at 330-435 km above the Earth's surface, the ISS is primarily a scientific laboratory for a number of research fields. One such project is the "Monitor of All-sky X-ray Image (MAXI)" study which uses highly sensitive X-ray detectors to record a complete survey of the sky (Matsuoka, 2013).

New Age Cartographers

Astronomical observations from Earth with even the most powerful telescopes are inherently inaccurate due to distortion from the Earth's atmosphere (Oswalt & McLean, 2013). Satellite telescopes are able to overcome this problem and provide clear images of faraway galaxies. Of these, the *Hubble Space Telescope* is perhaps the best known. It was launched in 1990 and is still currently operational. The *Hubble* telescope uses Cassegrain reflector technology to capture its images of the universe by concentrating large amounts of light using mirrors. It collects light from the near-infrared, ultraviolet, and optical wavelengths. These signals have provided researchers with information on the size of the universe, black holes, and the life cycle of stars (refer to Figure 5.6) (Oswalt & McLean, 2013). Additional satellite telescopes have been launched since the *Hubble* and often collect different types of signals. For example, the *Planck Observatory* launched in 2009 by the European Space Agency collects signals from microwave wavelengths, known as Cosmic Microwave Background (CMB) radiation. This facilitates the study of the origin of the universe as CMB is radiation remnant of the Big Bang (Planck Collaboration et al., 2013).

The *Kepler* telescope was launched in 2009 by NASA for the purpose of identifying exoplanets, or planets outside of the Earth's Solar System. It also determines the likelihood that an exoplanet could be habitable and examines the characteristics of stars hosting planetary systems (Borucki, 2010). As of 2013, it is estimated that 10 billion stars within the Milky Way Galaxy may host Earth-like planets (Klotz, 2013). These technologically advanced observers, such as *Hubble, Planck,* and *Kepler* can be considered cartographers of the modern age.

New Frontiers

The human desire to explore and map out new territory continues even as technology enables us to capture signals directly from space. Having already successfully landed on the moon, the next possible destination is Mars. There are a number of initiatives, both private and public, that plan to send a manned mission to Mars (Hogan, 2007). Cartography of new lands in the past required explorers to travel to the desired territory directly. Fortunately, unmanned rovers sent to Mars and other planets have already gathered information about the planet's surface, composition, and atmosphere (NASA, 2013). This preliminary exploration made possible by technology is vital for a future successful manned mission. Similar to exploratory missions of the past, however, travelling to a new world presents considerable danger. Despite this, when the not-for-profit Mars One Foundation began an open submission process to find candidates for a one-way mission to Mars in 2013, over 200 000 individuals volunteered (Gannon, 2013). This shows that the spirit of human exploration is timeless.

Figure 5.6. An image of a nebula as taken by the Hubble telescope.

Historical Mapping of Ocean Topography

"We must now discuss the origin of the sea, if it has an origin..." - Aristotle (Mackin, 2009, p.3).

There are many different theories on how oceans formed on Earth; however there are only two main ones. The first theory states that the "degassing" of the Earth's core by volcanism released water vapour into the atmosphere, where it remained until the Earth cooled enough for the water to condense. Once this occurred, the water fell into the dips and valleys that formed due to impact of asteroids during the creation of the Earth's crust. The second theory states that water was brought to Earth by ice comets. Ice comets found on Earth in present day have been measured to contain 10^{15} kg of water. To achieve the current amount of water on Earth, one million ice comets would have had to impact with the crust (Mackin, 2009). The true reason is not known, but it is likely that both of these were contributing factors. Apart from these two theories, mankind was not terribly interested in the ocean and as a result did not put much thought into what it may contain. Not surprisingly, they were more interested in the Earth itself. Early civilizations believed that the world was flat as they could see only to the horizon and thought that eventually they would fall off the edge. Although this is known to be incorrect today, it was not until 350 BCE that Aristotle (384-322 BCE) began to make observations of the ocean. He specifically looked at why the ocean did not experience drastic increases in water level over time, even though there were many rivers that flowed into it (Mackin, 2009). It was not until the 21st century, that it was found that the ocean depth does not change dramatically year to year as the inputs from rivers and outputs from evaporation are almost equal (Mackin, 2009).

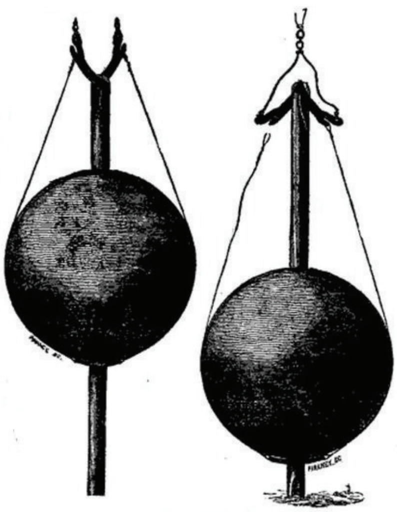

Figure 5.7 Baillie sounder: constructed of a piece of lead attached to a string, when the instrument reaches the bottom the weight is released and it can be pulled back to the surface.

The ocean was, and still is, an area that is a mystery to people. It is not unreasonable for people to fear that which they do not know. For this reason, many people feared the ocean up until the 19th century. Aside from the navy, sailors would only go to sea for fishing and trading, and did not venture past common fishing zones and trade routes (Rozwadowski, 2005). In the 19th century, there was growing interest in understanding large and unknown places, such as the solar system, and the oceans. Between 1840 and 1880, there was a dramatic change in awareness of the ocean that sparked considerable scientific interest, which has grown to the present day (Rozwadowski, 2005). The combination of deep-sea instruments, theories, and data volume has led to a large increase in the comprehension of the ocean floor (Tharp, 1982). The term used to describe this study is oceanography, and though it is a relatively new science compared to those of physics or geography, the concepts that have been built on over time and are just beginning to be understood.

Sounding Ocean Depths

One of the major components of oceanography is understanding the topography of the ocean floor, much like trying to understand the topography of the continents (Embley, 2012). A growing awareness of the ocean floor was first seen in the 1850s and 1860s when a submarine telegraph cable was laid across the Atlantic. Although this was not the initial purpose of the cable, the United States (U.S.) and the British Navies used the telegraph cable to sound the deep ocean, resulting in an increase in information regarding the ocean floor topography (Rozwadowski, 2005). The use of cables introduced the idea of using lines as a tool to record ocean depths.

In 1871, Lieutenant Charles William Baillie (1844-1899) created the Baillie sounder, which is used in a process called sounding (see Figure 5.7). Contrary to current uses of the word, sounding refers to any method that is involved in measuring ocean depth. In sounding, a line with a piece of lead attached is lowered into the ocean until the tension is slackened (Mackin, 2009; Embley, 2012).

Once this occurs, markings on the line, which corresponded to units of length, can be interpreted (Beck, 1996). In the 1850s, deep-water measurements in the Atlantic Ocean showed a realistic ocean depth of 1 829-3 657 metres (m); however, there were many exceptions to these measurements. For example, in 1851 Samuel Barron measured depths of 10 058 m while Henry Denham measured depths of 14 093 m in 1852. Both these depths were extremely unrealistic, therefore, in the 1870s hydrographers stated that the depth of the ocean did not exceed 9 144 m (Rozwadowski, 2005). This depth is still unrealistic, but has been accepted as a middle ground of the range of depths documented using the Baillie sounder. Mapping the ocean floor does not only consist of mapping depths but also includes mapping any changes in the composition of the ocean floor (Embley, 2012). The pieces of lead attached to the early sounding lines were covered in grease or tallow to pick up sediments from the ocean floor. These sediments could then be examined for different compositions and microorganisms in order to determine what the bottom of the ocean contained (Beck, 1996).

The two major American institutions that undertook early scientific study of the ocean's depths were the U.S. Coast Survey and the Depot of Charts and Instruments. In 1843, the U.S. Coast Survey's mandate included mapping the shorelines, islands, anchorages and waters that were 20 leagues off American territory. Meanwhile, the Depot of Charts and Instruments investigated and charted offshore waters. Matthew Fontaine Maury (1806-1873) and his team did this by studying winds, currents, and the distribution of whales (Slotten, 1994). In the 1850's Maury's team found that they could save 47 days during the trip from New York to San Francisco by improving navigation of ocean waters, thus saving the shipping companies millions of dollars every year (Herman, 2005).

In addition to mapping the ocean floor, another important finding was achieved through the laying of the submarine telegraph cable across the Atlantic. Edward Forbes (1815-1854), a British naturalist, had a theory that stated that no life existed in the ocean below a depth of 550 m. This theory was easily disproved in the early 1980s when the submarine telegraph cable was raised up for repair, and many unknown organisms were discovered growing on it, thus allowing them to be catalogued as new ocean life (Rozwadowski, 2005).

Single-beam SONAR

Sounding was an extremely inefficient and time consuming method of measuring ocean depths, especially in deep waters. During World War I, a more efficient method of mapping the ocean floor was created using underwater sound projections called single-beam Sound Navigation and Ranging (SONAR) (US Department of Commerce, 2013b). A SONAR device was first developed by Lewis Nixon I (1861-1940) in 1906 to prevent collisions with icebergs. The sinking of the *Titanic* in 1912 had a very large impact on the development and evolution of surveillance technologies, including SONAR. In 1915, Paul Langévin also invented a SONAR device to detect submarines used in World War I. Although he was too late to contribute to the war, his work had a large influence on the designs of future SONAR devices (Petersen, 2012). There are two types of single-beam SONAR, passive and active. Passive SONAR is used to listen to noise in the ocean. Therefore, it does not emit any signals and only detects signals coming towards it (US Department of Commerce, 2013b). This was the first type of SONAR used until the 1920s when Britain and the U.S. built active SONAR systems (Embley, 2012). Active SONAR was first invented in the 1920s by August Hayes and emits an acoustic signal into the water (Ingmanson and Wallace, 1973; US Department of Commerce, 2013b). Once the signal hits the ocean floor, it is reflected back as an echo, this is called the returning echo (see Figure 5.8). The time between the emitted signal and the returning echo is used to determine ocean depth. By the 1920s, the Coast and Geodetic Survey were mapping deep oceans

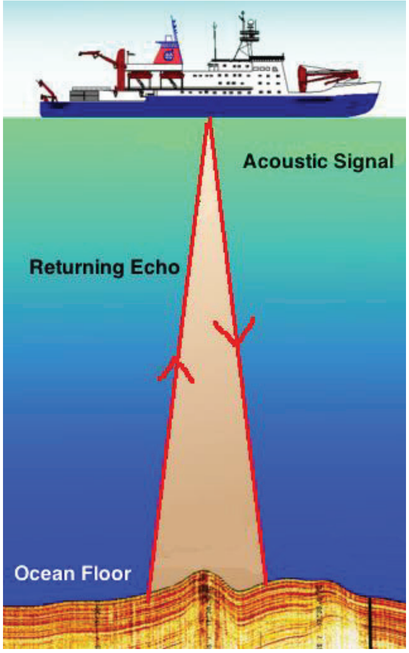

Figure 5.8 Acoustic signal and returning echo of active SONAR.

(Embley, 2012).

Much of the information gathered about the topographical features of the ocean floor was achieved through single-beam SONAR (Ingmanson and Wallace, 1973). SONAR imaging can produce pictures of the ocean floor, reefs, wrecks, and vegetation (Petersen, 2012). In the 1920s, A. C. Veatch (1878-1938) and P. A. Smith's team created one of the first detailed maps of the ocean floor, showing that the canyons off the East Coast of the U.S. extended into very deep waters. World War II dramatically improved SONAR allowing precise measurements of the ocean floor at great depths. Through improvements, such as long-range sound propagation, maps were constructed showing important features including mid-ocean ridges and trenches. For example, in 1873, a large rise in the central Atlantic Ocean floor was detected through sounding on the *Challenger*. This expedition was run by Captain George Nares (1831-1915), and aimed not only to measure depths of the Ocean, but also to dredge areas for sediment types and different organisms (Mackin, 2009). The large rise in the Atlantic Ocean floor was assumed to be a result of a barrier forming due to differences in water temperatures however was later identified as a mid-ocean ridge. Beno Gutenberg (1889-1960), a German-American seismologist, and Charles Richter (1900-1985), an American seismologist and physicist, worked at the California Institute of Technology in order to develop the Richter magnitude scale, which is used to quantify the size of an earthquake. To do this, some of their work included mapping the seismicity of the ocean showing that earthquake epicenters tend to occur along the mid-ocean ridge. As well, Marie Tharp (1920-2006), an American geologist and oceanographic cartographer, assembled drawings that showed that the central valley of the mid-ocean ridge coincides with the epicenters. Through these findings, they hypothesized that the presence of an expanding mid-ocean ridge supported the theory of continental drift (Tharp, 1982). This theory was proposed by Alfred Wegener (1880-1930) in 1912, and stated that the continents were moving over time; however the reason for this movement was unknown. Bruce Heezen (1924-1977) and Tharp published the first physiographic map of the North Atlantic in 1957, which allowed the general public to visualize the ocean floor. Many early maps were based of off hundreds of thousands of depths, which offered the framework for the plate tectonic revolution in the 1960s. For example, it was in the 1960s that Harry Hess proposed the Seafloor Spreading Hypothesis, which states that ocean crust forms at mid-ocean ridges and spread laterally away from them (Embley, 2012).

Multi-beam and Side-scan SONAR

Regardless of the improvements in single-beam SONAR there was still an issue: it only measured depths that were directly below the ship. To try to solve this problem, the U.S. Navy started using multi-beam SONAR in the 1960s, which produced projections not only under the ship but also significant distances perpendicular to the ship's track (Embley, 2012). Multi-beam SONARs function the same way as single-beam SONAR; however, they use more than one beam of acoustic signals, allowing a broader range of detection. Therefore, multi-beam SONARs produce a swath of the surroundings rather than the lines single-beam SONARs produce.

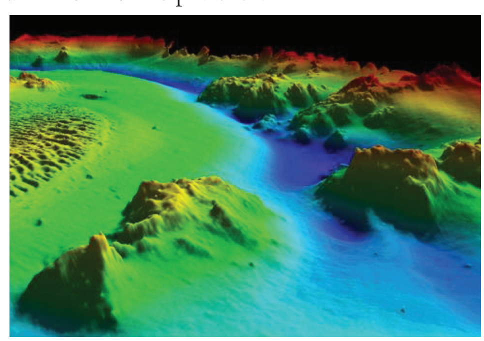

Figure 5.9 Image of the Entrance to Portsmouth Harbour, New Hampshire created using Multi-beam SONAR

Multi-beam SONAR was first used by the U.S. Navy to map large swaths of the ocean floor in order to assist the navigation of submarine forces. The first commercial multi-beam SONAR was put into service in 1977 on an Australian survey vessel and produced 16 beams across a 45 degree swath. Through this, the scientific community was able to produce detailed and complete maps of large areas of the ocean floor (Embley, 2012). In the 1980s and 1990s technology greatly improved, allowing multi-beam SONAR devices to become more accurate. In 1989, Atlas Electronics, a German company, installed an improved multi-beam

SONAR device called the Hydrosweep DS (HS-DS) on the German research vessel *Meteor*. The HS-DS produced up to 59 beams across a 90 degree swath, which was a vast improvement compared to the device used in 1977 (Krim and Viberg, 1996). Multi-beam SONAR was also used to create images, with a much higher resolution than single-beam SONAR, that resemble normal pictures (Figure 5.9). This allowed for high-resolution mapping of shallow waters in navigational charting (Petersen, 2012; Springer, 2007). Another advantage to multi-beam SONAR is that its use is not limited to mapping the ocean floor as it can also be used to explore offshore oil and gas, and to determine different benthic habitats by mapping the distribution of surficial facies and taking sediment samples to determine where microorganisms are most present (Dartnell et al., 2008).

A fourth method of mapping the ocean floor is using side-scan SONAR devices. One of the inventors of side-scan SONAR was a German scientist Julius Hagemann (died 1964). Hagemann was brought to the U.S. after World War II, where he worked on developing side-scan SONAR for the U.S. Navy Mine Defense Laboratory, however the information remained confidential. The main military use of side-scan SONAR during World War II was to detect mines (Hagemann, 1980). At the same time, the Institute of Oceanographic Sciences also developed the first side-scan SONAR in 1960 (Tyce, 1968). Unlike multi-beam and single-beam SONAR, side-scan SONAR is not used to measure ocean depths (US Department of Commerce, 2013a). Instead, side-scan SONARs send and receive signals at low angles allowing the detection of subtle features on the ocean floor (Embley, 2012). Martin Klein at Edgerton, Germeshausen and Grier developed the first commercial side-scan SONAR between 1963 and 1966.

The first side-scan SONAR only had a single transducer that sent and received acoustic signals (Hagemann, 1980). This later changed into two transducers in order to cover both sides of the ship. Finally, the transducers evolved into fan-shaped beams that allowed better images to be produced. Currently, side-scan SONARs require three important pieces of equipment: a tow fish containing the transducers (see Figure 5.10), a transmission cable that sends data to the ship, and the ship's processing computer. The tow fish is lowered into the water and dragged over the ocean floor as the ship moves. It continuously records the returning echo, creating a picture of the ocean floor. The Harder objects produce darker areas on the image while softer objects, such as mud and sand, produce lighter areas. These dark and light areas are analyzed and used to draw maps of the ocean floor (US Department of Commerce, 2013a). Throughout history, side-scan SONARs were used to find many sunken ships. For example, in 1963, it was used by Dr. Harold Edgerton, Edward Curley, and John Yules to find the *Vineyard Lightship* in Buzzards Bay. It was also used to find Henry VIII's flagship *Mary Rose* and a 2000 year old ship off the coast of Turkey (Åkesson, 1999).

Figure 5.10 Tow fish dragged behind ship for side-scan SONAR measurements

Until the mid-1980s, the images produced by commercial side-scan SONARs were paper records. In the late 1980s commercial side-scan SONARs began using newer and cost effective computers that allowed the images to be produced as television and computer displayed images and stored on videotape. Aside from detecting subtle features, the strength of side-scan SONARs can be used to determine the sedimentary composition of the ocean floor (US Department of Commerce, 2013a). For example, mud will return only a small percentage of the acoustic signal while rock will return most of it (Embley, 2012).

Multi-scan and side-scan SONAR can be used in combination to obtain more detailed data about the ocean. With the help of multi-scan SONAR, many different features can be detected by side-scan SONARs including areas with large rocks and boulders, sand-wave fields, hummocky areas, tabular erosional outliers, small hills and scarps, and trawl marks (McMullen et al., 2007). Also, the sedimentary environments present on the ocean floor can be determined by using a combination of multi-beam and side-scan SONAR. The sedimentary environments can be characterized by the processes of erosion or non-deposition, coarse-grained bedload transport, and sorting and reworking (McMullen et al., 2007).

Changing images of the ocean floor reflect the improvement of sounding techniques and technology. The ability to make complete maps of large areas of the ocean floor was first established in the late 1970s, and has been a great step forward in ocean exploration. Mapping the ocean has provided people with a lot of information about the depth and the composition of the ocean floor. As well, many different ideas and theories, such as continental drift, and the nature of marine life have been established on the basis of the information, and data gathered from mapping the ocean. These data, along with the shape of the ocean floor, are an extremely important step in advancing human knowledge about the ocean.

Marine Organisms and Changing Environments

Ideas about the Earth and its climate have changed drastically over time. In the 1970s, it was believed that the planet was undergoing global cooling. Contrast this with today, where advocates for a green Earth are warning about global warming and increased carbon dioxide in the atmosphere. This is a drastic change in a short geologic time period. In order to determine what is occurring, it is useful to compare modern environments to the past and see how they have changed. The ocean is the largest source of carbon exchange with the environment, so it is beneficial to start modeling changes there. A good way to reconstruct past temperature and environmental conditions has recently been developed through fossil composition. Before the fossils can be found and identified, their location on the ocean floor must first be determined. Modern uses of SONAR have created major breakthroughs in determining the distribution of benthic biota. Through using a combination of side-scan SONAR and sediment sampling, scientists are able to determine where the highest biodiversity of benthic organisms reside on the ocean floor (Kostylev et al., 2001). In a study conducted by Kostylev et al. side-scan SONAR was used to determine sediment composition while sediment samples were used to determine the benthic organisms and fossils present. From this study, it was determined that the majority of organisms resided in areas with poorly sorted gravel as the major sediment type. Modeling this in the oceans today provides good intel as to where benthic organisms from the past would be located. Therefore, side-scan SONARs and sediment sampling have allowed scientists to determine which sediments may have abundant fossils of past organisms, and therefore have helped advance the study of paleoclimatology.

Paleoclimatology is a process that allows geologists to reconstruct past climates and environments. This is accomplished by investigating the chemical composition of various features such as trees or ice sheets, where components of the ambient environment are trapped and are unable to change over time (Bradley and Jones, 1992). In recent years, the results from these investigations have been used to determine whether the Earth is undergoing global warming (Caldeira and Wickett, 2003). When ice core samples are obtained, various methods such as gas chromatography-mass spectrophotometry determine their chemical composition. This determines the carbon dioxide content in the ice from thousands of years ago, which can then be compared to the carbon dioxide content in the atmosphere in present day. Gas chromatography is a tool used that heats the sample into a gas and then separates the different components based on their charge and mass allowing them to be identified (Bradley and Jones, 1992). Typically, carbon dioxide is the main component being examined; and can be used to make inferences about the temperature of the Earth at that time. This is based on algorithms created from a comparison between changes in temperature and the carbon dioxide in the atmosphere.

Various marine organisms have been closely studied to determine the marine environments present up to 100 Mya (Branson et al., 2013). Benthic organisms, such as *foraminifera* (see Figure 5.11), have been specifically studied as their main source of nutrients comes from filtering the ocean water. Therefore, they are the best indicators of what was present in the ocean at that time (Branson et al., 2013). These organisms collect calcium carbonate from the water and use it to create a hard shell. They also collect small impurities, including magnesium, in the porous holes in the shell. Impurities are constituents other than hydrogen and oxygen, which alter the pure form of water. These impurities are both dissolved and suspended solids such as sand and sodium chloride, and provide information about the salinity and acidity of the oceans (R. Schöne et al., 2013). Scientists originally thought that the layers of magnesium found in *foraminifera* shells may have a correlation to the temperature found in the ocean, but until 2013 there was no definitive answer (Branson et al., 2013). Using X-ray microscope images of these organisms, scientists have discovered that these layers of magnesium are present throughout the shells in 30 nanometre lengths, and resemble growth lines on the shell. This is comparable in size to one hundredth of a human hair (Branson et al., 2013). The most intriguing part of this finding is that the layers of magnesium were found to be present as if they had been formed on an almost daily basis, as opposed to a yearly basis as seen in tree rings in dendrochronology (Branson et al., 2013). This magnesium is produced by the reduction of calcium in the shell, or loss of electrons, according to the temperature of the water (Branson et al., 2013). There is a greater amount of magnesium present in shells that were deposited in warm-shallow marine environments as opposed to deep-colder ones (R. Schöne et al., 2013). Within each shell, the magnesium layers that were thicker were associated with the warmer months of the year (R. Schöne et al., 2013).

The ratio of the magnesium to calcium can be used to date the fossil (Branson et al., 2013). Before this discovery, the ratio of strontium to calcium was measured in smaller benthic fossils (de Villiers, Shen, & Nelson, 1994). This method was effective, however, unlike with magnesium, the colder temperatures were associated with greater amounts of strontium (de Villiers et al., 1994). The magnesium dating method is three times more sensitive to temperature change than the strontium dating method (Branson et al., 2013). The sensitivity refers to how much the water temperature would have to change in order to be recorded in the magnesium present in the shells. The more sensitive, the smaller that change needs to be.

The shells of benthic organisms also contain impurities absorbed from the water, along with calcium and other nutrients. Through the same method as determining temperature changes, scientists can also measure the chemical composition of the oceans from past time periods (Branson et al., 2013). They are then able to make comparisons with modern-day conditions found in the ocean, and model the changes that have occurred in the ocean over time. This can be used to determine the effect of changes in the chemical composition of the oceans on marine organisms and aid in predicting potential effects in the future.

This method of fossil analysis provides a new means of using the oceans to gain knowledge about past environmental conditions. With the aid of modern technology, humans are able to accurately describe what the world was like at least a hundred million years in the past. Using this, it is possible to reconstruct what the world may become in the future. Hopefully by knowing what happened in the past, humans will be able to alter it to further their evolution.

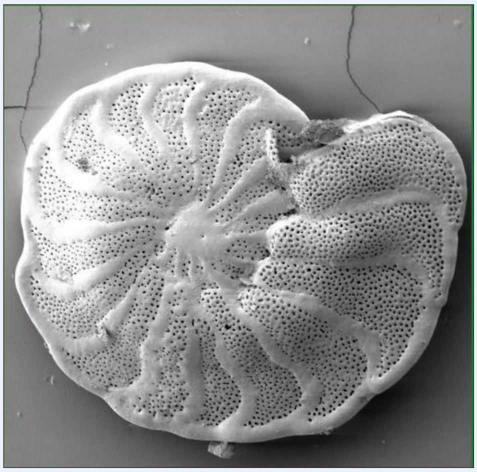

Figure 5.11 X-ray image of foraminifera (right): a benthic organism that can be up to 100 Mya.

Origins of Geospatial Thinking for Disease Mapping

Hippocrates (460-377 BCE), a Greek physician, was the first individual to analyze the environmental influences on disease. Hippocrates considered disease to be caused by a disturbance in the balance of the four humours in the body: black bile, yellow bile, blood, and phlegm. This balance was connected to the prevalence of the four elements: earth, water, fire, and air. Under the Hippocratic school of thought, it was believed that factors in the physical environment, such as wind strength, humidity, temperature, and height above sea level, affected the prevalence of disease (Cassel, 1964). This is an early example of geospatial analysis, which draws conclusions based on geographic or positional data. This type of analysis is the backbone of the Geographic Information System (GIS). GIS is a digital system designed to store, manipulate, analyze and manage all types of geographic data (Hanson, 1997). The history of the development of GIS began in the 1800s with John Snow. It was further developed by technological advancements throughout the 20th century, particularly at the dawn of the computer age.

John Snow

John Snow's (1813-1858) work on cholera was one of the first major instances in which geospatial analysis was used to determine the origin and method of disease transmission. This was vital in laying the groundwork for the development of GIS. The first cholera epidemic to hit London began in 1831 and killed 21 800 people in the UK alone, in the span of a year (Shephard, 1995). The second epidemic, beginning in September of 1848, and ending approximately a year later, was even more severe than the first. It took the lives of 54 000 people in the UK.

At the time of these epidemics, the transmission of cholera had not yet been linked to microbial activity. Thus, there was much debate over mechanism of transmission, dividing the scientific community into two main schools of thought: the contagionists and the anticontagionists (Snowden, n.d.). The contagionists believed that a disease could be transmitted either directly from an unhealthy person to a healthy one, or indirectly via fomites, which are surfaces or objects with which both people come into contact. The anticontagionists believed that disease is caused by poor quality air, known as miasma, from decaying organic matter. At the time, the anticontagionist perspective was generally more accepted, as the germ theory of disease was not yet prevalent.

John Snow was born in York, England, and became a surgeon's apprentice at age 14 (Shephard, 1995). When the first cholera epidemic hit London in 1831, Snow was 18 years old. He worked to treat the victims of the epidemic, but held no greater insight into its cause than any other medical professional. It was during the second epidemic that he began formulating his ideas on the method of transmission of cholera (Shephard, 1995). This epidemic began when a sailor docked his ship in London, and died of cholera shortly after. The next recorded cases also occurred in this general vicinity. Snow noticed that an open sewer existed within reach of the tide, which carried the sewage from the area where the sailor stayed to another grouping of houses. From this, Snow concluded that contaminants from the first victim were being transmitted, via water, to the surrounding area. This solidified his contagionist viewpoint, as it showed contact with matter contaminated by a cholera sufferer could cause cholera in healthy populations.

What John Snow described as the worst outbreak of cholera began suddenly in the residential area of London near Broad Street in 1854 (Shephard, 1995). He mapped the occurrence of cholera in this area, during the six week period between August 19th and September 30th denoting each home in which a cholera fatality occurred with a black line (see Figure 5.12; Snow, 1855). From this, he found that the highest concentration of deaths occurred in the street where the Broad Street Pump was located. In the surrounding streets, the concentration of deaths shows a decline. Within areas far enough away that water would be drawn from other pumps, the concentration of deaths was drastically reduced. Based on this, Snow convinced municipal authorities to remove the handle of the Broad Street Pump (Paneth, 2004).

After the removal of the pump handle, cholera rates are said to have dropped significantly.

However, it should be noted that this occurred near the end of the cholera outbreak, at which point incidence rates had already begun to decline (Paneth, 2004; McLeod, 2000). Thus, many historians believe that the actual impact of the handle removal has been exaggerated. However, even in the latter interpretation, Snow's work in mapping geospatial relationships, and analyzing them in the context of disease outbreak proved vital in the development of both epidemiology and GIS.

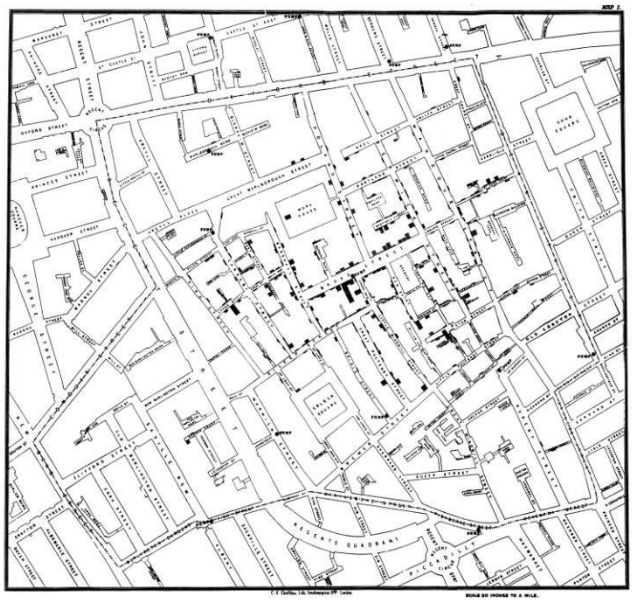

Figure 5.12. Snow's map of cholera fatalities surrounding Broad Street. Each bar indicates a house with a cholera fatality.

John Snow's work with cholera was instrumental in changing the way that humans view the potential of cartography. Previously, the approach taken to mapping, known as the communication paradigm, focused on the idea that the sole purpose of a map is to give a visual representation of an area (Demers, 2000). Since the viewer is only provided with the spatial relationship of items labelled on the map, there is no opportunity to extrapolate further knowledge from the data provided. The new perspective ushered in by work such as John Snow's is the holistic paradigm, which is the idea that maps can form a more intricate system, with several layers of data that can be re-evaluated to draw new conclusions based on the combined raw data.

The Ordnance Survey

In 1746, England was faced with the aftermath of the Jacobite uprising (Andrews, 2009). The fear instilled by this turmoil, inspired William Roy (1726-1790), a young engineer, to suggest surveying the surrounding area of a town to gain a military strategic advantage. This project was not conducted until 1791, when King George II (1683-1760) began to fear that the French Revolution would sweep over the English Channel (Owen and Pilbeam, 1992). Due to this impending danger, the king commissioned a military survey of the vulnerable southern side of England. The Ordnance Survey was conducted by the Board of Ordnance, a military department under the leadership of Charles Lennox (1735-1806), the third Duke of Richmond. Not long after the creation of the Ordnance Survey, the maps produced of the area were published and sold to the public. In order to keep up with the demands of the time, this organization developed its own sector to focus on an efficient and cost effective way to engrave and replicate the maps using copper plates (Owen and Pilbeam, 1992). The template used to produce the maps available to the public was created via pantograph, a device used to reduce the size of an image.

By 1850, the Board of Ordnance became interested in mapping the entirety of England. To accommodate this large territory, plans were made to use a 1:2500 scale, a map more compressed than anything previously developed (Seymour, 1980). This created a greater need for accuracy, due to the intricate details to be presented. This meant, the map could not be feasibly resized using the pantograph, due to its inaccuracy. Colonel Henry James (1803-1877), the leader of the board at the time, decided instead to utilize the emerging technology of photography to resize the image.

Also, Colonel James realized that the traditional method of copper engraving was no longer effective, leading the staff of the board to develop photozincography (See Figure 5.13). In this process, a negative of the image is created on a glass plate, and then silver deposits are blackened using corrosive chemicals (Bennett, 1967). Through this process a sun print of the image is created on a paper that has been coated with gelatin which becomes insoluble in water when exposed to light. The paper is then covered in greasy ink, and then washed off with water to remove the soluble gelatin. The remaining material produces an image which is transferred onto a zinc plate in order to be printed. This innovation saved time and money, while increasing the accuracy of the product. With this technology, a map was treated as a complex system composed of multiple layers, rather than a single, intricate, unified system (Mumford, 1971). As a result, it was no longer necessary to manually engrave each information point, such as a river or mountain. Instead, the information was sectioned into layers, such as water systems or topography. Each layer was drawn separately on to a glass plate and combined using photozincography. The user was able to manipulate different layers, without interfering or crossing different layers over onto other parts of the image.

Figure 5.13. A map of the city of Southampton produced in 1865 by the Ordnance Survey, using photozincography.

The development of photozincography further reinforced John Snow's holistic paradigm approach to mapping. GIS is a modern extension of the techniques developed during this period. However unlike photozincography, GIS offers no limitations to the amount of data or layers that can be added to the general infrastructure of a map. The search for a method that could analyze and make sense of infinite layers of data allowed society to progress from the limited geospatial analyses conducted by the Ordnance Survey to the development of the first GIS.

The Digital Age

The dawn of the digital age led to opportunities for computer mapping applications. Several institutions and individuals contributed to the development of GIS, as a result the motivations for developing GIS vary widely. They range from academic curiosity to the realization that a certain task could not be conducted in any other way. The latter was the greatest driving force for David Bickmore, the author of *The Atlas of Great Britain and Northern Ireland,* published in 1958 (Coppock and Rhind, 1991). This atlas was deemed to be out of date and inaccurate, leading him to realize that his only viable option to correctly recreate this project was through the use of computers. He did not manage to construct a completely automated mapping system; however, his efforts inspired other British thinkers. Digital computers became a viable tool to accomplish tasks such as this, since its cost began to decrease dramatically.

The earliest attempt to automate map production used modified punch tabulators to create maps on preprinted paper from cards containing grid references (Foresman, 1998). This method was first used to produce *The Atlas of the British Flora* by Franklyn Perring (1927-2003) and Max Walters (1920-2005). By the early 1960s, large mainframe computers were becoming widely available. These machines were being used for two purposes: administrative tasks in business and government, and for scientific applications involving extensive computations (Coppock and Rhind, 1991). Several agencies within the United States government began to discuss the possibility of applying computer technology to handle numerical data such as censuses. Increasing availability of computers within the universities was crucial to the eventual development of geospatial analysis, particularly for the statistical treatments of geographical information. At this time, these statistical treatments were not yet used for computer mapping making them largely aspatial. It was not until the 1980s that efforts would be made to connect statistical analysis to spatial geography (Coppock and Rhind, 1998).

In the development of automated map making, universities were taking a different approach; instead of creating digitized images, they were printing the images on a line printer (See Figure 5.14; Foresman, 1998). This was a cost effective method to reproduce maps. In this atmosphere, Howard Fisher established the Laboratory for Computer Graphics in 1965 in the Graduate School of Design at Harvard University. With this, he created a mapping package, called synergraphic mapping system (SYMAP), that would be capable of using the line printers as mapping device capable of producing different types of maps (Foresman, 1998). The package was used by over 500 institutions, across North America, Europe, and Japan. SYMAP was quite important to the development of GIS since it was the first widely distributed package for handling geographical data and developing digitized maps. It introduced a broad audience to the possibility of computer mapping and it was the precursor to a large number of other programs using the line printer (Foresman, 1998).

Figure 5.14.the IBM 1403 line printer developed in the early 1960s. During this era, line printers followed this general model.

At about the same time that Fisher was developing his ideas on computer programming, Roger Tomlinson (1933-present) was involved in the creation of what is considered the first GIS. He is often regarded as the father of GIS since he persuaded the Canadian Government to fund the creation of the Canadian Geographical Information System (CGIS). The idea for CGIS began in 1960 when Tomlinson was working for Spartan Air Services, an air service company, which was conducting a forest survey of East Africa (Coppock and Rhind, 2000). The firm hired him to analyze the maps available of the area, in order to identify viable locations for numerous plantations and a new mill (Foresman, 1998). The estimated cost to accomplish this task manually was so high that Tomlinson's proposal was rejected. Therefore, Tomlinson made an alternate proposal: instead of paying experts to conduct the analysis, computers could be used. With the company's approval, he approached several computer companies with this proposal, however all of them rejected his offer. Tomlinson later met Lee Pratt, an administrator at the Department of Agriculture who was at the time planning the Canada Land Inventory (CLI). The aim of CLI was to produce many maps showcasing the land capability of Canada, in order to aid the agricultural rehabilitation of marginal farms (Foresman, 1998). Tomlinson pitched his idea to Pratt, who accepted it. A contract was presented to Spartan Air Services to develop a computer mapping system for the CLI. This endeavor was supported by International Business Machines (IBM) which provided them with access to its intellectual property and staff (Coppock and Rhind, 2000). Tomlinson compiled a report which was accepted by the Department of Agriculture and he was later invited to direct the project's development within the Canadian Rehabilitation and Development Administration (ARDA). This development involved a high volume of people from both ARDA and IBM. This lead to much innovation in the field of GIS, such as the creation of the drum scanner for rapid digitization of maps. By 1971, the system was fully operational. During the early 1980s, the emergence of commercial GIS rendered CGIS obsolete.

GIS first gained prominence in the commercial sector with the development of the Environmental System Research Institute (Esri). Esri was not the only firm operating in this field, but it was one of the most highly successful (Coppock and Rhind, 1991). Esri started off as a non-profit organization in the field of environmental consultancy. To conduct its projects effectively, Esri needed a way to automate manual mapping processes.

In the 1970s and early 1980s, the staff at Esri took a great deal of project work. They developed ad used the package GRID as its main application package, until 1982 when it launched ARC/INFO, the first commercial GIS. This package combined computer display of geographic features, such as points, lines, and polygons, with a database management system for assigning attributes to these features (Coppock and Rhind, 1991). The 1980s brought about increased acceptance of GIS, shown through a rise in the amount of requests for information and advice. In the 1990s, developments such as faster and cheaper computers, network processing, and the development of GPS triggered rapid progress for Esri. ArcView, Esri's first desktop solution, opened up the possibility of GIS for a whole new audience. Esri is still active today and it continues to develop and sell programs to a broad audience.

As science progressed during the 20th century, scientists began to observe phenomena that were hidden from the human senses. As the scientific community gained a greater understanding of these phenomena, GIS allowed them to be viewed from unlimited layers or perspectives. Thus, geospatial thinking arose from the necessity to simplify the complexity of this new world.

Advancements of Geographic Information System Technology

With modern advancements in the technology used for GIS, it has potential applications in a wide variety of fields. It provides a set of tools with which to integrate data from multiple sources, and analyze them to draw complex conclusions.

Data Input

One of the most important developments of this technology is the ability to digitize data collected from a variety of analogue sources, in order for them to be integrated. One of the ways this is done is via digitizing software such as computer-aided design programs, which take images or maps that have already been scanned into a computer and traces them (Foresman, 1998). This is the most efficient method. Digitization can also be done manually, using a digitizing tablet to trace the features of physical maps and then recreate this information on a computer. This is typically done when the original maps are in poor condition. These data are stored as either a vector or raster dataset. In vector datasets, the data points are each represented as lines or arcs, defined by their start and end points. This is typically used to represent two-dimensional areas, such as cities or subdivisions, and linear data such as rivers or streets. Raster datasets are grid-based. They subdivide the map area into equally sized cells, each of which is assigned a value (Demers, 2000). This is used to measure quantitative data, such as temperature or population density, over an area.

Individual data can also be classified as objects. A single pair of coordinates forms a type of object called a point (Smith, Goodchild and Longley, 2007). The other two types of object are comprised of groups of points: a line is a series of points, connected by a straight line, and an area is a ring of points, forming a polygon. These objects are classified according to their attributes. For instance, nominal attributes distinguish between objects without implying a rank, such as the distinction between business, residential and educational buildings. Ordinal attributes rank objects but without necessarily defining the relative difference between each rank. This includes arbitrary distinctions such as high, medium, and low income areas. Finally, interval attributes are ranked using a regular, defined, interval. This is used for quantitative measurements such as annual income.

GIS Analysis

GIS data can be used to conduct a series of analyses to ascertain information about the area. The simplest forms of GIS analysis are queries and measurements, both of which draw information from the map layers present without creating new layers (Verjee, 2010).

Queries are used to determine whether relationships between layers exist and the nature of these relationships if they exist. Measurements quantify physical characteristics of the map layers, such as distance, area, slope and the shape of different components. This makes analysis of physical characteristics easier and more accurate than when using a physical map.

More complex analyses, known as transformations, are those that generate new data sets based on existing layers using simple rules. For example, buffer analysis creates new data layers by mapping a certain distance around existing points (Verjee, 2010). This is typically used for things such as generating environmental protection zones. This technique can be expanded by combining multiple layers in order to find areas that meet a series of parameters. Another type of transformation is spatial interpolation, which is used to estimate a distinct value within a vector field.

A common use of GIS is to solve optimization problems. This can be subdivided into point optimization, route optimization, and path optimization (Verjee, 2010). In point optimization, an ideal location is selected out of several distinct locations in a given area, based on a series of overlaid factors. This is useful in selecting the location for new facilities, such as hospitals. In route optimization, routes that minimize time and distance can be ascertained. Lastly, path optimization looks at methods of travel, but differs from route optimization in that it is not limited to a given network. It examines things such as travel through airspace, where things such as infrastructure of roads do not need to be taken into account.

Applications

Currently, GIS forms an integral part of many endeavors, in both the public and private sectors. It functions broadly to incorporate data from many sources and analyze them with respect to their spatial orientation and with respect to each other. One major example of this is in the field of epidemiology. Using data such as disease prevalence, child immunization, and infant mortality, GIS allows patterns to be determined amongst a community. This provides valuable information about the community's public health needs, by making connections between factors that might not have otherwise been observed. Another public use of GIS is crime mapping. For example, a study was conducted in Washington DC in order to determine the root causes of homicide (District of Columbia, 2006). GIS systems were used to overlay factors such as homicide rates, census data, and locations of schools (See Figure 5.15). Looking at these layers together allows the relationships between these factors to be observed and analyzed. GIS is also very prominent in the private sector, as it has the potential to provide information relevant to vital decisions that must be made in the context of business. For instance, point optimization can be used to determine the location of a new retail location based on spatial information about the location of competitors and the disposable income of people living in the surrounding area.

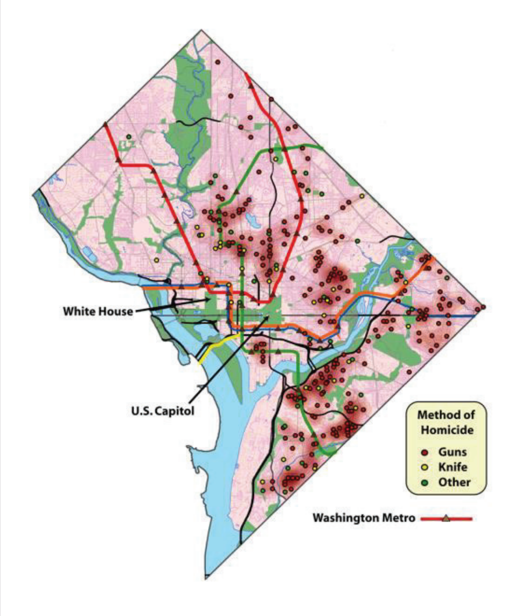

Figure 5.15. Map of homicides in Washington DC between November 2004 and November 2006.

GIS has nearly endless potential applications. It allows previously unseen connections to be made in nearly every field. The technologies behind this form of analysis have been evolving constantly, and continue to become more refined. What began as a radical idea of analyzing geospatial relations, has grown into a ubiquitous, innovative part of modern society.

The iconic skyline of Toronto, Canada's largest city. Large cities and urban development are pinnacle in modern human civilization

"The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them."

WILLIAM BRAGG

Chapter 6: Modern Civilization

The Age of Enlightenment has proven to be an exciting era in human development, specifically of scientific ideas surrounding the study of the Earth. This chapter will take a historical perspective in looking at some of the scientific discoveries of the past that have helped to shape the world today.

Electricity has been both a fascination of the earliest humans and the foundation of modern technology. Flashes of lightning that illuminated the skies of the earliest civilizations were misunderstood and attributed to the Gods. Thousands of years of human progress led the understanding and application of this power as electricity. Although electricity eventually became recognized as a power source, magnetism remained a mystery. Centuries of great minds showed that magnetic force was intrinsically linked to electricity. Without the discovery of this correlation, modern conveniences such as medical imaging, navigation, and electronic devices would not be possible.

To give rise to these discoveries, it is crucial that modern science is powered by modern energy sources. Throughout history, resources from the Earth have been harnessed by machines and used as sources of power. The ever-increasing energy requirements of society have fueled scientific discoveries in multiple fields since the earliest human civilizations. Higher energy consumption increases waste production and leads to the necessary development of waste management systems. It is the waste left behind that is often more useful than treasured artifacts in shedding light onto past civilizations. This trash elucidates the changing views of society, and the growing concern of sanitation through time. The interdisciplinary field of geochemistry has been instrumental in the tracking of resources and waste to reduce human impact on the environment.

Throughout this entire chapter one message resonates; the decisions and discoveries of the past have laid the foundations of the modern world. History provides unlimited examples of how human genius and perseverance have led to major revolutions in the way the Earth is understood.

Harnessing Earth's Energy: Fuel Through The Ages

Like it or not, the human race is dependent on Earth's resources. This dependence has been marked through history with distinct economic, social and cultural changes in human civilizations associated with our increasing ability to access Earth's resources.

The primary source of Earth's energy is the Sun; the Sun provides a large spectrum of electromagnetic radiation that heats the Earth and is essential for the process of photosynthesis. Early human civilizations were nomadic and directly dependent on photosynthesis, consuming plants and plant-dependent animals for energy. These civilizations consisted of groups of 10-50 individuals, and had an average lifespan between 21 and 37 years (Gurven and Kaplan, 2007). Several physiological traits, specifically bipedalism, ambidexterity, and brain to body ratio, allowed members of these ancient civilizations to increase their ability to hunt and forage through the invention of weapons, and stone tools.

Tools are the first record of human ambition to improve living conditions, as they allowed for an increase in energy harvest without a proportional increase in work. The first record of energy use in the form of wood fire, used for heating and cooking, was dated at 250 000 BCE (James 1989, Goudsblom 1992). These early nomadic groups were however limited by the work output of individuals now, in terms of their ability to collect wood fuel instead of food. This energy and resource limitation prevented the increase in complexity of these nomadic societies for many thousands of years.

Nomadic civilization eventually gave way to incipient agriculture, in a transition known as the "Neolithic Revolution". While the date of this transition is debated, the development of agriculture is considered to have occurred approximately 10 000 BCE (National Geographic, 2013). This shift led to an increase in efficiency in conversion of solar radiation to useable biomass energy and food. Agricultural processes evolved from extensive to intensive, resulting in the sustenance of increased population densities. Similarly to nomadic civilizations, ancient agriculture was limited by the work output of humans and domesticated animals (see Figure 6.2). Agriculture also requires a significant amount of water. For example: the most efficient crop in turning solar energy and water into biomass is corn (*Zea mays*), a crop with a water-to-grain ratio of 600:1 (Doorenbos et al. 1979). Much of ancient agricultural work involved lifting water to irrigate fields in low relief environments like the Nile river valley. Building canals and tools to lift water were energy intensive endeavors; further developments in energy production and conversion were required in order to allow further evolution of human society.

Agriculture and a consistent source of biomass energy led to the Formative Era, an era characterized by increasing population density, and the development of culture. This increase in population density is important, as it is theorized that an increase in population density will increase creativity, resulting in innovation and new inventions (Knudson et al. 2008). One significant result of the increase in population density due to agriculture was the invention of a wide variety of tools, initially made with chert and flint and evolving to tools made from bronze, then iron. These iron tools were created in blast furnaces due to the relatively high temperatures required. Blast furnaces were initially powered with biomass fuels,

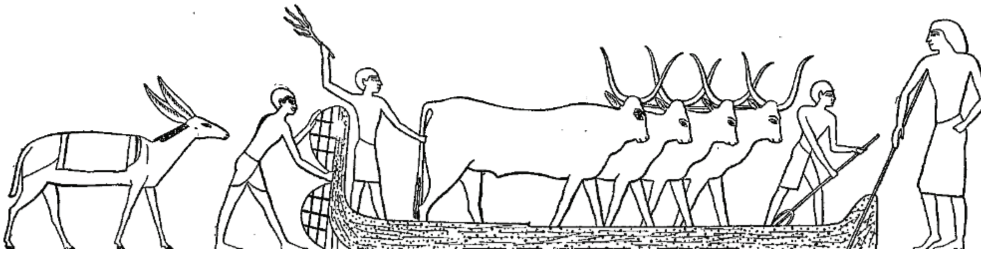

Figure 6.2. Ancient Egyptian agriculture relied on the work output of humans and domesticated animals

including hardwoods, softwoods, charcoal, crop residues, dry straw, dry dung and peat. These fuels were readily available but they lacked high energy density. The fuel density of these biofuels ranged from 6MJ/kg of peat to 15MJ/kg of hardwood (Smil, 1983). The low energy density of these fuels became an issue when an increased need for energy led to significant deforestation.

Figure 6.3. Anthracite is the most energy dense form of Coal, at greater than 32MJ/kg.

With energy requirements rising and simple energy solutions disappearing, human civilizations required a new way of accessing the energy available on Earth. Instead of using biomass fuels, which directly transformed solar radiation into biomass; humans turned to fossil fuels; dense forms that result from the slow alteration of biomass fuels through pressure and heating.

The most common transition in fuels was between biomass and coal, carbonized plant material. Coal is formed when plant material is turned to peat, which is transformed to lignite, then subbituminous coal, to bituminous coal, finally anthracite (see Figure 6.3). The densest form of coal, anthracite, has a fuel density of greater than 32.5MJ/kg, more than double that of hardwood (Smil, 1983). The first record of coal utilization was during the Han dynasty, two thousand years ago, for iron production (Needham, 1964). However, this technology was not seen again until the 16th and 17th centuries in England, when wood shortages resulted in the mining of outcropping coal seams. Exposed coal seams were rapidly depleted, resulting in mines of quickly increasing depth, and dangerous working conditions (Harris, 1974). The depletion of coal reserves, in hindsight, was an important foreshadowing of the many problems now associated with fossil fuels, as unlike biomass fuels, they take millions of years to regenerate.

The use of coal led to the development of the steam engine, initiated by Denis Papin (1647-1712), who built small models in 1690, and James Watt (1736-1819), who built the first steam engine that produced continuous rotating motion in 1781. The steam engine was the first reliable and economic machine that could convert the chemical energy in coal to mechanical energy, and played a crucial role during the Industrial Revolution (Allen, 2009).

The industrial revolution began in earnest in the mid-17th century and was primarily fueled by coal-driven manufacturing processes. Within a few decades, the industrial revolution spread to the United States and the remainder of European countries. The industrial revolution had profound effects on human civilization; population density increased yet again, the economic well-being of lower class individuals increased, and anthropogenic effects on the environment were greatly amplified.

Steam engines also revolutionized transportation, as they were incorporated into boats and trains. Improved transportation made sharing ideas and materials easier which helped perpetuate the development of modern civilization. However, as coal mining became more difficult and dangerous, another energy revolution was essential for sustaining the development of human civilizations. This energy revolution arrived in the form of crude oil and petroleum products.

Crude oil is typically liquid mixtures of hydrocarbons formed from dead biomass, specifically, algae and zooplankton. These hydrocarbons are formed under specific heating and pressure conditions. These liquid hydrocarbons are buoyant, resulting in their upwards migration and seepage to the surface. If the liquid hydrocarbons are prevented from reaching the surface by either a structural or stratigraphic trap, then an oil reservoir forms, often with large volumes.

Crude oil and petroleum have an energy density of 46MJ/kg, one and a half times as great as coal (Smil, 1983). The great energy density of crude oil and petroleum, combined with their liquid nature, was exactly what was needed for another major change in human civilization.

Figure 6.4. Image from the Skylitzes manuscript in Madrid depicting Greek fire in use against an enemy ship. The caption translates to "the fleet of the Romans setting ablaze the fleet of the enemies"

Figure 6.5. Persian scholar Rhazes (left) was one of the first to write about methods to distill kerosene from crude oil.

While the use of crude oil and petroleum really made their mark in early 19th century to fuel modern machinery, their debut appearance dates far earlier. While the archeological evidence is incomplete, historians can trace the origins of hydrocarbon usage back to ancient Mesopotamian civilizations that depended largely on a substance called bitumen. Found in natural deposits, bitumen was a tar-like form of unrefined petroleum with a plethora of uses including gluing, waterproofing, insecticides, medicine and even in 'magic potions' to ward off evil spirits (Bertman, 2005). These early civilizations were also aware of the thermal properties of bitumen, not yet as a fuel source but enough to punish criminals by pouring hot bitumen over their head.

The use of bitumen continued for centuries. Even the ancient Egyptians used bitumen, to wrap and embalm their dead; in fact the term "mummy" is said to have been derived from the ancient Persian word *mumiai* which meant bitumen. As time progressed, humans began to experiment with bitumen. During the Middle Ages (around 600-700 CE), 'chemists' in Persia and ancient Arab civilizations made "Greek fire" by mixing bitumen with other lighter derivatives of petroleum. Greek fire burned well and served as a napalm-like weapon used in warfare; extremely efficient against large ships and castles (see Figure 6.4) at the time (Sweeny, 2010). Now that the spark of interest was lit for this new usage for hydrocarbons it wasn't long before humans recognized their potential as a fuel source, and so came the era of oil.

During the 9th century, chemists like Muhammad ibn Zakariya Razi, also known as Rhazes (854-925 CE), of Persia wrote about methods of distilling crude oil (see Figure 6.5) using clay or ammonium chloride as an absorbent to make a perfectly clear, "safe to light" substance termed *naft abyad* (white napththa). This was the first record of refined lamp oil or kerosene in the history of mankind. Since the distillation process removed most of the explosive volatile hydrocarbon fractions in the crude oil, the substance left behind allowed for a safer, controllable burn that would prove extremely useful for civilization (Bilkadi, 1995).

Moving into the 19th century, oils now had a new found role as lubricants for emerging modern machinery. Fueled by its new relevance and demand, chemists around the world looked for methods to refine oil even in places where oil was scarce, in order to secure a share in this emerging market. Among many who claimed to have invented modern oil distillation was Canadian geologist Abraham Gesner (1797-1864), who patented his new oil product, Kerosene. Gesner made Kerosene by heating coal and distilling the resulting product to a clear, thin fluid. Kerosene was safer and cheaper than whale oil, used by the wealthy in North America. The use of Kerosene spread, especially in Western Pennsylvania and New York City, where Gesner's "North American Gas Light Company" had mining rights to bituminous coal and oil shale. It should be noted that Gesner first considered mining albertite, a type of bitumen-like asphaltum, for the production of Kerosene in New Brunswick. After losing a court case, where experts deemed albertite to be a form of coal, a New Brunswick coal conglomerate prevented Gesner from mining in New Brunswick, which resulted in his emigration to Long Island, New York (Wright & Miller, 1990).

Meanwhile, modern machinery continued to develop rapidly. By the 19th century, the thermodynamic concepts of an ideal heat engine were understood and some recognized that one could use an 'explosion' of petroleum to move a piston in the engine more efficiently than steam (Sweeny, 2010). With adequate distillation techniques, the only obstacle in commercializing the internal combustion engine was extracting petroleum in sufficient volumes. Humans were teased by sites of surface crude oil seepage that were scattered around the world, but this source was insufficient to satiate the requirements of all the industries that were emerging All the world needed was an efficient solution for subsurface drilling to access buried oil reserves.

On August 28th 1859, working with a small team of local workers in Pennsylvania, Edwin Drake (1819-1880) struck black gold (see Figure 6.6)! While there were instances of successful subsurface drilling in France, Japan and a few other Asian countries, especially Azerbaijan, Drake's method was the first commercially practical solution. Just a year earlier, James William (1818-1890) of Canada struck oil in Oil Springs, Ontario. While some may argue that this was the first commercial oil well, most refer to Drake's as the first as William did not drill below bedrock. Building upon the idea of using a steam-driven wheel counteracting an iron bit through use of a pulley to excavate a hole, as done in Azerbaijan in 1847, Drake suggested driving a pipe around the iron bit so that water and loose material from the sides of the hole did not fall in and impede the iron bit's path. Improved with rotary drilling in Texas in 1901, modern day oil excavation has not changed much since then. Edwin Drake also introduced 'the barrel', the fundamental measure of production and consumption still in use today in the oil market. The barrel was coined simply because Drake chose to gather and transport his crude oil using Pennsylvania's 42 gallon wooden barrels that were mainly used in the whiskey business at the time (Maugeri, 2006).

With commercial drilling and production of petroleum well underway, in 1862, the world's first commercially successful internal combustion engine was sold by German engineer Nikolas Otto (1832-1891). Later improved by countless other scientists, the internal combustion engine led to a new revolution, not just in machinery, but in transportation. The first modern car was sold in 1885 by Karl Benz (1844-1929), and the first airplane, invented by Orville and Wilbur Wright (1871-1948; 1867-1912) in 1903 (Smil, 1983).

By the dawn of the 20th century, the world was buzzing. On October 1st 1908, Henry Ford (1863-1947), introduced his ingeniously designed Model T (see Figure 6.7), the first car to have a fully enclosed engine and transmission, allowing for it to be built by the iconic assembly line. The Model T was cheap, easy to repair and easy to drive which made it a giant commercial success almost immediately. Meanwhile, as the First World War started in 1914, research went into improving engines to work faster and more efficiently, especially in aircraft. By the 1920s, the internal combustion engine was well integrated into the life of the developed human; no longer a concept, it was now a working reality. There was however a major problem; engine knock (Hounshell, 1985).

Figure 6.6. The Drake well and Edwin Drake (right). The Drake well was the first commercial oil well, drilled in 1859.

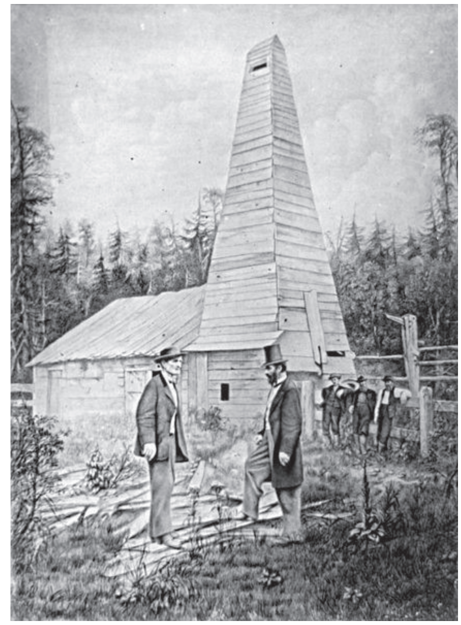

Figure 6.7. The Ford Model T was the first mass-produced combustion engine vehicle.

In an internal combustion engine, air/fuel mixtures are exploded in a controlled fashion by a spark plug within a cylinder to move a piston. Engine knock describes when air/fuel mixtures explode when they should not, which could lead to devastating effects. While owning an engine driven car was commercially practical at the time, engine knock made it incredibly unsafe. In desperate need of a solution, the General Motors Research Corporation began looking for alternatives to the current system.

It should be noted that at the time, while petroleum worked extremely well as a fuel for engines, leading engineers and inventors in the automotive industry including Henry Ford of Model T fame and Charles F. Kettering (1876-1958), head of research at General Motors, were convinced that the fuel of the future was an ethanol-like fuel made from farmed by-products (New York Times, 1925). In 1922, Thomas Midgley Jr. (1889-1944), working with a team of chemists under Kettering, recognized that alcohols and benzenes from biomass sources could be used as additives to petroleum to stop engine knock, supporting Kettering's view of the benefits of ethanol-like fuels (Midgley & Boyd, 1922). However, there was a significant obstacle between ethanol-like fuels and the fuel market: supply. As the use of food for fuel instead of human consumption could not be justified commercially, the engine knock problem was solved instead with tetraethyl lead.

Getting The Lead: The Use Of Lead In Petroleum

Tetraethyl lead was discovered in 1921 during a search for a back-up plan, should alcohol and benzene not work. As opposed to ethanol-like fuels, known as a "high-percentage class" solution due to the high percentage of alcohol in the fuel; this search was for a "low-percentage class" solution, with a highly effective additive. The search started with iodine, which was deemed effective but too expensive, and moved through other elements. Soon the chemists realized a pattern; elements down the carbon group column (silicon, germanium, tin…) were most effective. On the morning of December 9th 1921, the chemists finally reached the bottom of the column, lead, and following their predictions, lead had a remarkable ability to quiet the engine knock, even when diluted to 1000:1 (Kettering, 1947).

Lead is a neurotoxin; even during this time people were aware of the irreversible damage lead poisoning had on the brain and central nervous system. Yet, at the same time, lead was extremely easy to extract and work with, making its use highly profitable. There was little opposition in 1923 when the "Ethyl Gasoline Corporation" started mass-producing their anti-knock tetraethyl lead additive for public consumption. One must however note a few nuances to this statement. Firstly, in order to throw the prying eyes of opposition off their scent, the additive was marketed as "Ethyl" (see Figure 6.8) as it sounded friendlier and less toxic than "tetraethyl lead". Secondly, the Ethyl Gasoline Corporation had considerable influence, being formed from three of America's largest companies: General Motors, DuPont and Standard Oil of New Jersey (now known as Esso or ExxonMobil). To this day, the sale of tetraethyl lead is used to show how allowing private regulation rather than government oversight may lead to toxic and unethical consequences for the public, all for the sake of increasing profit margins (Kovarik, 2005).

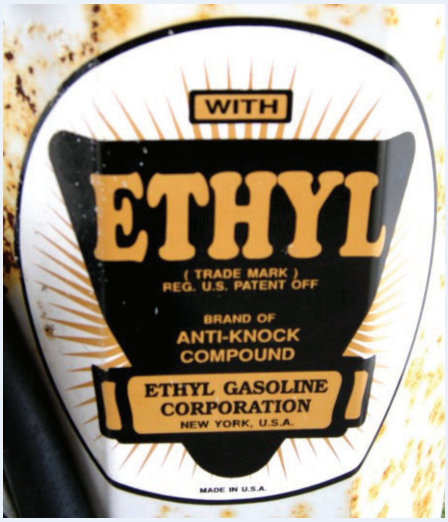

Figure 6.8. A sign on a gasoline pump advertising tetraethyl lead additive by the Ethyl Corporation.

In the late 1940s, more than 25 years after the birth of Ethyl, a graduate student named Clair Patterson (1922-1995) presented sufficient proof to end the detrimental reign of tetraethyl lead in gasoline. Ethyl was controversial since its conception; especially after events like that of 1924 when five production workers died and 35 others became permanently ill at an ill-vented tetraethyl lead production facility. Yet, backed by their immense influence, Ethyl stood their ground. Ethyl spokespeople reported "these men probably went insane as they worked too hard". Even Thomas Midgley Jr. himself, Vice President of General Motors Research Corp., stated publicly that clinical studies on animals (run by Ethyl Corp.) showed no adverse effects of the ethyl additive and further insisted that there were no alternatives to tetraethyl lead to prevent engine knock (New York Times, 1925). Note that this was the same man who only years earlier researched safer alcohol and benzene additives that were equally effective, but weren't commercially practical.

Perhaps the best example of Ethyl Corp. using its powers to silence its opposition was a study that Patterson himself referenced (but quickly realized was wrong) which studied the effects of lead on humans. In this study, participants were asked to inhale or swallow large quantities of lead, and for a period of five years their urine and feces samples were tested. The results showed no trace of lead in urine or feces, therefore lead was given a clean bill of health. Clearly, the researchers running the study had little knowledge of chemical pathology; the ingested lead was not excreted because it accumulated in the body (specifically in blood and bone), making lead a dangerous toxin. These poorly conducted studies allowed Ethyl Corp. to make said dubious statements (McGrayne, 2001).

Clair Patterson's initial intention was unrelated to tetraethyl lead but rather to find the age of the Earth. As he neared graduation, Harrison Brown (1917-1986) devised a new method to measure relative concentrations of lead isotopes in igneous rocks. Harrison encouraged Patterson to use this method to find the ratio of lead to uranium in ancient rocks to find an age for the Earth, for his dissertation. Patterson observed however that whenever his samples were exposed to air, they would be contaminated with unaccountable amounts of atmospheric lead. In order to continue his experiments, Patterson would go on to create one of the world's first sterile labs, but this contamination also made him question: why was there so much lead in the atmosphere (Bryson, 2004)?

Patterson was convinced the lead was coming from automotive exhaust, but he needed a way to prove it. Patterson realized, if he could compare the level of lead in the atmosphere now with the levels before 1923 when tetraethyl lead was introduced, he could pinpoint it as the cause. To do this, he figured that if he looked at the concentration of lead in layers of snowfall in places like Greenland, he could map out the global lead concentration through history (see Figure 6.9). This study would lay the foundation for a vast field that is known today as ice core studies. As Patterson suspected, atmospheric lead concentrations were virtually zero before 1923, then rapidly increased after the introduction of tetraethyl lead (Murozumi, et al., 1969). Using these results, Patterson made it his mission to remove lead from gasoline and other industrial uses.

By this time, Ethyl Corporation was larger and more powerful than ever, with a plethora of "industry experts" at its disposal. Almost immediately, Patterson felt the effects of his anti-Ethyl position: his research funding was withdrawn, and new funding was difficult to acquire. In 1971 when the National Research Council appointed a panel to investigate the dangers of atmospheric lead, they did not include him despite his new reputation as a leading expert on atmospheric lead. Patterson remained persistent and to his effort, came results (McGrayne, 2001).

It took until 1969, exactly 46 years after the birth of tetraethyl lead, for scientists to start publishing the papers that outlined the toxic effects of tetraethyl lead on humans (Stasik, et al., 1969). The Clean Air Act of 1970 suggested a phase-out of the tetraethyl lead additive, launched in 1972 by the United States Environmental Protection Agency (EPA). Although Ethyl Corp. initially sued the EPA, the EPA won an appeal and by 1986, tetraethyl lead was completely phased out of the United States (Kovarik, 2005). Studies have shown drastic drops in the blood concentration of lead post-phase out. For example: from 1976 to 1991, the concentration of lead in the blood of the U.S. population dropped 78% (Pirkle, et al., 1994). By 1996, selling leaded gasoline was completely banned in the United States and in 2011, the United Nations announced that the tetraethyl lead additive had been phased out from gasoline worldwide. In a press release, the United Nations Environment Program stated "Ridding the world of leaded petrol , with the United Nations leading the effort in developing countries, has resulted in $2.4 trillion in annual benefits, 1.2 million fewer premature deaths, higher overall intelligence and 58 million fewer crimes" (United Nations Environment Program, 2011). This announcement was slightly premature however as a few third world countries are still selling leaded gasoline, and it is still used in aviation fuel and racing fuel.

Figure 6.9. An illuminated ice core with visible layers. Analyzing ice cores give insight into past atmospheric composition, such as the composition of atmospheric lead over the years.

As for Clair Patterson, he finally did answer his primary research question, finally giving the world an age of 4,550 million years (plus or minus 70 million years) a figure that stands nearly unchanged today. Despite its value to understanding our world, Patterson never received a Nobel Prize or any such recognition for his work. Textbooks rarely mention him and a review of one of his works in *Nature* actually refers to him as a woman (Bryson, 2004). Despite never attaining fame and glory, Clair Patterson remains to be one of the most influential geologists of the 20th century; he not only gave us an age for our planet, but we can now live longer to experience its wonders, no longer with clouds of lead.

Thunderstruck: Understanding the Power of Lightning From Ancient Greece to Modern Physicists

Thunder is good, thunder is impressive; but it is lightning that does the work. - Mark Twain, 1908

From the earliest civilizations, curiosity of the unknown has led humans to fear and worship natural powers such as lightning. In 3 000 BCE, the ancient civilization of Mesopotamia, worshiped the storm god Adad, who provided fertile rain and even fierce lightning (Dalley, 2000; Rogers, 1998). Every civilization, culture, and religion that emerged in the next 2 000 years involved lightning gods – from Egyptian mythology to Hinduism in the Far East. One of the most well known mythological characters from ancient Greece was Zeus: the supreme ruler of the Olympian gods who used his thunderbolt to win numerous battles against the Titans (Murray, 2003; Partington, 1960).

The emergence of the classical scientific method allowed humankind to observe natural phenomenon, including lightning, from different perspectives. In ancient Greece, it was discovered that the rubbing of amber caused attraction of lightweight particles such as straw. In fact, the Greek word for amber is *elektron*, a constant reminder of the origin of electrostatic studies. Aristotle and other early scientists in Greece pioneered the method that would evolve into modern science, and began the journey to a more accurate understanding of lightning (Dunsheath, 1967; Murray, 2003).

Figure 6.10. First photograph of lighting taken in 1882 by Mr. Jennings of Philadelphia. This photograph was published in Scientific American *in September of 1885.*

In 1600, William Gilbert of Colchester wrote the first book in history dedicated to experimental physics and wrote about the electric force in particular. As scientific interest in electricity developed, more attention was paid to increasing the size and power of electric machines. In 1745, Pieter van Musschenbroek unknowingly invented the first capacitor; an electric device that stores energy. In an attempt to lead electricity into a jar of water, van Musschenbroek accidentally electrocuted his assistant. Immediately after, he insisted on repeating the experiment on himself, and described his experience by exclaiming: "I received in my right hand a shock of such violence that my whole body was shaken as by a lightning stroke. The arm and the body were affected in a manner more terrible than I can express. In a word, I believed that I was done for" (Dunsheath, 1967, p.35).

Musschenbroek and many other scientists were beginning to observe a correlation between the shock from artificially created sparks and the power of a lightning bolt. The 18th century, known as The Age of Enlightenment, proved to be an exciting time for science when ideas experienced a paradigm shift from tradition and faith to individual reason and scientific experiment (Dunsheath, 1967). The first to write about the resemblance of electric sparks to lightning was the French abbot, clergyman, and physicist Jean-Antoine Nollet. Nollet was known to frequently entertain King Louis XV of France by shocking mile-long chains of monks and guards with iron wire and a Leyden jar. The Leyden jar was an early capacitor; essentially glass jars that were able to store static electricity inside the glass walls. Nollet was the first to write about the relationship between lightning and the electric spark, stating; "Thunder is, in the hands of nature, what electricity is in ours" (Dunsheath, 1967, p.46).

Franklin's Forecast

One man stands out during this time as not only a founding father of America but also a founding father of our modern understanding of electricity. This man is Benjamin Franklin, and through his work with atmospheric lightning, humanity has come to understand the electric force and its implications to our society.

When Benjamin Franklin was not busy managing a printing shop, establishing libraries, organizing police forces, or signing the Declaration of Independence, he was looking to the troposphere and theorizing about the mysterious properties of lightning (Turner, 1927). His thoughts may have been inspired by other scientists at the time, such as Englishman Stephen Gray, who in 1734 observed that "electric fire" or static electricity seemed to have a similar nature to that of lightning seen during thunderstorms (see Figure 6.10).

Great discoveries of electricity were being made in Europe and Britain during the first half of the 18th century, and this excitement quickly spread to America, where Franklin began to connect the emerging ideas of electricity and the natural phenomena of lightning. Franklin conducted many experiments with the use of Leyden jars. From these experiments, he recognized similarities between lightning and electric sparks, which convinced him of the electric nature of lightning (Turner, 1927). Of these similarities, one of the most important was the observation that, like electrostatic sparks, lightning was most attracted to pointed objects and elevated areas such as houses, churches, and ships. Franklin proposed that metal rods with pointed ends 20 to 30 feet high could be erected and used to draw "electric fire" from the clouds, just as pointed objects were known to draw sparks from charged objects. He proposed that these lightning rods could then be attached to the ground to dissipate the charge from a lightning strike. This invention was used in practice to prevent lightning from striking and destroying homes and other wooden structures. Franklin did complete many experiments in the field with lightning rods that were well received, encouraging rods to be erected across major cities of Europe and America in the 1760s (Turner, 1927).

Figure 6.11. Artist rendition of Benjamin Franklin preforming his famous kite experiment c. 1752. This experiment is thought to be one of the first to confirm the identity of lightning as electric discharge.

The summer of 1752 saw Franklin's famous kite experiment. Franklin's experiment included tying a key to a kite to obtain elevation and observing its behavior during a thunderstorm (see Figure 6.11). He held the kite apparatus by an insulating silk ribbon to avoid electrocution. Franklin hypothesized that sparks would be seen from the key, and when they were not visible he touched the key and felt a strong shock. This was used as evidence that the key had been charged by the electric matter of lightning and therefore the identification of lightning as electric discharge had been demonstrated (Dunsheath, 1967; Miller, 1937).

There is however, a lot of controversy surrounding this experiment. Franklin had only briefly and vaguely described this experiment in a short letter a few months later, regardless of the rather large statement it seemed to make (Tucker, 2003). Additionally, there were no witnesses to this experiment other than his own son. Franklin may have faked his famous kite experiment out of frustration regarding the rebuttal of his prior theories due to his lack of scientific background (Dunsheath, 1967). Regardless of whether or not Franklin's kite experiment was truly conducted, he did contribute many theories and other experimental evidence of lightning as electricity (Miller, 1937). Franklin received various academic honours for his success in the study of electricity, including being appointed to the Royal Society of

London for Improving Natural Knowledge.

In his later work, Franklin began to investigate other natural phenomena in the context of electricity. He became very interested in the aurora borealis and in 1779, hypothesized the origin of these lights (Miller, 1937). He had thought that the lights were produced by a bulidup of electric charge in the atmosphere at the poles of the Earth due to high levels of snow and moisture, which illuminated the air. Although this is not exactly how aurora borealis are formed, Franklin was correct in assuming that charged particles played a role in their formation (Miller, 1937).

The influence of Benjamin Franklin spread to many scientific minds in America at the time, including professor Joseph Henry of Princeton (Skilling, 1948). In 1845, Henry wrote about atmospheric electricity and had a particular interest in the uses of lightning rods. He used concepts of lateral discharge and paths of least resistance to explain the behavior of lightning as it strikes objects on the Earth's surface. He improved Franklin's lightning rods and also explained the use of electrical grounding to protect metal-roofed homes from lightning strikes. Henry continued to study electricity and made colossally important contributions to the field, including the discovery of the induction of electricity via magnets in 1831, alongside Michael Faraday (Skilling, 1948).

Do the Math

As Franklin's experiments were becoming famous worldwide, he encouraged many scientists to continue his work and perform his experiments elsewhere. Joseph Priestley was an English scientist who met with Franklin during a meeting of the Royal Society (Miller, 1937). In 1766, Priestley repeated one of Franklin's experiments that involved charging a hollow conductor and observing a null electric force on the inside of the hollow container (Priestley, 1755). Priestley used this observation to infer that the electrostatic force detected outside of the conductor behaved as if it were inversely proportional to the distance from the conductor. This mathematical observation was similar to the inverse square law known to govern the gravitational force, and would one day be formulated into Coulomb's law of electrostatics. Priestley used this proportionality to explain the fact that there is no electric force inside a conductor (Priestley, 1755). He used this discovery to explain that the Earth itself must be a conductor as well, since it is a shell and any object inside it would not be more attracted to one side of the shell or the other.

Priestley had other hypotheses about lightning, such as his thought that heated or cooled air could propagate electricity transfer to or from the Earth (Priestley, 1755). Additionally, Priestley had thought that lightning was responsible for earthquakes, and proposed that lightning rods may prevent earthquakes from happening in areas prone to them. Of course, this theory has proven to be incorrect as the understanding of plate tectonics has developed over time.

Life in Lightning

Italian professor of anatomy, Luigi Galvani, may be viewed as the non-fictional Dr. Frankenstein due to his work with electrifying corpses. On a fateful day in 1780, Galvani, during a dissection, accidentally touched a nerve in a frog leg that was near an electric machine and it unexpectedly twitched (Skilling, 1948). Galvani was intrigued by this result, and wanted to replicate it in his garden. He set up an experiment in which severed frog legs were attached by the nerve to brass hooks, which were then connected in circuit with a lightning rod. Galvani knew of lightning as electric discharge and so the twitching of the frog legs during a thunderstorm did not surprise him. Galvani had unknowingly created the first sensitive electometer (Skilling, 1948). Upon further analysis however, he also observed twitching as iron and copper were pressed together, regardless of atmospheric electric conditions. It is now known, however, that this was due to the transfer of charge between the different metals, essentially acting as a galvanic cell battery (Miller, 1937). Galvani had originally thought the source of the charge was the nerve of the frog leg. He called this "animal electricity" and spent many unsuccessful years investigating it. Though he did not realize it at the time, Galvani's experiments had made significant early impressions that would later lead to the discovery of nerve communication, as well as Alessandro Volta's invention of the battery (Dunsheath, 1967; Skilling, 1948).

Sparks of the Future

More than 100 years after the electric nature of lightning had been confirmed, a young Serbian engineer appeared on the scientific playing field, and changed the game forever. It seems appropriate that Nikola Tesla was born during a thunderstorm in 1856, because of his numerous contributions to the field of electromagnetism and revolutionary electric inventions (Bernard, 2013). In a time when many physicists were no longer concerned with the study of electricity, Tesla was interested in improving existing electric circuits, as well as inventing a means of worldwide wireless communication (Tesla, 1977).

The Tesla coil stood out as one of Tesla's most impressive inventions (see Figure 6.12). It was a type of transformer that used the novel alternating current to produce high voltage discharges very similar to those produced by lightning (Bernard, 2013). High potentials are built up in the transformers of the coil until it is large enough for the electrical breakdown of air to occur. This happens when the voltage across open space (air) exceeds the breakdown voltage of $3x10^6$ V/m, causing the resistance to rapidly decrease and allowing charge to travel through ionized air, or plasma (Bernard, 2013). The Tesla coil was extremely useful in its ability to transfer charges wirelessly. This is the same process that occurs in the atmosphere, as charge separation in the clouds produce an electric potential difference.

One of the many aspects of electric theory Tesla was interested in was the understanding that Earth had an electric potential (Tesla, 1977). He wanted to know how exactly currents propagated through the Earth's crust and used lightning to find his answer. Tesla monitored vibrations of the ground with receivers and discovered that the vibrations caused by far away lightning strikes were more severe than those caused by closer lightning strikes. He realized that this occurred because lightning striking the earth must create a vibration that travels through the crust and builds up a standing wave, with the node being located at the point of the lightning strike (Tesla, 1977). Tesla used these observations to confirm his belief that the Earth has its own resonant frequency. These ideas were recognized by observing lightning, and are implemented today in technology such as extremely low frequency SONAR communication. Tesla's results also led to his conclusion that the Earth must behave like a conductor, and he ran many experiments in attempts to imitate the low frequency waves created by lightning (Tesla, 1977).

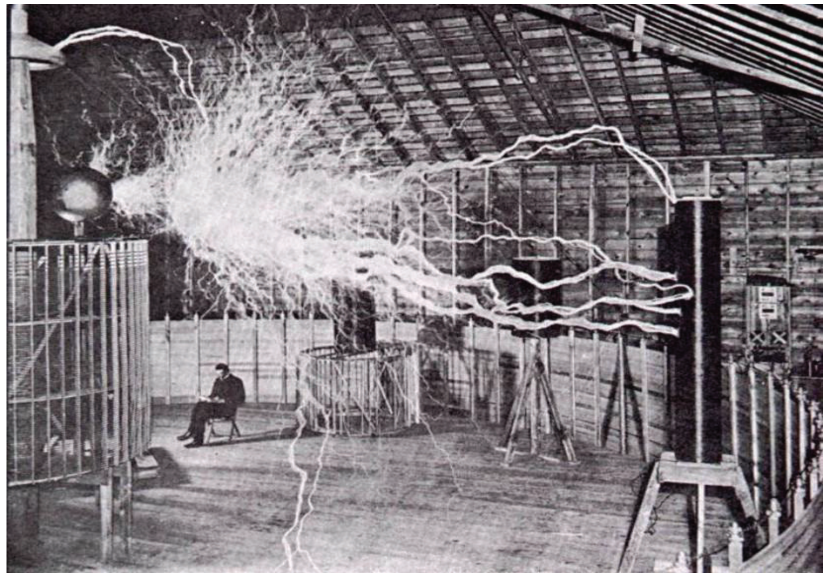

Figure 6.12. Nikola Tesla photographed in his Colorado laboratory with one of his Tesla coils demonstrating induced lightning-like behaviour.

A unique interest of Tesla was the study of ball lightning, a natural electrical phenomenon that is still not understood by modern scientists (Bernard, 2013). Ball lightning is described as a luminous sphere observed during thunderstorms, being seen to exist longer than a lightning flash. In 1904, Tesla was the first individual to re-create ball lightning effects in the lab, and he demonstrated it to the public. This was one of the many important paths Tesla took during his lifelong quest of solving the puzzle of wireless communication (Bernard, 2013).

To Infinity and Beyond: Lightning in the Ionosphere

The rapidly growing world of electrical invention along with increasing societal pressure for global communication employed Nikola Tesla and Guglielmo Marconi in a race for the first trans-Atlantic electric signal. On December 12 of 1901, the Italian physicist, Marconi sent the the first trans-Atlantic transmission in history from the UK to St. John's, Newfoundland, with his famous Morse code message of the letter "S"

(Appleyard, 1930; Belrose, 1995). Even with his 152.4 metre kite-supported antenna, Marconi knew that the curvature of the Earth would have led the electric signal to outer space. The success of his radio transmission initiated scientists' belief that there was a layer of charged particles in the atmosphere which could reflect electric signals back to the Earth's surface (Corazza, 1998; Davis, 2005).

Within the following year, funding was invested into researching the radio-electrical properties of the ionosphere. The Kennelly-Heaviside Layer, currently known as the E region of the ionosphere, was independently yet simultaneously proposed by the British physicist Oliver Heaviside and American engineer Arthur Edwin Kennelly in 1902. This layer of ionized gas was predicted to allow electromagnetic signals to be transmitted beyond the horizon (Kelley, 1989; Volland, 1984).

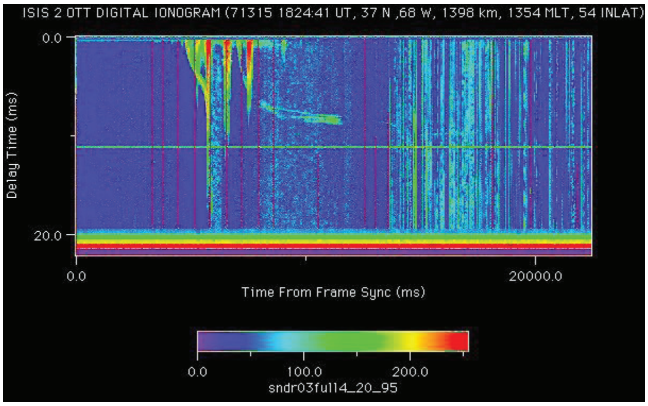

Figure 6.13. The first ionogram of the atmosphere, produced in 1962 by the ionosonde on Canada's Alouette I. *This ionogram graphs frequencies of electric signal in relation to height of the ionosphere, and was considered successful in inspirnig future missions to collect more data on atmospheric electricity.*

Between World War I and World War II, the Golden Age of Aviation brought pilots to fly above the troposphere. At these high altitudes above the clouds, bursts of light were observed by pilots. A mechanism for this upward lightning was not known until 1925, when C.T.R. Wilson theorized that electric breakdown should occur over large cumulonimbus clouds (Kelley, 1989; Volland, 1984).

The idea that a region in the atmosphere was ionized by solar radiation would be essential to the development of radar, and in 1926 it was finally given the name "ionosphere" by Robert Watson-Watt of Scotland. Watson-Watt, who worked at the Radio Research Station in Slough, UK, strengthened the link between the ionosphere and lightning in his theory that lightning storms intensify the ionosphere's sporadic layer. It was not until 2005 that Watson-Watt's theory was confirmed by C. Davis and C. Johnson, working at the Rutherford Appleton Laboratory in Oxfordshire, UK. Further studies on the ionosphere were out of reach until the Space Age begun, in which Canada's first satellite was launched to measure a global ionogram in 1962 (see Figure 6.13). The *Alouette I* was the first satellite to be constructed outside of the USA and USSR, and its success in measuring the electric properties of the ionosphere inspired the launch of the International Satellites for Ionospheric Studies. (Albany University, 2013; Kelley, 1989; Volland, 1984).

Moving Mountains

When ancient human civilizations thought of lightning as being a god-like entity, they may have not been very far off. After all, they were very correct in defining this force of nature in terms of its great power that even after thousands of years it partially remains a mystery to humankind. This electric phenomenon has its origins in the ionosphere above the Earth, however; its effects on the surface of our earth are the most striking.

Today, lightning is known to be a result of the electric discharge from the strong potential built up in storm clouds as warm moving air induces the separation of charges (Rakov and Uman, 2003). This causes the ionization of air, which temporarily allows a current to flow through it; however, air is a very poor conductor and so the large amount of resistance results in the rapid superheating of the plasma channel (Rakov and Uman, 2003). The intense heat and pressure of the plasma causes the air around it to rapidly expand, creating a sonic shock wave heard as thunder. Any given lightning strike may reach a core temperature of up to 30 000 K, which is six times hotter than the surface of the sun (Rakov and Uman, 2003; Hathaway, 2013).

Instant Rock

Lightning travelling towards the surface of the Earth superheats the surrounding air, which is able to damage anything it strikes – commonly seen through the destruction of flammable structures or injuries to people struck by lightning (Navarro-Gonzalez, 2007). The powerful heat force of lightning even affects presumably durable objects such as rocks. In fact, lightning has the power to form rocks through the extreme heating of sand. When lightning strikes sand or soil, the heat from the air around it causes the melting and fusing together of quartz in the grains. This process produces a silica glass tube known as *fulgurite*, as seen in Figure 6.14, which may be used as a tool to look into the geologic past (Navarro-Gonzalez, 2007). The silica glass, *lechatelierite*, is an isotopic substance that may be used to date the age of the fulgurite using thermoluminescence. As well, because these fulgurites form so rapidly, gasses are commonly trapped within the glass and remain preserved for thousands, or millions of years. These gases can be chemically analyzed to provide information about soil characteristics at the time of the lightning strike in order to provide clues about climate and carbon/nitrogen gas ratios (Navarro-Gonzalez, 2007).

Shaping the Horizon

In addition to making rocks, lightning is known to be quite efficient at breaking rocks as well. Over the past few years, lightning has been accepted by observation and experiment to be a prominent cause of weathering in mountain ranges (Wakasa, S., et al., 2012). Since lightning strikes over 40 thousand times a day across the Earth, with each strike producing currents of up to 300 kA, it is not surprising that this ongoing process would have a damaging effect on even the strongest of Earth's landforms (Wakasa, S., et al., 2012). Just as the extreme heat from a lightning strike fuses silica together in soil grains, the heat can cause explosive blasts when lightning strikes already formed rock (Knight and Grab, 2013). This type of weathering is characterized by fractured, angular bedrock debris, particularly on the summits of mountain ranges. The peak areas are frequently struck by lightning because of their high altitude. This discovery has sparked much interest because it infers that mountains are able to erode quite rapidly via lightning strikes compared to the usual gradual weathering from climate effects (Knight and Grab, 2013).

Magnet Madness

The closely correlated concept of magnetism may be used to determine if a rock has been eroded by lighning. The orientation of the magnetic grains in cooling igneous rock align with the the current magnetic field of the Earth (Knight and Grab, 2013). As mentioned above, the heat from lightning instantly melts rock, allowing its poles to realign with the Earth's magnetic field at that time (Verhoogen, 1965). Thus, the magnetic orientation of newly cooled rock will differ from the surrounding rock, given that the Earth's magnetic field experiences frequent anomalies and changes. The changes in magnetic orientation can be determined by simply using a compass since the magnetic north of the two orientations will be different (Knight and Grab, 2013). This makes it possible for geologists to recognize which areas have historically been struck by lightning. This knowledge of divergence in magnetic fields may be used in conjunction with knowledge of plate tectonics to possibly determine the history of geological formations using ancient lightning strikes.

Figure 6.14. Fulgurite glass caused by the superheating of sand during a lightning strike. The quartz is fused together almost instantaneously to create these natural sculptures.

The Pursuit of Unity: How Magnetism and Electricity were Unified

The history of magnetism is a very long one extending from its discovery ca. 800 BCE to the current theory expressed in the standard model of physics. There have been countless scientists that have contributed to the evolution of the theory of magnetism. Earth science has been used by many of these contributors to provide evidence for their hypotheses. Eventually, as a theory developed and more was learnt about electricity, many different observations began to become a single unified theory.

Origins of Magnetism

Figure 6.15: A model of the first compasses made in about 200 BCE during the Chinese Han Dynasty. During that time, the compass was called the "south-pointer" (above).

The discovery of lodestone and its directive properties of aligning to north-south were the key to the invention of the compass and understanding magnetism. Greek philosophers around the time of 800 BCE were the first to discover lodestones and write about them (Lowrie, 1997). Lodestones are an ore of iron (Fe_3O_4), which, unlike other ores of iron, has permanent magnetic properties. It was noticed by the Greeks that these stones had the power to pull needles, nails, and other metals toward themselves (Silverberg, 1969), with some specimens strong enough to lift several times their own weight (Meyer, 1971). During this time, lodestones were an object of philosophical discussion as their attractive powers were believed to have metaphysical powers (Lowrie, 1997). The Greeks are also credited with the discovery of static electricity, as Thales (640-546 BCE), a Greek philosopher, was the first person to observe the electrical properties of amber. He noted that when amber is rubbed, it is able to pick up light objects such as straw or dry grass. He also experimented with lodestone and realized that the lodestones could attract iron. The Greeks then named the lodestones *magneta*, thus creating the origin of the word magnetism (Lowrie, 1997).

First Magnets and Compasses

Although the Greeks were the first to discover lodestone and its properties, ancient artifacts show that the Chinese also discovered the lodestone and its properties around the Han Dynasty (300-200 BCE). The Chinese found that when an iron needle was rubbed against a chunk of lodestone, the needle itself would take on magnetic powers and gain the ability to attract other needles. Though there are mentions of compass like objects before 300 BCE, the first clear written reference to a compass is in 300 BCE. The source, a book titled *Kuei Ku Tzu,* has the line "when people of Cheng go out to collect jade, they carry a south-pointer with them as not to lose their way" (Silverberg, 1969). It is known that the Chinese were the first to invent a rudimentary compass from the lodestone. The compass consisted of a spoon carved from lodestone, whose bowl was balanced and could rotate on a flat surface (see Figure 6.15; Silverberg, 1969).

Despite being the first to invent the compass, the Chinese did not immediately use it for navigation at sea. Instead, they used it to search for gems and to perform magic and feng-shui (R. Silverberg, 1969; W. Lowrie, 1997). Feng-shui is an old Chinese pseudoscience that studies the local spirits, the wind, and water. Compasses were used in feng-shui to find sites for houses, temples, roads, or tombs so that the architecture followed the principles of ancient Chinese philosophy. A Sung Dynasty polymath scientist and statesman Shen Kuo (probably the most influential mind of his time) in 1088 CE wrote, "the magicians would rub the point of a needle with the lodestone and it would start to point to south". This made the lodestone especially important as in feng-shui, south is strongly associated with luck (R. Silverberg, 1969).

During the Tang Dynasty (500 CE), the

Chinese realized that the magnetic compass did not point exactly to geographical north (now termed magnetic declination). They were not, however, able to correct for this discrepancy. The Chinese continued to use suspended and pivoted needle compasses for magic and location until after 1000 CE when the compass was finally used for navigation and exploration of the oceans (Silverberg, 1969). Flavius Blondus, an Italian historian, is said to be the first person to use a floating magnet as a compass for sea navigation, at Amalfi Harbour (1269 CE). After this development, the design of the compass was continually refined across the world for many centuries (Meyer, 1971).

De Magnete

After the ancient societies of Greece and China, the next major step in the understanding of magnetism was the publication of the monumental treatise *De magnete Magneticisque Corporibus, et de Magno Magnete Tellure* (On the Magnet and Magnetic Bodies, and on That Great Magnet the Earth) by William Gilbert (1544-1603). When viewing *De magnete* from a historical perspective it is a fascinating book, written as a scientific textbook or monograph whose structure would be somewhat familiar to modern day readers. But at the time of its publication (1600) *De magnete* was an unusual book, although similar ideas of magnetism had been stated before in *Epistola de magnete* in 1269 (Power, 2006). Major treaties such as Kepler's *Astronomia Nova* (1609), Galileo's *Sidereus Nuncius* (1610), Newton's *Principia* (1687), and most importantly Francis Bacon's *Novum Organum* (1620) were not yet published, meaning that at the time, there was no major 'yardstick' to which *De magnete* could be compared. Not even the scientific method had been formalized (Cropper, 2011).

De magenete starts with a survey of what was known at the time about magnetism but Gilbert then goes on to describe the difference between electricity (he is the first one to coin this term) and magnetism (Meyer, 1971). He describes the differences between electricity and magnetism through two experiments: one constructing an electroscope and showing that many materials that can be made electric (statically charged) can attract both metals and nonmetals, while magnets can only attract metal objects (Meyer, 1971). The next experiment he did showed that cutting a lodestone creates two smaller magnets. While this may have been known previously, Gilbert showed that the process could continue indefinitely (Meyer, 1971). He also rejected the idea that one can create a perpetual motion machine stating "O that the gods would at length bring to a miserable end such fictitious, crazy, deformed labours!" (Gilbert, 1893). He further proposed that the Earth was a large magnet. He based this claim on the fact that a lodestone reorients itself anywhere on the Earth's surface. In addition, iron heated and cooled at the meridian can also acquire magnetism. In the following sections of *De magnete*, he further refines and explains magnetic declination and magnetic dip, in a form that is very close to our current understanding.

Looking at this book it is amazing to see how many light years ahead of its time it was. The many well-designed experiments and rigorous application of the scientific method was 20 years before Sir Francis Bacon laid out the scientific method in *Novum Organum* (1620; Gaukroger, 2001). *De magnete* provides an excellent example of scientific work that any skeptic can be proud of.

Figure 6.16: One of the magnetic observatory sites (above) that were used to study the Earth's magnetic field in the 1800s by Gauss and Weber located at the University of Göttingen. This is the main magnetic observatory of the worldwide network of magnetic observatory stations created by Gauss and Weber called Magnetischer Verein (Garland, 1979; Verschuur, 1993).

Characterizing the Earth's Magnetic Field: Gauss and Weber

One of the most important discoveries in the early 1800s was made by German scientist and mathematician, Carl Friedrich Gauss (1777-1855). In 1834, Gauss with the assistance of Wilhelm Weber, set up numerous magnetic observatories to obtain the direction and intensity of the Earth's magnetic field at various points. As one of the fathers of geophysics in Canada, G. D. Garland, stated "Gauss… made great strides in the organization and equipping of magnetic observatories" (1979). This project,

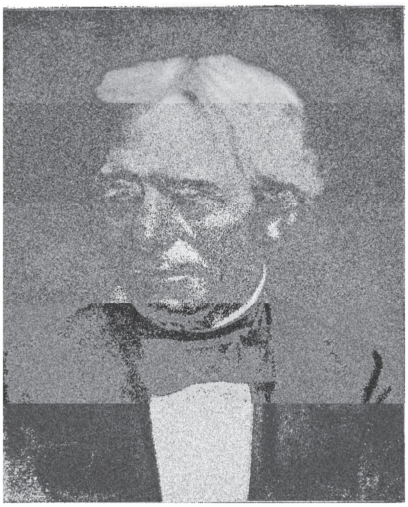

Figure 6.17: A photograph of Michael Faraday (1791-1867), ca. 1860 (above). He is famous for countless contributions to the physical sciences. A few notable mentions include Faraday cages, founding the field of electrochemistry, the creation of the first electric generator and the discovery of diamagnetism (Cropper, 2001).

Figure 6.18: An engraving of James Clerk Maxwell (1831- 1879) by G. J. Stodart (right). One of the greatest physicists of all time, Maxwell is also known for this work in thermodynamics and many mathematical models for physical systems (Tolstoy, 1981).

known as Magnetischer Verein, is considered by most scientists to be the first global scientific collaboration. Observatories were established across the world with the assistance of the British Empire. The main observatory is located in the University of Göttingen (see Figure 6.16; Verschuur, 1993). A bifilar magnetometer (which measures torsion of a magnet on a string) was used to determine the direction and intensity of Earth's magnetism. Using these measurements Gauss was able to construct a theory: each magnetic field is composed of dipoles. His law proves that it is impossible to have a monopole (Garland, 1979). This was an important step as it forms the basis of understanding complex magnetic fields. He used a similar concept to explain electric charges but failed to make a deeper connection between magnetism and electricity.

The Age of Electromagnetism: Faraday and Maxwell

Michael Faraday (1791-1867) is remembered as one of the greatest success stories in the history of science (See Figure 6.17). Born into a poor family receiving little formal education, Faraday went from apprentice bookbinder to pioneer in the world of electricity (Cropper, 2001). Faraday's life changed forever when he attended lectures by Sir Humphry Davy in 1812, a leading chemist of the time (Meyer, 1971). Inspired, Faraday left his career as a bookbinder in 1813 to become Davy's assistant.

In 1820, Hans Christian Ørsted published results from an experiment that showed that an electric current causes a compass needle to reorient itself so that it is perpendicular to the current. After hearing about this experiment, Faraday was taken aback by its implications (Cropper, 2001). Two separate concepts in science, electricity and magnetism, seemed to interact though not through physical contact. The result was as unexpected as if the mass of an apple had caused a compass needle to turn. He obsessed over the experiment repeating it many times. For 11 years, he tried to do the opposite, writing "convert magnetism into electricity" as if it were dogmatic chant in his notebook (James, 2008). Finally, after many years of research he published *Experimental Researches in Electricity* in which he outlined his law of induction (Faraday, 1834). He proved that the movement of a magnet relative to a conductor 'induced' a current into a conductor (the reverse of Ørsted's experiment). This principle alone made Faraday one of the most famous scientists of his time and led to the development of the electric generator. The theory, which Faraday developed to explain how electricity and magnetism could interact at a distance, is field theory. Although Faraday was an excellent scientist, he was unable to come up with a mathematical basis to describe these fields, due to his lack of formal education (Cropper, 2001).

Fortunately in 1861, James Clerk Maxwell (1831-1879) came up with a theory that would explain Faraday's fields in *On Physical Lines of Force* (See Fig. 6.18). Maxwell's theory has forever labeled him in the eyes of physicists as the greatest 19th century physicist (Tolstoy, 1981; Campbell and Garnet, 1884). In part three of *A Dynamical Theory of the Electromagnetic Field,* Maxwell proposed equations that used mathematics and field theory to unite magnetism and electricity as a single force (Everitt, 1975). The keystone of his theory was that it combined experimental and mathematical evidence to show that light is composed of an electric and a magnetic field.

"The agreement of the results seems to show that light and magnetism are affections of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws" (Maxwell, 2010).

Over time, the original twenty equations Maxwell published were reduced to four (See Figure 6.19; Verschuur 1993). Note that this final set of equations encompasses the results of centuries if not millennia of human discovery. All of classical magnetism and electricity can be derived from these equations.

Towards Unity

As we have seen in this section, humanity's pursuit of knowledge has lead to a greater understanding of our world and the forces which control it. From the ancient Greeks to Faraday and Maxwell, great scientists have sought to understand our world. Throughout history, we have strived to solve complicated phenomenon through the use of powerful yet simple ideas that combine into a single concept. Using this concept we can relate and explain very different observations. The process is unification. We can see this in Alfred Wegener's theory of plate tectonics (see pages 95-98), which united and explained observations of sediment deposits, fossils, and geologic structures around the world. We also see this in Darwin's theory of evolution, which allowed biology to explain all of the variations seen in animals into a single theory. No matter what problem it seems we tackle, we must repeat the process similar to the one that generated Maxwell's equations, or any great theory. Begin at primitive knowledge, which may be only fragments and step-by-step use mathematics, the Earth, and our ingenuity to make a whole unifying theory.

Names	Equations	Describes	Critical Implications
Gauss' Law for electricty	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$	Charge and the electric field	Like charges repel and unlike charges attract. A charge on an insulated conductor moves to its outer surface.
Gauss' law for magnetism	$\nabla \cdot \mathbf{B} = 0$	The magentic field	It is impossible to create a magnetic monopole
Ampères-Maxwell law	$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$	The magnetic effect of a changing electric field/current	A current in a wire sets up a magnetic field near the wire. The speed of light can be calculated from movement of a elctromangnetic field.
Faraday's law of induction	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	The electrical effect of a changing magnetic field	A bar magnet, thrust through a closed loop of wire, will set up a current in the loop.
Lorentz force	$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$	The force produced by the magnetic and elecrtic fields.	Charges are effcted by magnetic and electric fields.

Figure 6.19: The modern vector calculus form of Maxwell's equations together with the Lorentz force as the definition of the electric and magnetic fields that form the basis of classical electromagnetism. The first two of the equations describe the fields; the second two describe how the change of one field affects the other. All vector quantities are bolded while all scalar quantities are italicized. Note that $\boldsymbol{E}$ *is the electric field,* $\boldsymbol{B}$ *is the magnetic field,* $\boldsymbol{J}$ *is the current,* $\mathbf{v}$ *is velocity,* ρ *is the free charge density,* μ_o *the magnetic permeability constant,* ε_0 *the permittivity of free space constant, t is time and* ∇ *is the nabla operator. (Verschuur, 1993).*

Mapping Through Time and Space: The Earth's Magnetic Field and Magnetic Stratigraphy

Earth's Magnetic Field

Since *De magnete* the Earth's magnetic field has been modeled as a large bar magnet. The model accounts for approximately 80% of Earth's magnetic field (Reynolds, 2011). This bar is represented by the two geomagnetic poles. The geomagnetic poles are the two points on Earth's surface located on an axis that runs through the Earth's core, with the greatest magnetic field strength (see Figure 6.20; Reynolds, 2011). This model, though useful for measurements in the field, does not represent the true nature of the Earth's magnetic field.

In the modern theory of the Earth's magnetic field, the liquid outer core of the Earth is responsible for generating the magnetic field. The conductive and convective properties of the core allow an induced electric current to produce a magnetic field (as seen in Maxwell's equations, a change in the electric field produces a magnetic field; Korte, 2011). Without the spinning and convection currents of the core, Earth's field would decay to near zero within 20,000 years as a permanent magnet cannot form due to the high temperatures found within the core (Reynolds, 2011).

Because of the changing nature of the magnetic field, it is asymmetric. Currently, the Earth's magnetic field has not one set of poles but two sets of poles, with different positions and strength. Throughout time, the location, and number of poles have varied considerably (though it is impossible to create a monopole; Reynolds, 2011). The changes that occur in the Earth's magnetic field are known as secular variation. Secular variation can occur over a period of hours to millions of years. Secular variation comes

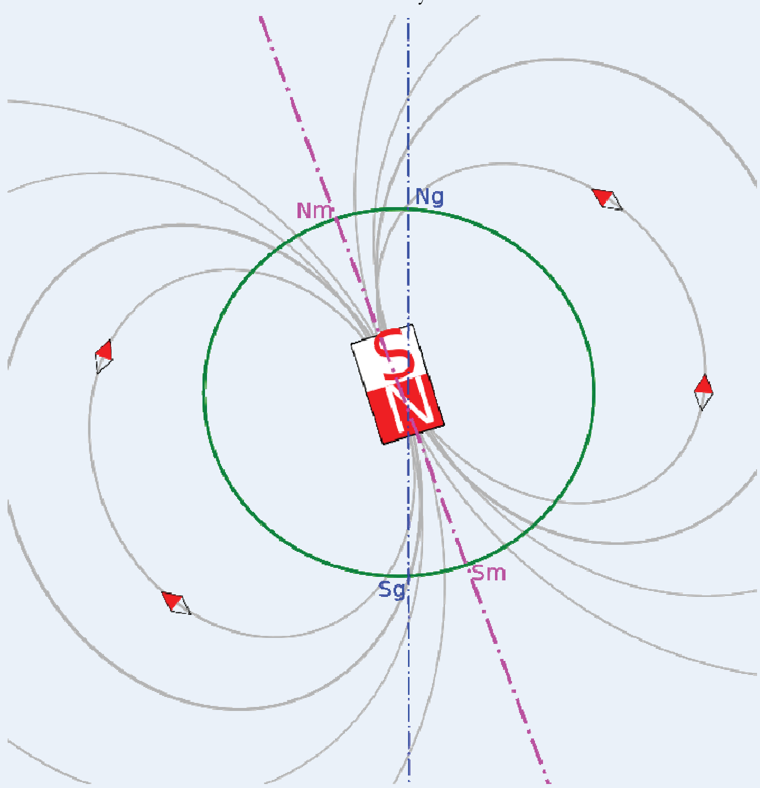

Figure 6.20: This figure (right) shows the difference between geographical poles (Ng and Sg) and the geomagnetic poles (Nm and Sm). The geographical poles are on the axis which Earth rotates around. The geomagnetic poles are on the axis that best represents a bar magnet model of the Earth's field (seen in the center of the circle). Compasses on the Earth's surface orient themselves in the direction of the magnetic field lines (Stanley, 2006).

from fluctuations in the Sun's activity (external) and fluctuations in the outer liquid core (internal). Normally, the internal field is much stronger than the external field. However, when high energy ionized particles from the Sun, in the form of solar winds and coronal mass ejection, contact the Earth's ionosphere the external magnetic field changes considerably. This effect is so strong that the effects of external and internal changes cannot be separated (Korte, 2011). In comparison, very little is known about what stimulates internal changes. Although it is known that differences in the rotation and convection of the fluid core causes the magnetic field to vary, it is not known what causes these changes. The fluctuations cause a cycle in which two/four dominant poles decay into multiple small chaotic poles, and eventually the Earth's magnetic field reaches a state of zero overall magnetic strength. The cycle completes with the return of a dominant dipole but with the location of the north and south poles switched (Reynolds, 2011).

Magnetic Stratigraphy

Knowing the properties of Earth's magnetic field we can apply this knowledge in magnetic stratigraphy. When combined with isotopic dating of rocks, magnetic stratigraphy provides an unparalleled resolution in terms of dating. This is done through the use of a Geomagnetic Polarity Time Scale (GPTS; see Berggren et al., 1995 for the most recent and widely used version). A GPTS is the record of the magnetic pole reversals that have been dated. It is used by correlating magnetic anomalies in rocks to magnetic anomalies which have been dated in the GPTS. Many methods can be used such as isotopic dating and biostratigraphy, to provide the best age range for pole reversals. Because pole reversal is a global phenomenon, it can be used to find either the date of anomalies or the orientation of the Earth's field in the dated sample (Berggren et al., 1995).

But how are magnetic anomalies created? Magnetic anomalies form only in rocks that contain atoms of metal with ferromagnetic properties such as iron. When rocks solidify from magma (or any material in which the atoms are free to move) the atoms, no longer free to vibrate and rotate, lose energy and must adopt an orientation. The most favourable orientation is with the Earth's magnetic field at that time of solidification, as atoms with ferromagnetic properties possess electron configurations that act similar to bar magnets (Khanna and Linderoth, 1991). Once the rock has formed the orientation of the atoms is set and cannot be changed. Their combined individual magnetic fields are what give a rock its magnetic properties. The natural state of magnetism of any rock is referred to as natural remnant magnetization (NRM; Fuller, 2013). Although there are many types of NRM the two most studied are thermoremanent magnetization (TRM; the magnetism acquired by rocks when they have cooled from magma) and chemical remnant magnetization (which is associated with a phase change, most often from ion into crystal precipitate; Fuller, 2013).

With a GPTS and NRM data you can determine many characteristics of the paleoenvironment in which rocks formed. Using magnetic stratigraphy, we can measure the rate of sediment deposition and construct a timeline on which to relate other observations. Simply plotting the depth of a deposit against the number of years ago the reversal occurred and finding the first derivative gives you an estimation of the rate of sedimentation (Fuller, 2013). Constructing a paleomagnetic timeline can be a powerful tool showing, for example, that ocean crust gets younger as it moves away from a mid ocean ridge, an important element of plate tectonic theory (Stanley, 2009).

Case Study: Establishing a Timeline for Loess

The Chinese land of loess has always attracted many geologists all over China. Loess is generally yellow in color, formed by wind-blown silt (Heller and Tungsheng, 1984). It has been said that more than 6% of China is covered with loess. Different colors indicate different sub environments in which the deposits were formed. For example, greyish-brown to dark red loess are strongly depleted in calcium carbonate and quite enriched in clay minerals. Some loess deposits with Cathaicae (a gastropod) within them suggest the loess is formed in dry, cold conditions (Heller and Tungsheng, 1984).

Geologists have been trying to determine the age of a loess deposit in China at 33-47°N and 127-75°E since the 1900s (Heller and Tungsheng, 1984). Mammalian and invertebrate fossils in the loess suggest an early to late Pleistocene age. However, geologists recently investigated the loess borehole using magnetic stratigraphy that relates the polarity of the loess NRM to a local borehole. This work determined the age of loess rocks in the region to be between 1.0 to 1.2 Mya (Heller and Tungsheng, 1984). Additional studies will be able to establish a more detailed timeline. Without magnetic stratigraphy, a timeline would be impossible to establish.

Garbage: A Common Denominator Among Civilizations

Since the dawn of civilization, one factor has consistently increased in proportion with human population density: garbage. Waste management has grown as a prevalent issue in conjunction with the expansion of technology and the use of inorganic materials. The ways in which civilizations disposed of their waste provides insight into the technological advancements of the time. Documented methods of waste disposal can also lend evidence to the progression of knowledge of the Earth's subsurface geology, and the patterns of sediment and groundwater flow that allow for effective waste containment. It is crucial to understand the ways in which toxins and chemical compounds flow through the subsurface in order to develop better techniques to properly manage waste; this also encompasses the realm of disease transfer through populations. It remains clear that garbage and waste disposal methods can today serve as a relevant proxy to determine the ways in which various civilizations lived, and their interpretation of the Earth's subsurface as a repository for waste that they left behind (Kelly, 1973).

Figure 6.21. A modernized version of the horse-drawn wagons used to collect garbage in the Roman Empire. This photo was taken in Seattle, Washington in 1915.

In the Beginning there was Garbage

It is suspected that early nomads (6 000 BCE-present) did not produce much, if any, waste (Encyclopaedia Britannica, 2013). Game that was killed was used to its entirety as a source of food, shelter, clothing, and tools. With this in mind, the earliest forms of garbage were items left behind by groups of migrating humans; that which could not be carried or moved to the next destination was left behind (Neal and Schubel, 1987). In the 15th century BCE, Greece had what is regarded as the first organization of town dumps. These were unsightly, unsanitary landfills. Wide ranges of undesirable items were discarded at these sites, including food, feces, broken ceramic, and even unwanted babies. The Roman Empire (27 BCE-476 CE) introduced the first sanitation workforce. Wagons pulled by horses were directed down streets where unconsolidated garbage was picked up and hauled to a centrally located dump in town (see Figure 6.21; Lightfoot, 2000). These dumps, similar to those of Greece, were equally as unsightly and were infested with rats, flies, and mosquitos. While the Romans were known for their feats of engineering and architecture, waste management was not a strength. Various entertainment events held at the Flavian Amphitheatre resulted in the death of thousands of animals, and hundreds of humans. These carcasses were disposed of in large open pits on the outside of town. It was clearly unknown that the unsanitary and open disposal of such material could result in the spread of disease as evidenced by the various plagues that riddled the Empire sporadically from 23 BCE to 162 CE. Even though the systems instilled by the Greeks and Romans were imperfect, they were far better than the waste management techniques, or lack there of, of the Dark Ages and Renaissance periods (500-1600) (Kelly, 1973; Hartnett, 1992).

Littering was the most common disposal method after the fall of the Western Roman Empire through the Dark Ages and the Renaissance. Until the late 1700s, citizens of England threw their garbage out of their windows and onto narrow, unpaved streets. As refuse built up, the lowermost layers began to decompose, mixing with human excrement and animal feces, creating an ideal breeding ground for disease-causing bacteria. In an attempt to control this problem, laws were put in place to prevent littering, however they were not enforced. In 1388, the English Parliament passed an act forbidding the dumping of garbage into ditches, rivers, and other bodies of water.

Similar to previous attempts to slow the accumulation of waste, this too went unenforced. The late 1500s ushered in an entirely new form of waste disposal with the introduction of the water closet to the Western world. In addition to this new technology came the Chinese import of toilet paper, yet another component of the growing waste problem. The revolution of refuse disposal practices has been the key to the progression of healthy cities. Entire cities have been saved from plague with disease-preventing waste management practices involving improved drainage and collection techniques (Kelly, 1973).

Subsurface Geology

Along with producing garbage, humans have been exploiting water and groundwater as a resource since the earliest ancient civilizations (Emilio and Alfaro, 2009). It became increasingly important to understand waste disposal and its possible effects on groundwater as populations and cities grew in size. However, the understanding of this resource was limited because groundwater lies beneath the ground surface and cannot be seen or studied. This persisted until the development of subsurface geology and groundwater hydrology, beginning in France in the 1500s.

The book *Admirable Discourses,* written in 1580 by Bernard Palissy (c. 1510-1590), united many previous observations and principles on water movement into a cohesive theory including evaporation and precipitation, and the cyclic nature of the movement of water (Karterakis et al., 2007). Years later, several individuals began to measure the movement of water, and their observations suggested the existence of groundwater. The first was Pierre Perrault (1611-1680), who measured rainfall along the Seine River, and estimated the amount of water lost to drainage and surface runoff (Jones et al., 1963). He found that the water input was six times greater than the output, pointing to another source for water loss (Narasimhan, 2009).

The idea of infiltration was introduced by Italian scientist Antonio Vallisnieri (1661-1730). By extensive investigation of Monte S. Pellegrino in 1715, he observed that precipitation travelled on the surface until reaching pervious areas. It then flowed under the surface, and travelled underground from Modena to Bologna (Karterakis et al., 2007). With the knowledge that water could infiltrate the surface and travel underground through unseen paths, the picture of hydrology became more complete.

These observations were put into practice by François Arago (1786–1853) of the French Academy of Sciences, who proposed drilling for a well based on groundwater trapping principles (Narasimhan, 2009). Interest was developing to exploit groundwater for drinking water, due to a growing population requiring a better source of potable water, and the increased contamination of surface water. In 1831, Arago proposed a location based on the observed rock facies, namely Albian Greensands of the Cretaceous period overlain by confining Tertiary clay layers. This illustrated the application of subsurface geology and served the growing need of water supply to Paris (Delleur, 2010).

These principles and observations relating to subsurface water flow were modelled quantifiably by Henri Darcy (1803-1858). In 1856 he developed the mathematical law for the flow of water through porous material, in an empirical formula which gives the apparent velocity of a fluid depending on the permeability constant of that material, and the changes in pressure over a given distance (Nader, 2009). He developed these laws by experimenting with the movement of water through different filter sands (Mahajan, 2008). This was expanded upon in 1863 by Jules Dupuit (1804-1866), who introduced a steady state equation for the flow of water into a well (Fetter, 2004).

Thomas Chamberlain (1843-1928) and the United States Geologic Survey published a report in 1885, which improved the laws of Darcy and Dupuit with the knowledge that there are no truly impervious geologic stratum, and therefore every aquifer has some leakage of water (Narasimhan, 2009). Chamberlain was not entirely correct in all of his observations, however his publications were important additions to the knowledge of groundwater movement and contamination (Fetter, 2004).

Benjamin Franklin

By the 1700s, port towns and cities across Canada and the United States were booming, and so too was their accumulation of waste

(McMahon, 1992). Benjamin Franklin (1706-1790) was only 17 years old when he arrived in Philadelphia, Pennsylvania, a growing industrial center. While this prominent figure in American history is most well known for his various inventions and ventures, which include bifocal lenses, he also devised a plan to deal with the ever-growing waste management issues in Philadelphia. This is generally overlooked in his history, though it was a significant accomplishment. Franklin was among the first to publish a connection between pollution, environment, and disease. He was deeply affected by the death of his son as a result of smallpox, and was concerned for the growing issue of waste and pollution in the watershed of the Delaware River, along which Philadelphia was expanding to encompass a region called the Dock. As a printer for the *Gazette* newspaper in Philadelphia, he was able to use this outlet as a public domain to express his distaste for the arrogance of the industrial employees of the city, and their ignorance of the issue of pollution. Franklin related the disease causality of pollution to the observations made in a book of medical practices, which also associated environment with disease. He recognized the fact that Philadelphia had a similar "lowness and moistness" that rendered it to have the same susceptibility to disease that Virginia did, the state in which the book was published. As yellow fever ran rampant in the area in the summer and fall of 1747, the concern of waste contamination was increasing, and by winter a committee was struck to restore and maintain the sanitation of the Dock. Franklin proposed a common sewer system for the deposition of wastewater south of the Delaware River, away from the watershed of the Dock. This innovative thinking clearly displayed Franklin's knowledge of the system of water transport, and by isolating the polluted water to a region outside of the city, the risk of disease contraction from bacteria and contaminants would be decreased. In yet another attempt to curb the city's still progressing waste issues, he implemented waste removal practices, street gutters, and an improved drainage system from the city. These too were evidence of forward thinking, resulting in the eventual deposition of the waste downstream of the Delaware River, preventing its mixing with the city's water source. While, in theory, these improvements had the potential to clean Philadelphia and rid the streets of refuse, they fell to the same fate as bills passed in 12th century England and were largely ignored. Domestic and industrial waste pits were continuously developed, and so contaminant leakage from waste was still an issue due to its continued presence in the water system of the Dock (McMahon, 1992). While the work done by Benjamin Franklin toward the improvement of Philadelphia as a city centre was not necessarily fruitful, it demonstrated the knowledge of the connection between waste, water contamination, and its negative implications. Franklin is an important figure in the development of waste management practices. His ideas were clearly influential and their legacy can be seen in modern cities and their methods of dealing with wastewater and garbage (Gaustad, 2006).

Groundwater Contamination

Since groundwater is an invaluable resource for countless people, it is a high priority to make sure that processes involved in its movement and contamination are fully understood.

Groundwater is fresh water that percolates through aquifers underground in saturated, unconsolidated geologic material such as sand and gravel, as well as in porous and permeable rock such as carbonate, volcanic, and fractured rock (Patrick, 1987). Groundwater may be confined if surrounded by impermeable material, or can be unconfined if surrounded by permeable material.

Unconfined aquifers have areas of recharge, where surface water supplied by precipitation percolates downward through the unsaturated zone, into the saturated zone and the aquifer (Patrick, 1987). This poses a great threat to groundwater quality. If areas of recharge are exposed to contaminants, this may cause contamination of the aquifer, and loss of the resource (see Figure 6.22).

There are many sources of contamination to aquifers, and anthropogenic sources are a huge contributor (Patrick, 1987). Waste disposal practices result in sanitary, industrial, solid, and radioactive waste all potentially being placed in areas of recharge. For solid waste (garbage) disposal, the easiest and most common practice is, and has historically been, dumping in landfills (Melosi, 2000). This method is criticized for endangering groundwater sources.

The harmful contents of landfills are not always known, and even if they are known, their interactions cannot always be predicted. Within these landfills comes the production of leachate, which occurs when excess precipitation percolates through the material in landfills and absorbs contaminants through microbial, chemical, and physical processes (Kjeldsen et al., 2002). In this process, the contaminants sometimes undergo reactions that form new and possibly more dangerous compounds (Patrick, 1987).

If not contained, leachate infiltrates the surrounding subsurface material and travels downward through permeable materials. The movement of leachate and other contaminants is a function of their properties, including solubility and density, and may be slowed by attenuation processes. (Patrick, 1987). All of these factors are important for societies to consider when choosing waste disposal sites and methods.

Colonel George E. Waring Jr.

Colonel George E. Waring Jr. (1833-1898) was another figure at the forefront of the waste revolution (Melosi, 2005). Born in New York, Waring was an American civil and sanitation engineer. In 1853, he became the apprentice of renowned agricultural scientist James J. Mapes (1806-1866) (Wilson, 1882). In this time he gained a wealth of knowledge regarding drainage engineering and scientific farming techniques. Waring also associated himself with landscape architect Frederick Law Olmsted (1822-1903), who worked to revolutionize and humanize the city environment in New York, namely with the construction of Central Park (National Park Service, 2013). Waring gained his rank of Colonel when his commission to the Civil War interrupted his career in 1861. Upon his return to the city in 1865, he published several books regarding drainage practices for agricultural purposes and for the sake of sanitation (Melosi, 2005).

Yellow fever was still a major issue in many expanding cities, rendering sanitation of utmost importance. Memphis, Tennessee had over 5 000 fatalities due to the disease, and city officials claimed that the sewage system implemented by Waring had "saved the city from ruin" (Melosi, 2005). The system employed in Memphis, aptly named the "Waring System", involved two separate pipes. One pipe carried rainwater, and the other carried sewage, which eased the disposal of unsanitary material. However, controversy arose when another sanitary engineer, Rudolph Haring (1847-1923), debated this system (West Laurel Hill Cemetery, 2008). He and many others in this field proposed that the smaller pipes used in the Waring system clogged more easily, and that a single combined pipe would be more efficient, both in cost and in function, for large cities. However, despite criticism, Waring's innovative ways of waste drainage in cities was a crucial expansion on the thoughts of Benjamin Franklin developed in the previous century (Melosi, 2005).

Waring was recruited to be New York City's street cleaning commissioner in 1894 (Stuart, 1981). While holding this position, Waring implemented various initiatives to conform the city to Hippocrates's ideal of "Pure air, pure water, and a pure soil". This, Waring believed, was the true measure of civilization; how a city disposed of its waste was indicative of its degree of development. He noted that the water pollution problem that was mounting in New York could be eradicated with the use of the existing sewage system, and its natural drainage path as a result of its proximity to the Atlantic Ocean. As well, a street cleaning force was put in place to keep the city clean not only aesthetically, but from a health standpoint as well. He applied his knowledge of disease

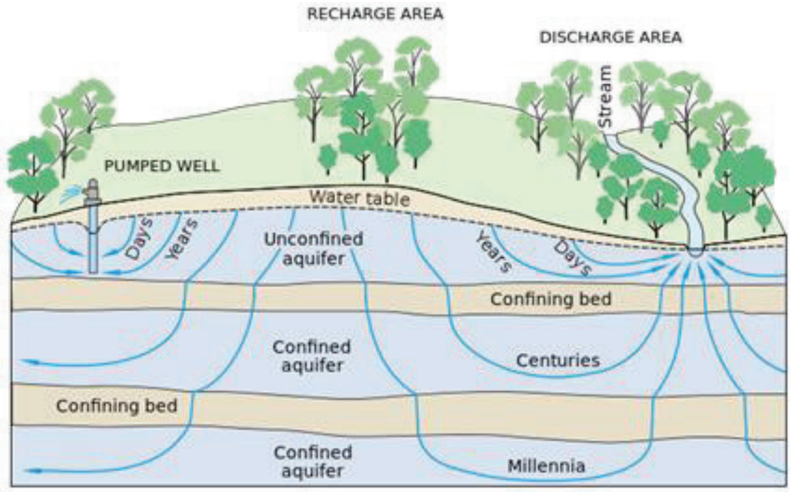

Figure 6.22. The movement of groundwater and contaminants into aquifers depends on the surrounding geologic material, leading to confined aquifers and unconfined aquifers. The short and long term movements of water are shown for days, years, centuries, and millennia.

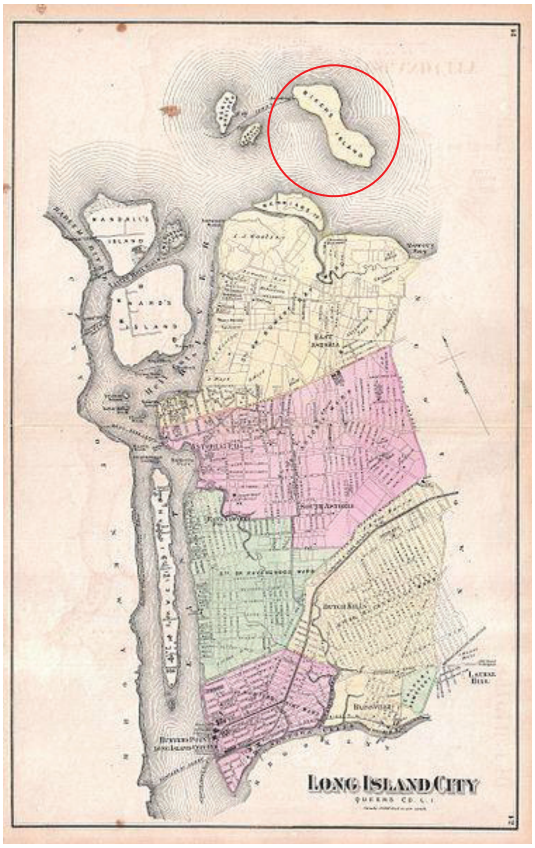

Figure 6.23. A map of Long Island, New York, showing Rikers Island to the northeast of Manhattan, the major land mass opposite Long Island.

causality as a result of waste, and made its proper disposal an important aspect of his city reform plan. More than 2 000 workers were organized to make up New York's street cleaning force, cleaning 675 kilometres of street every day. In addition to the cleaning force, Waring implemented "source separation", which involved the division of trash into discrete categories: organic waste, ashes, and rubbish. This lead to the development of various other methods of disposing of refuse, and reduced the net accumulation of waste in the city. Waring commissioned the construction of a landfill around the shoal of Rikers Island, in the East River (see Figure 6.23). Here, ashes and material swept off the streets were deposited. This location was not ideal due to the possibility of leachate seeping into the river system, which is suspected to be an over thought. To further detract from the amount of refuse accumulating in the city, Waring also launched an initiative to experiment with the use of ashes and organic waste in the production of fireproof bricks (Melosi, 2005).

Waring was a vital member of the refuse revolution. He died of yellow fever, the very disease that was killing thousands in the country, and the one he was attempting to control the spread of through his sanitation efforts. Building on the thoughts of Benjamin Franklin, Colonel George E. Waring Jr. was the first to implement large-scale waste removal and city cleansing efforts. As a result, seepage from pollution in the streets to the groundwater system was greatly decreased (Melosi, 2005).

Improvement to Disposal Methods

With developments in subsurface geology and hydrology, groundwater contamination has been significantly decreased due to improved landfill design and better siting (Patrick, 1987). In 1929, an American Public Health Association committee recommended that landfills should not be located on river banks, as was the common previous practice. In some areas, regulations were developed that required local groundwater characteristics to be researched before allowing a landfill to be sited there (Melosi, 2000). By realizing the implications of subsurface geology on the movement of contaminants from landfills, and regulating landfill location, finally garbage could be contained and groundwater protected.

Improving Landfills Using Geomaterials

As has been discussed, garbage contributes to groundwater contamination, but this can be mitigated by improved landfill design. The sanitary landfill was the first major improvement in design. This method alternates thin layers of garbage with other material such as ashes or soil, to reduce the amount of garbage undergoing decomposition in each layer (Melosi, 2000). Methods were also developed to collect leachate, and prevent it from entering the surrounding rock to contaminate groundwater (Neal and Schubel, 1987). However there was room for improvement (Melosi, 2000).

A major problem with all landfills is the production of methane and leachate. For the problem of leachate production, there are many strategies to reduce the chance of leakage and resulting contamination. One of these is that the actual location of the landfill must be in an appropriate hydrogeological location. The next factor involves the design of the landfill, including liners and leachate drains (Neal and Schubel, 1987). These often use geomaterials, which are any material of geologic origin. A subset of these are geosynthetic materials including geomembranes, which are any synthetic or natural materials used in contact with geologic material in a civil engineering application such as landfill liners (Jones and Dixon, 1998). Geomembranes must be very impermeable, because they are used to prevent the escape of leachate. They must also be durable to resist physical deformation, and stable to avoid chemical alteration (Westlake, 1995). Geomembranes are designed to absorb contaminants, but not allow them to pass through. One natural geomaterial used in waste management is clay, which is very effective within specific ranges of moisture content and compaction (Oweis and Khera, 1990). Natural geomembranes have a high level of impermeability, and are resistant to chemical and physical attack (Westlake, 1995). A class of synthetic geomembranes is flexible membrane liners, made using medium and high-density polyethylene (Westlake, 1995). These liners can include features such as thermoplastics, which become soft when heated to assist with moulding (Oweis and Khera, 1990). Flexible membrane liners are less permeable than natural geomembranes, but are thinner and more prone to physical deformation such as tearing. These two varieties of liners complement each other, so a double liner system is ideal and can diminish leakage by two or more orders of magnitude (Fluet, Badu-Tweneboah and Khatami, 1992).

All of these membranes are subject to functionality tests. The main concern is permeability, which may vary for different solvents in the different liners (Westlake, 1995). The physical strength of the liner is evaluated by testing for puncture and tear resistance (Oweis and Khera, 1990). For synthetic geomembranes, tests must be completed on the strength of the seams, as well as the material's deformation with temperature change (Westlake, 1995). Finally, the compatibility of the geomaterial with the potential contaminants in the leachate should be tested, to ensure that no adverse effects occur from this interaction (Oweis and Khera, 1990). All of the features of these liners help to contain the leachate, preventing it from leaking out and contaminating groundwater.

Smectites, layered double hydroxides, and

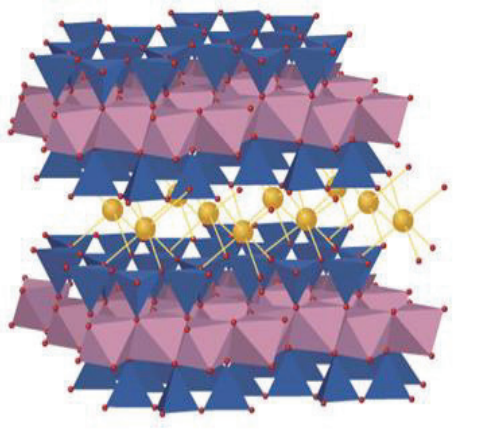

Figure 6.24. The structure of smectite, showing in blue and purple the silicate layers, and in yellow the cations.

zeolites are all geomaterials used to protect the environment from landfill contamination (Yamada et al., 2011). Firstly, smectites are layered silicates (clay minerals as seen in Figure 6.24) that can perform cation-exchanges (Yamada et al., 2011). Smectite's high cation-exchange capability allows it to remove many of the contaminants in the leachate as it slowly passes through the clay (Musso, 2010). Since there are many metals used both in daily life and industrial processes, removing these from any escaping leachate is a necessary function for a liner (Yamada et al., 2011). Another class of geomaterials are layered double hydroxides, which are anionic clays. They are composed of positively charged layers and negatively charge interlayers which have exchangeable anions (Yamada et al., 2011). They are capable of removal and degradation of anionic contaminants, including ones that are stable and difficult to remove such as phenol. Anionic clays may also be able to remove phosphates from water (Yamada et al., 2011). These features make them an attractive choice to incorporate into landfill liners. Finally, zeolites have applications for environmental protection through landfill liners. They have high cation-exchange ability similar to smectites, but are also able to remove harmful molecules such as ammonium and formaldehyde. These molecules are absorbed into the pores of zeolites, and therefore removed from the leachate (Yamada et al., 2011).

With all of these new and still developing technologies, leachate is prevented from entering the environment. This protects the integrity of groundwater, which is a vital resource for so many people.

Figure 6.25. Sketch Drawing of Victor Moritz Goldschmidt at the age of 15

Goldschmidt and the Birth of Geochemistry

For centuries, science favored a certain type of disciplinary focus, where the common researcher and scholar focused on one scientific discipline. However, the truly great scientists often were the ones that acknowledged the relationships between different scientific disciplines and used them to their advantage. Certain subjects like chemistry and biology are an obvious match, and have been researched together for hundreds of years, while others are more subtle. It was not until the late 19th and early 20th century that scientists began to look at the application of chemistry to earth science. One scientist who was particularly influential on the marriage of these scientific disciplines was Swiss-born Victor Moritz Goldschmidt (1888–1947), who is now universally known as the founder of modern geochemistry (see Figure 6.25). His life was highly influenced by politics, leading him to explore a wide spectrum of scientific fields, but his passion predominantly laid in studying elements and their genesis (Kauffman, 1997).

Victor Moritz Goldschmidt was born on January 27th, 1888 in Zurich, Switzerland to a scholarly family (Kauffman, 1997). His father was a physical chemist who was highly influential in Goldschmidt's life (Tilley, 2013). In many ways, he followed in his father's footsteps and developed an undeniable fixation for research, mineralogy, geological science, and academia. In 1904, during his summer vacation, Goldschmidt studied fine quartz crystals that displayed strong pyroluminescence (emission of light upon heating), provoking him to undergo research in an attempt to explain a possible relation between pyroluminescence and triboluminescene (emission of light, induced by friction), and phosphorescence (emission of light after removal from source) and pyroluminescence (Kauffman, 1997). In 1905, he enrolled at the University of Christiania (renamed Oslo in 1925) in Norway) and during this time, famous Norwegian petrologist and mineralogist Waldemar Christofer Brøgger (1851–1940) presented his studies on the quartz crystals to the Christiania Academy of Science (Kauffman, 1997). In 1906, at age 18, he published his first paper in the academy's journal (Tilley, 2013). He spent summers and fall semesters as a field mapping assistant for the Geological Survey of Norway or studying optical mineralogical techniques with mineralogist and petrologist Friedich Becke (1855–1931) (Kauffman, 1997). From 1907 to 1916, the majority of his work focused on contact metamorphic rocks and the factors that govern mineral associations, that later earned him his doctorate in 1911. Specifically, he examined hornfels in the Oslo region that are the resultant rocks from thermal metamorphism, a process that occurred when the Permian plutonic igneous masses came in contact with Paleozoic sediments (Weintraub and Shamoon, 1991). He later redirected his focus to the possibility that heat and stress could be a driving force behind the formation of crystalline schist (Tilley, 2013). His research involved tracing 500 kilometres of sedimentary successions through intermediate stages into crystalline metamorphic schist through the Great Caledonian Geosyncline in Southern Norway. These observations led him to formulate his own mineralogical rule known as the Goldschmidt Mineralogic Phase Rule, which is an ingenious application of the Gibbs Phase Rule to systems of rocks (Gooch, 2013). Goldschmidt's mineralogical phase rule states that under stable equilibrium (constant pressure and temperature), the number of components is equal to the number of phases that can exist (Speidel, 2013). Despite spending extensive time in the field, Goldschmidt still remained a prominent member of academia and by 1914 at 26 years of age; he was appointed professor and director of the University of Christiania's Mineralogical Institute (Kauffman, 1997).

Up till this point, Goldschmidt's research was driven by his personal interest, but due to political pressures of the time, Goldschmidt soon found himself conducting research that pertained more to the interest of the nation. For example, in 1917 during World War 1, when Norway was isolated from resources by German submarines, the government established the Governmental Commission for Raw Materials (Kauffman, 1997). Goldschmidt was appointed as the Chairman as well as the Director of the State Raw Materials Laboratory (Kauffman, 1997; Tilley, 2013). This position required him to conduct detailed research on the country's mineral resources (Kauffman, 1997; Eckert, 2012). This position also led to many discoveries involving the industrial use of mineral resources such as the separation of apatite from carbontite rocks for fertilizer use (see Figure 6.26) (Wedepohl, 1996). This was important because apatite is a phosphate mineral and is an excellent source of phosphorus, which is one of the limiting macronutrients necessary for plant growth and function. He also developed the use of dunite rocks as a refractory material. Refractory materials are substances that retain strength at high temperatures, and are commonly used for lining furnaces, incinerators, and reactors. These two examples highlight the importance of geochemistry to the industrial sector, making it no surprise that even after the war, Victor continued researching the utilization of raw minerals (Tilley, 2013).

Goldschmidt set out to make sense of these concepts by taking "…the viewpoint of atomic physics and atomic chemistry to find out the relationships between the geochemical distribution of the various elements and the measurable properties of their atoms and ions" (Goldschmidt). Although this interdisciplinary approach was revolutionary in itself, it was made possible by methods developed by Max von Laue (1879–1960), William Henry Bragg (1862–1942), and his son Sir William Lawrence Bragg (1890–1971) (Eckert, 2012; Bragg, 1921). In 1912, von Laue sent x-ray beams towards a crystal and observed a diffraction pattern (Wedepohl, 1996; Eckert, 2012). Max von Laue hypothesized that the atoms in a crystal could absorb x-rays, and then the emitted photons could be diffracted between atoms, similar to visible light through a grating (von Laue, 1915). One year later, the Braggs discovered a method that used x-ray diffraction to calculate the chemical structures of simple ionic crystal (Wedepohl, 1996). This gave rise to new techniques such as x-ray crystallography that facilitated Goldschmidt's future work (Manten, 1966).

Figure 6.26. Carbonatite from Jacupiranga Estado de São Paulo, Brazil, with the presence of magnetite, calcite and olivine

From 1923 to 1929, Goldschmidt and a group of researchers used some of these novel x-ray techniques to analyse a variety of chemical compounds (Tilley, 2013). However, due to his limited knowledge and available apparatus, he could not analyse complex minerals such as silicates (Weintraub and Shamoon, 1991). As a result, he examined simple structures that exhibited linear geometry, such as rock salt, cesium chloride, rutile, corundum, and calcium fluorides. Within two years, Goldschmidt and his lab analysed the structures of 200 chemical compounds, including 75 different elements (Tilley, 2013).

By 1925, Goldschmidt presented the first table of empirical atomic radii, which was complementary to values obtained later by Linus Carl Pauling (1901–1994), who derived values using quantum mechanics (Kauffman, 1997; Weintraub and Shamoon, 1991). While doing this, Goldschmidt noticed trends within the table of atomic radii, and defined a set of rules to address these relationships (Kauffman, 1997). The first rule stated that elements in the same periodic table group increase in ionic radii as the atomic numbers increase (see Figure 6.27) (Goldschmidt, 1929). Another rule stated that for positive ions of the same structure, the radii would decrease if the charge was increased (Ringwood, 1955). The last general rule stated that if elements were capable of forming ions of multiple charges, the highest positively charged ion would have the smallest radius.

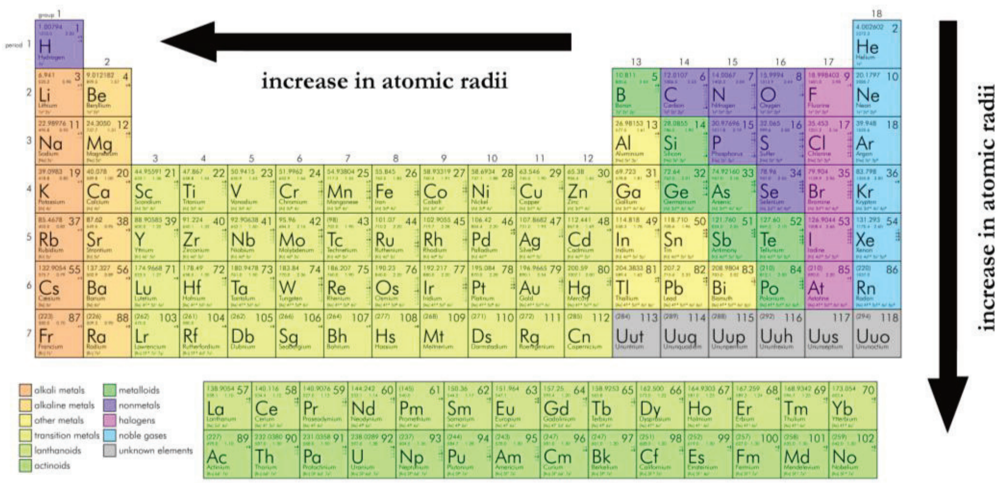

Figure 6.28. An illustrative example of the effects of radius ratio on stability. The blue spheres represent anions and the red spheres represent cations

Furthermore, he noticed a relationship between ionic size and changes to the overall structure (Weintraub and Shamoon, 1991). To theorize this relationship properly, he assumed that ions were spherical and were of fixed radii (Kauffman, 1997). From this, he calculated the stable arrangements of cations and anions, taking into account their geometry (see Figure 6.28) (Kauffman,

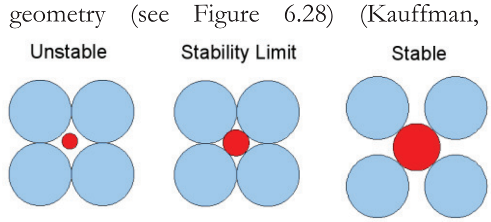

Figure 6.29. Relationship between radius ratio and the specific arrangement of anions around cations.

Figure 6.27. Trends in atomic radii across periods and groups of the periodic table

1997). He noticed a transition from various crystal types when the radius of an atom or its constituent ions underwent alterations (Weintraub and Shamoon, 1991). He determined that it was ultimately the radius ratio (r_{cation}/ r_{anion}) that determined the structure as seen in Figure 6.29. (Goldschmidt, 1929; Weintraub and Shamoon, 1991). From this observation, he formulated the first general laws of chemistry that related the structure of a crystal to its numerical proportions and the ratio of radii.

These crystal structures were also important because they served as the basis for his laws of geochemical distribution of elements (Kauffman, 1997). He hypothesized that size is the primary factor underlying atom and ion selectivity in the crystalline phases of igneous and metamorphic rocks, rather than mass. This meant that during gradual crystallization, atoms or ions that are not the ideal size for integration into the crystal lattice would become concentrated in a solid phase. He then went on to apply his knowledge of crystal chemistry to the division of chemical elements between systems of co-existing liquid phases (Tilley, 2013). Specifically, Goldschmidt hypothesized that the earth's interior was comprised of a three-phase system, with a silicate outer shell, a metal core, and an intermediate sulphide-oxide shell (Manten, 1966). In addition, Goldschmidt subdivided common elements into groups that included siderophiles, chalcophiles, and lithophiles; which are characteristic of metallic iron, sulphide, or silicate melt respectively

Radius Ratio	Arrangement of anions around cation
0.15-0.22	Corners of an equilateral triangle
0.22-0.41	Corners of a tetrahedron
0.41-0.73	Corners of an octahedron
0.73-1	Corners of a cube
>1	Closest packing

(Weintraub and Shamoon, 1991). He later added two more groups to named biophile (involving living organisms) and atmophiles (gas phase of the atmosphere) to his classification.

By the 1920s, Goldschmidt was a highly acclaimed member of the scientific community and was offered professorships from countless European universities (Kauffman, 1997). Despite his genius, Goldschmidt's life involved many cultural struggles, particularly anti-semitism. For example in 1924, Paul Heinrich von Groth (1843–1927) retired from the University of Munich and requested Goldschmidt as his successor. The request was rejected upon the grounds that Goldschmidt was of Jewish descent. This outraged many members of academia, leading Richard Martin Willstätter (1872–1942), the 1915 Nobel Prize winner and Jewish professor at the University of Munich to resign (Kauffman, 1997). Regardless, in 1929 Goldschmidt accepted a position at the University of Göttingen in Germany, as a Professor in the Faculty of Natural Sciences and Head of the new Mineralogical Institute (TGS, 2007). There, Goldschmidt primarily worked on research involving trace elements, which was later developed into the Goldschmidt Rules. The first rule stated that if one ion is to replace the other in a crystal structure their ionic radii must not vary more than 15% (Ringwood, 1955). The second rule stated that given any two identically charged ions in a lattice site, the crystal structure would preferentially integrate the ion with smaller radii into the crystal lattice over the ion with larger radii. The third rule stated that given any two-same radii ions in a lattice site, the crystal structure would preferentially integrate the ion with a higher charge. Unfortunately, in 1935 the ongoing rise of the Nazi regime forced Goldschmidt to resign from his position and flee back to Oslo (Kauffman, 1997). He was unable to escape the ever-growing power of the Nazi regime and in April of 1940, Germany invaded Norway (Tilley, 2013). Goldschmidt knew his future looked grim and started carrying a cyanide pill around incase he needed to commit suicide (Kauffman, 1997). When asked by the Nazi-controlled Ministry of Education to fill out "ancestry" questionnaires, Goldschmidt declared he was of full Jewish descent and was arrested on October of 1942 (Tilley, 2013). He was later temporarily released due to health-related issues and with the help of Norwegian police; he was relocated to neutral Sweden.

Although Goldschmidt was safe in Sweden, he knew that the Nazis had to be stopped and was flown into Britain by the Secret Intelligence Service, where he passed on information about the technical developments in Norway (TGS, 2007). He later became a member of the British Agricultural Research Council, devoting the majority of his time to research involving trace elements and utilizing geochemistry to prevent silicosis and skin cancer in foundry workers (Ringwood, 1955). In 1944, he had a severe heart attack and was hospitalized, staying in a nursing home for an extended period of time (Kauffman, 1997). In May of 1945, when Norway was freed from the Nazi regime, Goldschmidt knew it was once again safe to return to Oslo. Sadly, he was hospitalized before he could resume his anticipated work. Nearing the end of his life, he attempted to compile his life's work, but was unable to complete it due to a sudden cerebral hemorrhage (Kauffman, 1997).

Without ideas change cannot occur, progress is stalled, and the world remains motionless. Fortunately, many humans have voiced innovative ideas that have shaped our understanding of the world. Before Goldschmidt, the scientific community was mainly comprised of specialists, knowledgeable in one specific field. Victor Moritz Goldschmidt did not allow tradition or popular convention to restrict his creativity, instead he was driven by a burning curiosity to define and explore the unknown relationships across various disciplines. He did not confine himself to one particular field; rather he integrated a wide variety of scientific disciplines such as crystal chemistry, metamorphism, geology, and ultimately founded geochemistry. Although his life was limited by time, his discoveries and his interdisciplinary approach to science are timeless. He will continue to inspire future generations and his discoveries will undoubtedly help others discover new laws and principles that underlie the geological processes that occur on Earth.

Applications of Geochemistry

Victor Goldschmidt revolutionized the field of geochemistry, taking it from "a somewhat incoherent collection of factual data to a philosophical science based on the concept of the geochemical cycle" (Swaine, 1988). He widened the scientific understanding of geological processes through his application of physics and chemistry. Today, geochemistry is a massive field with a vast range of modern applications, such as the distribution and tracing of fuel and toxins through geologic structures.

The modern world is incredibly dependent on non-renewable energy, and all of these forms of energy must be located and harvested. Although these fuels are generally efficient, the supplies of fuel are not infinite, and as time progresses they become harder and harder to find. In addition, upon locating the limited number of fuel sources, they can be very difficult and expensive to excavate. As a result, the use of geochemical techniques, as a tool for predicting the location of large deposits of hydrocarbons is a topic of grave economic importance (Durand, 2003).

Figure 6.30. The use of hydrocarbons and other non-renewable resources are a large source of anthropogenic trace elements.

Once a potential site has been determined, analogues are often used to inexpensively determine if excavation is worthwhile given the associated costs. The vast majority of hydrocarbons are formed in aqueous environments when the remains of living organisms rapidly accumulate on the seafloor and are deposited in sediments (Okunova et al., 2010). The carbohydrates and proteins of the buried organic material are degraded, forming an insoluble kerogen substance.

When these kerogens are subjected to extreme heat for prolonged periods of times the kerogens undergo a conversion into hydrocarbons through a cracking process (Okunova et al., 2010). However, the deposited organic material must be subjected to an anaerobic environment, as oxygen can be extremely detrimental to the process. This is because oxygen allows bacteria to break down the organic material into unfavorable products. The presence of oxygen, favors the formation of acidic compounds over hydrocarbons and oxidizes hydrocarbons that do manage to form (Okunova et al., 2010). Other environmental conditions that influence the formation of hydrocarbons are the levels of heat and pressure. For example, when there is a high level of heat and pressure, there will be a higher ratio of lighter hydrocarbons formed. One of the most isolated light hydrocarbons is methane, that under high levels of heat and pressure forms thermogenic methane gas (Ni, 2012). In addition, subterrestrial anaerobic bacteria can produce methane gas, which is known as biogenic gas. The distinction is important to fuel companies, as each type of gas has specific advantages and disadvantages. Luckily, geochemists can tell the origin of a specific gas from its isotopic signature (Ni, 2012). Once formed hydrocarbons can then move through porous rocks such as sandstone, but cannot penetrate tighter packed rock types such as shale. As such hydrocarbons can move large distances and can travel hundreds of kilometres from their source (Durand, 2003).

Similar to Goldschmidt's interests, geochemists can look at the type of rocks that best coincide with the conditions required for hydrocarbon formation. For example, it is known that methane is commonly formed in environments that have experienced 150°C or over. This can help scientist determine possible locations for hydrocarbon formation, such as around plate boundaries and hot plumes (Okunova et al., 2010). Although fuels are an essential component of the life of a modern citizen, their usage can bring about many highly toxic by-products, often referred to as anthropogenic trace elements (Swaine, 1998)(see Figure 6.30). Over the last century, the emission of toxic byproducts has become a highly relevant problem, where more people are becoming aware of the negative environmental and health effects waste and its movement through geologic materials can have. This has led countless scientists around the world to follow in Goldschmidt's footsteps, by systematically mapping and tracking the movement of elements and compounds through the environment. There is also an increasing interest in the classification of elements and their corresponding concentrations (Swaine, 1998). This is because the level of toxicity is highly influenced by the identity of the element and its relative concentration. For example, certain elements such as mercury, lead, and arsenic, although naturally found at low concentrations can still be dangerous. Many of these toxic elements form through geologic processes, but anthropogenic activities can produce large quantities of these elements (Swaine, 1998). For example, the mines used for the excavation of coal have a large potential for producing anthropogenic trace elements, many of which are highly toxic. In addition, the weathering of pyrite in mines can lead to a number of dangerous effects, such as the lowering of pH, and leaching of arsenic and other trace elements into the surrounding soil. These trace elements can then be absorbed by organic material, or contaminate ground water (Swaine, 1998). In specific conditions found by Goldschmidt they can even be crystallized into the surrounding rocks. For example a amethyst is a type of quartz that has had certain silicates replaced by iron as shown in Figure 6.31 (Balitsky et al., 2000).

Although trace elements can be highly abundant in rocks, they can also exist in the air, water, rocks or soil. If trace elements are found in solid structures such as coal, the burning of such compounds can release trace elements into the atmosphere. Every element possesses unique properties, allowing it to undergo a unique movement through the environment at varying concentrations (Plant et al, 2001). The pH and moisture levels of soil also hold particular importance to the mobility of elements. However, the effect is not uniform due to the different chemical properties of toxic elements. For example, arsenic is an anion and will move more easily through a high pH environment, while mercury and lead are cations that will move more slowly. The reverse is also true for both anions and cations in low pH environments (Plant et al., 2001). Climate regions also play a role in the motility of trace elements, with arid environments preferentially favoring cation movement. Therefore, although understanding the origins of trace elements is an important part of effectively monitoring their levels, it is also important to have a firm understanding of how these trace elements are able to move within their environment (Plant et al., 2001).

Understanding the production and movement of trace elements has had a large impact on numerous economic sectors, affecting fuel and trace element distribution. While the locations of mines are fixed based on the availability of resources, many environmental regulations have been put in place, enforcing practices on site (Swaine, 1998). However, abandoned mines have a high potential for weathering, leading to various negative environmental impacts. As a result, strict rules are now in place, whereby companies can only abandon sites upon completion of certain environmental specifications. This often impacts the location of waste management sites, which must take into account the movement of the trace elements in the specific environment (Swaine, 1998). As our understanding of the world around us continuously evolves, so must our views and practices. By following in the steps of Victor Goldschmidt, modern day geochemists can properly meet the needs of an ever-growing population, while also qualitatively studying geologic problems important to the environment and economy.

Figure 6.31. The deep colouration of amethyst is a result of the crystallization of trace iron followed by radiation. The difference in colours depicts different crystallization conditions of iron.

Terraced rice fields in the Ailao mountains, Yuanyang County, China. Interactions between natural processes and human civilizations have produced the abstract pattern visible from the air.

Conclusion

The Earth is an extraordinarily intricate system. Although it is not entirely understood, every region of the planet is riddled with hints to its complex past. Centuries of deciphering these signs and clues have lent both understanding and wonder of the planet we call home. Though our understanding of the world's formation, processes and future is incomplete, what society has gained in the pursuit of understanding is invaluable. Time is an artist, a sculptor forever occupied with the canvas of Earth. Time has raised mountains, carved valleys, created oceans, and though the work is ongoing, crafted a planet with unique geology and a rich history. It is this history and progression of ideas that has been explored here. It has been our intention to highlight not only the processes that shape the Earth, but also those which have shaped the progression of scientific thought.

Like the forces that mold the surface of the Earth, the process of scientific investigation will continue on for the foreseeable future. Debates, rivalries and collaborations between great minds have driven scientific discovery throughout the ages, and are still propelling our understanding of the Earth. The concepts that we accept as truth today may be disproved tomorrow.

History of the Earth IV is a testimony to the multifaceted nature of geology, which can be viewed through any number of vantage points, ranging from the origins of the Earth and evolution of life to modern civilizations and the development of the technology that facilitates our scientific expedition. In the words of "the founder of paleontology" Nicolas Steno, "Fair is what we see, fairer what we have perceived, fairest is what is still in veil."

References

Ade, P.A.R, et al., 2013. *Planck 2013 results. I. Overview of products and scientific results.* [online] Available at: <http://arxiv.org/abs/1303.5062>.

Åkesson, P., 1999. *Side Scan Sonar*. [online] Available at: <http://www.abc.se/~pa/mar/sidescan.htm>.

Albany University, 2013. *The Ionosphere*. [online] Available at: <http://www.albany.edu/faculty/rgk/atm101/ionosph.htm>.

Allen, R.C., 2009. *The British industrial revolution in global perspective*. Cambridge: Cambridge University Press. pp. 135-181.

Allison, P.A. and Bottjer, D.J., 2011. *Taphonomy: Process and Bias through Time*. New York: Springer Science and Business Media.

Allison, P.A. and Briggs, D.E.G., 1991. *The Processes of Fossilization*. London: Belhaven. pp. 120-140.

American Chemical Society, 2013. *The Chemical Revolution of Antoine-Laurent Lavoisier: International Historic Chemical Landmark*. [online] Available at: <http://www.acs.org/content/acs/en/education/whatischemistry/landmarks/lavoisier.html>.

American Museum of Natural History, 2000. *Earth: Inside and Out*. [online] Available at: <http://www.amnh.org/education/resources/rfl/web/essaybooks/earth/p_lehmann.html>.

Andrews, J.H., 2009. *Maps in Those Days: Cartographic Methods Before 1850*. Dublin: Four Courts Press.

Andrews-Hanna, J.C. and Lewis, K.W., 2011. Early Mars hydrology: 2. Hydrological evolution in the Noachian and Hesperian epochs. *Journal of Geophysical Research*, 116(E2), p. E02007.

Andrews-Hanna, J.C., Zuber, M., Arvidson, R.E. and Wiseman, S.M., 2009. Early Mars hydrology: Meridiani playa deposits and the sedimentary record of Arabia Terra. *Journal of Geophysical Research,* 115(E6).

Anon, n.d. *MT. Pelée Eruption (1902).* [online] Available at: <http://www.geology.sdsu.edu/how_volcanoes_work/Pelee.html>

Appel, T., 1987. *The Cuvier-Geoffroy Debate: French Biology in the Decades Before Darwin*. New York: Oxford University Press.

Apple, R., 2005. *Thomas A. Jaggar, Jr., and the Hawaiian Volcano Observatory*. U.S. Geological Survey. [online] Available at: <http://hvo.wr.usgs.gov/observatory/hvo_history.html>.

Appleyard, R., 1930. *Pioneers of Electrical Communication*. London: Macmillian.

Aristotle, 350 BCE. *Meteorologica.* Translated from Latin by H.D.P. Lee. Harvard University Press.

Avise, J.C., Arnold, J., Ball, M.R., Bermingham, E., Lamb, T., Neigel, J.E., Reeb, C.A. and Saunders, N.C., 1987. Intraspecific Phylogeography: The mitochondrial DNA bridge between population genetics and systematics. *Annual Review of Ecology and Systematics*, 18, pp. 489–522.

Bagrow, L., 1964. *History of Cartography*. 36th ed. London: Watts & Co. pp.31–38.

Baker, V.R., 1998. Catastrophism and uniformitarianism: logical roots and current relevance in geology. *Geological Society, London, Special Publications*, 143(1), pp. 171–182.

Bakker, R. T., 1986. *The Dinosaur Heresies*. New York: William Morrow and Company Inc.

Bakker, R.T., 1975. Dinosaur renaissance. *Scientific American*, 232(4), pp. 58–79.

Balitsky, V., Machina, I., Mar'in, A., Shigley, J., Rossman, G. and Lu, T., 2000. Industrial growth, morphology and some properties of Bi-colored amethyst–citrine quartz (ametrine). *Journal of Crystal Growth*, 212(1), pp. 255–260.

Barrow, I.J., 2003. *Making History, Drawing Territory: British Mapping in India, c. 1756-1905.* 1st ed. New York: Oxford University Press. pp. 1–28.

Bascom, W., 1963. *A Hole in the Bottom of the Sea: The Story of the Mohole Project*. Garden City: Doubleday and Company.

Baxter, J., 1989. Children's understanding of familiar astronomical events. *International Journal of Science Education*, 11(5), pp. 502–513.

Beck, H.P., 1996. *Folklore and the Sea.* Mystic Seaport Museum Inc. p. 545.

Bede, 725. *The Reckoning of Time*. Translated from Latin by Faith Wallis. Liverpool: Liverpool University press.

Bell, M.S., 2010. *Lavoisier in the Year One: The Birth of a New Science in an Age of Revolution (Great Discoveries)*. 1st ed. New York, NY: W. W. Norton & Company. pp. 1–25.

Belrose, J.S., 1995. *Fessenden and Marconi: Their Differing Technologies and Transatlantic Experiments During the First Decade of this Century*. [online] Available at: <http://www.ieee.ca/millennium/radio/radio_differences.html>.

Bender, M., Sowers, T. and Brook, E., 1997. Gases in ice cores. *Proceedings of the National Academy of Sciences*, 94(16), pp. 8343–8349.
Ben-Menahem, A., 1995. A concise history of mainstream seismology: Origins, legacy, and perspectives. *Bulletin of the Seismological Society of America,* 85(4), pp. 1202–1225.
Bennett, H.A., Hogg, L.A. and Lockyer, A. A.H., 1967. The land map and air chart at 1:250,000.*The Cartographic Journal,* 4(2), pp. 89-96.
Berger, A., Loutre, M.F. and Mélice, J.L., 2006. Equatorial insolation: From precession harmonics to eccentricity frequencies. *Climate of the Past*, 2(4), pp. 519–533.
Berggren, W., 1998. The Cenozoic Era: Lyellian (chrono)stratigraphy and nomenclatural reform at the millennium. *Geological Society, London, Special Publications,* 143, pp. 111–132.
Berggren, W.A., Kent, D. V., Swisher, C. and Aubry, M., 1995. A revised Cenozoic geochronology and chronostratigraphy. *Geochronology, Time Scales, and Global Stratigraphic Correlation,* p. 1-84.
Bernard, C.W., 2013. *Tesla: Inventor of the Electrical Age*. New Jersey: Princeton University Press.
Berthault, G., 2002. Analysis of main principles of stratigraphy on the basis of experimental data 1. *Lithology and Mineral Resources,* 37(5), pp. 442–446.
Bertman, S., 2005. *Handbook to Life in Ancient Mesopotamia.* New York: Oxford University Press. pp. 184-211.
Bilkadi, Z., 1995. The oil weapons. *Saudi Aramco World,* 46(1), pp. 20-27.
Binney, R., 2006. *Nature's Ways: Lore, Legend, Fact and Fiction*. Great Britain: David & Charles.
Bohn, J., 1863. *The Reader, Volume 1*. [e-book] London: William Stevens Printer. Available through: <http://books.google.com/books?id=fX1NAAAAYAAJ&pgis=1>
Bolt, A., Horn, W., Macdonald, G. and Scott, R., 1975. *Geologic Hazards.* New York: Springer-Verlag. p. 330.
Bolt, B., 1993. *Inge Lehmann*. University of California, Berkeley. [online] Available at: <http://www.physics.ucla.edu/~cwp/articles/bolt.html>.
Borucki, W.J., 2010. *Kepler History: Brief History of the Kepler Mission.* NASA: Ames Research Center. [online] Available at: <http://kepler.nasa.gov/Mission/QuickGuide/history/>.
Bower, F. O., 1926. *The Ferns (Filicales): Volume 2, The Eusporangiatae and Other Relatively Primitive Ferns: Treated Comparatively with a View to their Natural Classification*. Cambridge: Cambridge University Press.
Bradley, R. and Jones, P., 1992. *Climate Since A.D. 1500*. London: Routledge.
Bragg, W., 1921. The structure of organic crystals. *Proceedings of the Physical Society of London,* 34(1), pp. 33–50.
Branson, O., Redfern, S., Tyliszczak, T., Sadekov, A., Langer, G., Kimoto, K. and Elderfield, H., 2013. The coordination of Mg in foraminiferal calcite. *Earth and Planetary Science Letters*, 383, pp. 134-141.
Brennan, S.T., Lowenstein, T.K. and Horita, J., 2004. Seawater chemistry and the advent of biocalcification. *Geology*, 32(6), pp. 473–476.
Bricker, H.M., Bricker, V.R., Aveni, A.F., Closs, M.P., Edmonson, S., Lounsbury, F.G. and Taladoire, E., 1983. Classic Maya Prediction of Solar Eclipses. *Current Anthropology,* 24(1), pp. 1–23.
Briggs, D.E.G. and Kear, A.J., 1993. Decay and preservation of polychaetes: Taphonomic thresholds in soft-bodied organisms. *Paleobiology*, 19, pp. 107-135.
Briggs, D.E.G., 2001. *Palaeobiology 2*. Oxford: Blackwell. pp. 328-332.
Briggs, D.E.G., 2003. The role of decay and mineralization in the preservation of soft-bodied fossils. *Annual Review of Earth and Planetary Sciences*, 31, pp. 275-301.
Broad, W. J., 2007. Long-Term Global Forecast? Fewer Continents. *The New York Times,* [online] 9 September. Available at: <http://www.nytimes.com/2007/01/09/science/09geo.html?pagewanted=all&_r=0>.
Brutsaert, W., 1982. *Evaporation Into The Atmosphere*. Boston: D. Reidel Publishing Company.
Bryson, B., 2004. *A Short History of Nearly Everything.* New York: Random House Inc. pp. 149-161.
Bryson, R.A., 1974. A perspective on climatic change. *Science*, 184(4138), p. 753.
Budyko, M., 1969. The effect of solar radiation variations on the climate of the Earth. *Tellus*, XXI(5), pp. 611–619.
Budyko, M., 1990. *Oral History Transcript-Dr. Mikhail Budyko*. Interviewed by Spencer Weart [tape] Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA.
Bullen, K., 2008a. *Andrija Mohorovicic.* [online] Available at: <http://www.encyclopedia.com/topic/Andrija_Mohorovicic.aspx>.
Bullen, K., 2008b. *Emil Wiechert.* [online] Available at: <http://www.encyclopedia.com/topic/Emil_Wiechert.aspx#1-1G2:2830904638-full>.
Bullen, K.E. and Bolt, B.A., 1947. *An Introduction to the Theory of Seismology.* New York: Cambridge.
Burling, L., 1917. Was the lower Cambrian trilobite supreme? *Transactions of The Ottawa Field-Naturalists' Club*, 31, pp. 78-80.

Butterfield, N.J., Balthasar, U. and Wilson, L.A., 2007. Fossil Diagenesis in the Burgess Shale. *Palaeontology*, 50(3), pp. 537-543.

Caldeira, K. and Wickett, M.E., 2003. Oceanography: anthropogenic carbon and ocean pH. *Nature*, 425(6956), p. 365.

Camp, V., 2000. *Mt. Pelee Eruption*. [online] Available at: <http://www.geology.sdsu.edu/how_volcanoes_work/Pelee.html>

Campbell, I.H. and Allen, C.M., 2008. Formation of supercontinents linked to increases in atmospheric oxygen. *Nature Geoscience*, 1, pp. 554-559.

Campbell, L. and Garnett, W., 1884. *The Life of James Clerk Maxwell: With Selections from his Correspondence and Occasional Writings*. London: MacMillan and Co.

Canfield, D.E., Poulton, S.W. and Narbonne, G.M., 2007. Late-Neoproterozoic deep-ocean oxygenation and the rise of animal life. *Science,* 315(92), pp. 92-95.

Cassel, John, 1964. Social science theory as a source of hypotheses in epidemiological research. *American Journal of Public Health and the Nations Health*, 54(9), pp. 1482-1488.

Catchpole, J.E., 2008. *The International Space Station: Building for the Future*. Chichester: Praxis Publishing Ltd.

Chandler, M. and Sohl, L., 2000. Climate forcing and the initiation of low-latitude ice sheets during the Neoproterozoic Varanger glacial interval. *Journal of Geophysical Research*, 105, pp. 20737-207556

Chaney, A., 2011. *Iztaccihuatl*. [online] Available at: <http://www.princeton.edu/~achaney/tmve/wiki100k/docs/Iztacc%C3%ADhuatl.html>.

Chouet, B., 1996. Long-period volcano seismicity: Its source and use in eruption forecasting. *Nature: Reviews*, 380(6572), pp. 309–316.

Chouet, B., 2003. Volcano seismology. *Pure Applied Geophysics*, 160(103), pp. 739–788.

Cloud, J., 2000. Crossing the Olentangy river: The figure of the Earth and the military-industrial-academic-complex, 1947–1972. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics*, 31(3), pp. 371–404.

Cloud, P.E. and Licari, G.R., 1968. Microbiotas of the banded iron formations. *Proceedings of the National Academy of Sciences*, 61(3), pp. 779-786.

Cohn, N., 1996. *Noah's flood: the Genesis story in Western thought*. New Haven-London: Yale University Press. pp. 73–93.

Colligan, D., 1973. Brace yourself for another ice age. *Science Digest*, 73(2), pp. 57–61.

Collins, D., 2009. Misadventures in the burgess shale. *Nature*, 460, pp. 952-953.

Coppock, J.T. and Rhind, D.W., 1991. The history of GIS. *Geographical information systems: Principles and applications,* 1(1), pp. 21-43.

Corazza, G.C., 1998. Marconi's history. *Proceedings of the IEEE*, 86(7), pp. 1307–1311.

Cornford, F.M., 2004. *Plato's Cosmology: The Timaeus of Plato Translated with a Running Commentary*. Cambridge: Kessinger Publishing. p. 230.

Corsi, P., 1988. *The Age of Lamarck : Evolutionary Theories in France, 1790-1830*. California: University of California.

Crone, G.R., 1968. *Maps and Their Makers: An Introduction to the History of Cartography*. 4th ed. London: Hutchinson & Company Ltd.

Cropper, W.H., 2001. *Great Physicists: The Life and Times of Leading Physicists From Galileo to Hawking*. Oxford: Oxford University Press.

Crowley, T., Hyde, W. and Richard, W., 2001. CO_2 levels required for deglaciation of a "near-snowball " Earth. *Geophysical Research Letters,* 28(2), pp. 283–286.

Cullen, C., 1980. Joseph Needham on Chinese astronomy. *Past and Present*, 87(1), pp. 39–53.

Cullen, K., 2006. *Earth Science: The People Behind the Science.* New York: Facts On File.

daVinci, L., 1519. *Codex of Leicester*. London: Scala.

Dalley, S., 2000. *Myths from Mesopotamia: Creation, the Flood, Gilgamesh, and Others*. London: Oxford University Press. p. 337.

Danielson, D.R., 2001. The great Copernican cliché. *American Journal of Physics,* 69, p. 1029.

Dartnell, P., Collier, R., Buktenica, M., Jessup, S., Girdner, S. and Triezenberg, P., 2008. *Multibeam Sonar Mapping and Modeling of a Submerged Bryophyte Mat in Crater Lake, Oregon*. [online] Available at: <http://pubs.usgs.gov/ds/366/index.html>.

Darwin, C. and Mayr, E., 1964. *On the Origin of Species*. Cambridge: Harvard University Press.

Darwin, C., 1859. *On the Origin of Species*. London: John Murray.

Davis, C.J. and Johnson, C.G., 2005. Lightning-induced intensification of the ionospheric sporadic E layer. *Nature*, 435(7043), pp. 799–801.

De Villiers, S., Shen, G.T. and Nelson, B.K., 1994. The SrCa-temperature relationship in coralline aragonite: Influence of variability in (SrCa) seawater and skeletal growth parameters. *Geochimica et Cosmochimica Acta*, 58(1), pp. 197–208.

Dean, D.R., 1991. *Robert Mallet and the founding of seismology*. Annals of Science, 48(1), pp. 39–67.

Delleur, J.W., 2010. The Handbook of Groundwater Engineering. 2nd ed. Boca Raton: CRC Press. p. 1320.
Demers, M. N., 2000. *Fundamentals of Geographic Information Systems*. 2nd ed. New Mexico: John Wiley & Sons Inc.
DeSalle, R. and Tattersall, I., 2008. *Human Origins: What Bones and Genomes Tell Us About Ourselves*. 1st ed. New York: Nevraumont Publishing Company.
Devyatova, A. and Yurkevich, N., 2013. Trace elements atmospheric pollution from high temperature anthropogenic processes. *International Proceedings of Chemical, Biological, and Environmental Engineering*, 57, pp. 110–114.
Dick, H., Natland, J. and Ildefonse, B., 2006. Past and future impact of deep drilling in the oceanic crust and mantle. *Oceanography*, 19(4), pp. 72-80.
Dill, S., 2005. *Roman Society and the Circle of the Younger Pliny*. New York: Kessinger Publishing. pp. 432–500.
District of Columbia, 2006. *DC Police Crime Mapping*. [online] Available at <http://crimemap.dc.gov>.
Doorenbos, J., and Kassam, A.H., 1979. *Yield Response to Water*. Rome: FAO.
Dorman, J., Ewing, M. and Oliver, J., 1960. *Study of shear-velocity distribution in the upper mantle by mantle rayleigh waves*. 50(1), pp. 87–115.
Downie, S.R., Katz-Downie, D.S., and Watson, M.F., 2000. A phylogeny of the flowering plant family Apiaceae based on chloroplast DNA RPL16 and RPOC1 intron sequences: Towards a suprageneric classification of subfamily Apioideae. *American Journal of Botany*, 87(2), pp. 273–292.
Dunsheath, P., 1967. *Giants of Electricity*. New York: Thomas Y. Crowell Company.
Dunsworth, H.M., 2007. *Human Origins 101*. 1st ed. Westport: Greenwood Publishing Group.
Durand, B., 2003. A history of organic geochemistry. *Oil & Gas Science and Technology*, 58(2), pp. 203–231.
Dutka, J., 1993. Eratosthenes' measurement of the earth reconsidered. *Archive for History of Exact Sciences*, 46(1), pp. 55–66.
Eagle, C.T. and Sloan, J., 1998. Marie Anne Paulze Lavoisier: The mother of modern chemistry. *The Chemical Educator*, 3(5), pp. 1–18.
Eckert, M., 2012. Max von Laue and the discovery of X-ray diffraction in 1912. *Annual Physics*, 524 (5), pp. 83–85.
Eicher, D.L., 1976. *Geologic Time*. New Jersey: Prentice-Hall.
Elnashai, A.S., 2002. A very brief history of earthquake engineering with emphasis on developments in and from the British Isles. *Chaos, Solitons & Fractals*, 13(5), pp. 967–972.
Embley, B., 2012. *Seafloor Mapping*. [online] Available at: <http://oceanexplorer.noaa.gov/explorations/03fire/background/mapping/mapping.html>.
Emilio, P. and Alfaro, M., 2009. Groundwater Volume I. Oxford: EOLSS Publishers Co Ltd.
Engels, D., 1985. The length of Eratosthenes' shade. *The American Journal of Philology*, 106(3), pp. 298–311.
[EPA] Environmental Protection Agency, 2013. *Dredging and Dredged Material Management*. [online] Available at: <http://www.epa.gov/region02/water/dredge/>.
Etherington, N. ed., 2007. *Mapping Colonial Conquest: Australia and Southern Africa*. Crawley: University of Western Australia Press.
European Geosciences Union, n.d. *Awards & Medals: Beno Gutenberg*. [online] Available at: <http://www.egu.eu/awards-medals/portrait-beno-gutenberg/>.
Evans, J., 1998. *The History and Practice of Ancient Astronomy*. Oxford University Press. p. 47.
Everitt, C.W.F., 1975. *James Clerk Maxwell: Physicist and Natural Philosopher*. New York: Scribner.
Ewing, M., 1999. Mechanisms of global climate change at millennial time scales. *Geophysical Monograph Series*. 3(2).
Eyles, N. and Januszczak, N., 2004. "Zipper-rift": a tectonic model for Neoproterozoic glaciations during the breakup of Rodinia after 750 Ma. *Earth-Science Reviews,* 65(1-2), pp. 1–73.
Faraday, M., 1834. Experimental researches in electricity. Seventh series. *Philosophical Transactions of the Royal Society of London*, 124, pp. 77–122.
Felsenstein, J., 2004. *Statistical Methods in Determining Phylogeny*. Massachusetts: Sinauer Associates Inc.
Fernández-Remolar, D.C., Prieto-Ballesteros, O., Gómez-Ortíz, D., Fernández-Sampedro, M., Sarrazin, P., Gailhanou, M. and Amils, R., 2011. Río Tinto sedimentary mineral assemblages: A terrestrial perspective that suggests some formation pathways of phyllosilicates on Mars. *Icarus*, 211(1), pp. 114–138.
Ferrari, G. and Mcconnell, A., 2005. Robert Mallet and the "Great Neapolitan earthquake" of 1857. *Notes and Records of the Royal Society*, 59(1), pp. 45–64.
Ferreiro, L.D., 2011. *Measure of the Earth : The Enlightenment Expedition That Reshaped Our World*. Pennsylvania: Basic Books.
Fetter, C.W., 2004. Hydrogeology: a short history, part 2. *Ground water*, 42(6-7), pp. 949–53.
Field, J. V., 1984. A Lutheran Astrologer: Johannes Kepler. *Archive for History of Exact Sciences*, 31(3), pp. 189–272.

Finocchiaro, M.A., 2011. A Galilean approach to the Galileo affair, 1609–2009. *Science & Education*, 20(1), pp. 51–66.

Firestone, M., 2006. *Volcanologist*. Buffalo: Haights Cross Communications. pp. 31–45.

Fluet, J.E., Badu-Tweneboah, K. and Khatami, A., 1992. A review of geosynthetic liner system technology. *Waste Management & Research*, 10(1), pp. 47–65.

Foresman, T.W., 1998. *The History of Geographic Information Systems: Perspectives from the Pioneers*. New Jersey: Prentice-Hall, Inc.

Fortey, R.A., 2012. Harry Blackmore Whittington 24 March 1916-20 June 2010. *Biographical Memoirs of Fellows of the Royal Society*, 58, pp. 299-325.

Fowler, C.M.R., 2005. *The Solid Earth: An Introduction to Global Geophysics*. Cambridge: Cambridge University Press.

Frankel, C., 1996. *Volcanoes of the Solar System*. Cambridge: Cambridge University Press. pp. 7–8.

Fuller, M., 2013. *Our Beautiful Moon and its Mysterious Magnetism*. New York: Springer International Publishing. pp. 57–66.

Gabriel, M.L. and Fogel, S., 1956. *Great Experiments In Biology*. 3rd ed. Englewood Cliffs: Prentice-Hall Inc. p. 317.

Galileo, G., 1610 *Sidereus Nuncius (Starry messenger)*. Translated from Latin by Peter Barker. Oklahoma City: Byzantium Press.

Gannon, M., 2013. *One-Way Mars Colony Project Draws 200,000 Volunteers*. [online] Available at: <http://www.space.com/22758-mars-colony-volunteers-mars-one.html>.

Garland, G.D., 1979. The contributions of Carl Friedrich Gauss to geomagnetism. *Historia Mathematica*, 6(1), pp. 5–29.

Garwood, C., 2007. *Flat Earth*. New York: Thomas Dunne Books.

Gaukroger, S., 2001. *Francis Bacon and the Transformation of Early Modern Philosophy*. New York: Cambridge University Press.

Gaustad, E.S., 2006. *Benjamin Franklin*. Oxford University Press.

Gee, H., 2000. *Shaking the Tree: Readings from Nature in the History of Life*. Chicago: University of Chicago Press. p. 411.

Giblin, M., 1950. Frank Alvord Perret. *Bulletin Volcanologique*, 10(1), pp. 191–195.

Gilbert, W., 1893. *De magnete Magneticisque Corporibus, et de Magno Magnete Tellure (On the Loadstone and Magnetic Bodies, and on the Great Magnet the Earth)*. 1st ed. Translated from Latin by P. Mottelay. London: Benard Quaritch.

Glaessner, M.F., 1984. *The Dawn of Animal Life: a Biohistorical Study*. Cambridge: Cambridge University Press.

Goldschmidt, V.M., 1929. Crystal Structure and Chemical Constitution. *Physik*, 25, pp. 253–283.

Gooch, J.W., 2013. *Gibb's Phase Rule*. [online] Available at: <http://www.springerreference.com/docs/html/chapterdbid/211604.html>.

Goodman, L.E., 2006. *Avicenna*. Cornell: Cornell University Press, p. 31.

Goudsblom, J., 1992. *Fire and Civilization*. London: Allen Lane.

Gould, S.J., 1987. *Time's Arrow, Time's Cycle*. Cambridge: Harvard University Press.

Gould, S.J., 1989. *Wonderful Life*. London: Hutchinson Radius.

Graham, D.W., 2006. *Explaining the Cosmos: The Ionian Tradition of Scientific Philosophy*. New Jersey: Princeton University Press.

Grayzeck, E., 2006. *ISIS/Alouette Topside Sounder Data Restoration Project:* [online] Available at: <http://nssdc.gsfc.nasa.gov/space/isis/isis-status.html>.

Greenberg, J.L., 1995. *The Problem of the Earth's Shape from Newton to Clairaut*. Cambridge: Cambridge University Press.

Grotzinger, J., Beaty, D.W., Dromart, G., Gupta, S., Harris, M., Hurowitz, J., Kocurek, G., McLennan, S., Milliken, R., Ori, G.G. and Summer, D., 2011. The sedimentary record of Mars. *The Sedimentary Record*, 9(2), pp. 4 – 8.

Gurven, M. and Kaplan, H., 2007. Longevity among hunter-gatherers: A cross-cultural examination. *Population and Development Review*, 33, pp. 321–365.

Hagadorn, J.W., 2002. *Exceptional Fossil Preservation: A Unique View on the Evolution of Marine Life*. New York: Columbia University Press. pp. 91-116.

Hagemann, J., 1980. Facsimile recording of sonic values of the ocean bottom. *The Journal of the Acoustical Society of America*, 68(5), p. 1550.

Halacy, D.S.J., 1974. *Earthquakes: A Natural History*. New York: The Bobbs-Merrill Company Inc. pp. 9–19.

Hallam, A., 1998. *Lyell: the past is the key to the present*. London: Geological Society Special Publications, 143. pp.133–136.

Hallam, T., 2004. *Catastrophes and Lesser Calamities: The Causes of Mass Extinctions*. New York: Oxford University Press.

Hallerberg, A.E., 1973. The metric system: Past, present-future? *The Arithmetic Teacher*, 20(4247-255), pp. 247-255.
Halverson, G., Hoffman, P., Schrag, D. and Kaufman, A., 2002. A major perturbation of the carbon cycle before the Ghaub glaciation in Namibia: Prelude to snowball Earth. *Geochemistry, Geophysics, Geosystems*, 3(6), pp. 1-24.
Hanson, S., 1997. *10 Geographic Ideas that Changed the World.* New Jersey: Rutgers University Press.
Hardin, C.L., 1966. The scientific work of the reverend John Michell. *Annals of Science*, 22(1), pp. 27–47.
Harland, W., and Bidgood, D., 1959. Palaeomagnetism in some Norwegian sparagmites and the late pre-Cambrian ice age. *Nature*, 184, pp. 1860–1862.
Harland, W., 1964. Critical evidence for a great infra-Cambrian glaciation. *Geologische Rundschau*, 54, pp. 45–61.
Harley, J.B. and Woodward, D. ed., 1987. *The History of Cartography Vol. 1: Cartography in Prehistoric, Ancient, and Medieval Europe and the Mediterranean*. Chicago: The University of Chicago Press.
Harper, C.W. and Platnick, N.I., 1978. Phylogenetic and cladistic hypotheses: a debate. *Systematic Zoology*, 27, pp. 354-362.
Harris, J.R., 1974. The rise of coal technology. *Scientific American,* 233(2), pp. 92-97
Hartnett, D.W., 1992. *Dark Ages*. London: Secker & Warburg.
Hathaway, D.H., 2011. *The Solar Interior.* [online] Available at: <http://solarscience.msfc.nasa.gov/interior.shtml>.
Haug, G.H., Günther, D., Peterson, L.C., Sigman, D.M., Hughen, K. and Aeschlimann, B., 2003. Climate and the collapse of Maya civilization. *Science*, 299(5613), pp. 1731–1735.
Heidel, W., 1976. *Frame for the Ancient Greek Maps*. New York: Arno Press Inc.
Heilmann, G., 1927. *The Origin of Birds*. New York: D. Appleton & Company.
Helden, A. Van, 1986. *Measuring the Universe: Cosmic Dimensions from Aristarchus to Halley*. Chicago: University Of Chicago Press. pp. 4–5.
Heller, F. and Tungsheng, L., 1984. Magnetism of Chinese loess deposits. *Geophysical Journal of the Royal Astronomical Society*, 77(1), pp. 125–141.
Henshilwood, C.S., D'Errico, F., Yates, R., Jacobs, Z., Tribolo, C., Duller, G.A.T., Valladas, H., Mercier, N., Sealy, J.C., Watts, I. and Wintle, A.G., 2002. Emergence of modern human behaviour: Middle stone age engravings from South Africa. *Science*, 295, pp. 1278–80.
Herak, D. and Herak, M., 2010. The Kupa Valley (Croatia) earthquake of 8 October 1909 - 100 years later. *Seismological Research Letter*, 81(1), pp. 30–36.
Herman, J., 2005. *Leadership Embodied: The Secrets to Success of the Most Effective Navy and Marine Corps Leaders*. Annapolis: Naval Institute Press.
Hess, P.M.J. and Allen, P.L., 2008. Catholicism and science. ABC-CLIO Greenwood.
Hiebert, E.N., Ihde, A.J. and Schofield, R.E., 1980. *Joseph Priestley*. Cranbury: Associated University Presses. p. 117.
Hine, M.H., 2002. *Science and Mathematics in Ancient Greek Culture*. Toronto: Oxford University Press. p. 379.
Hoare, M.R., 2005. *The Quest for the True Figure of the Earth*. Aldershot, England: Ashgate Publishing Limited. pp. 1–111, 203–231.
Hoffman, P. and Schrag, D., 2002. The snowball Earth hypothesis: Testing the limits of global change. *Terra Nova,* 14(3), pp. 129–155.
Hoffman, P., Kaufman, A., Halverson, G. and Schrag, D., 1998. Neoproterozoic snowball Earth. *Science*, (281), pp. 1342–1346.
Hogan, T., 2007. *Mars Wars: The Rise and Fall of the Space Exploration Initiative*. Washington DC: National Aeronautics and Space Administration.
Holliday, T.W., 2012. Body size , body shape , and the circumscription of the genus Homo. *Current anthropology*, 53(S6), pp. S330–S345.
Holloway, R.L., 1981. Culture, symbols, and human brain evolution: A synthesis. *Dialectical anthropology*, 5, pp. 287–303.
Hounshell, D., 1985. *From the American System to Mass Production, 1800-1932: The Development of Manufacturing Technology in the United States.* Baltimore: The Johns Hopkins University Press. pp. 217-263.
Howell, B., 1990. *An Introduction to Seismological Research*. New York: Cambridge University Press.
Hsu, K.-T., 2009. The Path to Steno's synthesis on the animal origin of glossopetrae. *Geological Society of America Memoirs*, 203, pp. 93–106.
Hussmann, H., Sohl, F. and Spohn, T., 2006. Subsurface oceans and deep interiors of medium-sized outer planet satellites and large trans-neptunian objects. *Icarus*, 185(1), pp. 258–273.
Hutton, J. and Playfair, J., 1970. *System of the Earth, 1785: Theory of the Earth, 1788. Observations on Granite, 1794. Together with Playfair's Biography of Hutton.* Darien, Conn: Hafner Pub. Co.
Hutton, J., 1785. *Abstract of a Dissertation Read in the Royal Society of Edinburgh, Upon the Seventh of March, and Fourth of April, M, DCC, LXXXV, Concerning the System of the Earth, Its Duration and Stability*. Edinburgh: Unknown.

Hutton, J., 1785. *Theory of the Earth*. Edinburgh: Edinburgh University press. p. 30.
Hyde, W., Crowley, T., Baum, S. and Peltier, R., 2000. Neoproterozoic "snowball Earth" simulations with a coupled climate/ice-sheet model. *Nature,* 4005, pp. 425–429.
IERS, 2003. *IERS CONVENTIONS (2003).* IERS Technical Note No. 32. [online] Available at: <http://www.iers.org/IERS/EN/Publications/TechnicalNotes/tn32.html>.
Imbrie, J. and Imbrie, J.Z., 1980. Modelling the climatic response to orbital variations. *American Association for the Advancement of Science*. 207(4434), pp. 943–953.
Ingmanson, D.E. and Wallace, W.J., 1973. *Oceanology: An Introduction*. California: Wadsworth Publishing Company Inc. pp. 101–102.
[IODP] International Ocean Discovery Program, 2011. *Illuminating Earth's Past, Present and Future Science Plan for 2013-2023*. [online] Available at: <http://eprints.esc.cam.ac.uk/2417/>.
[IODP] International Ocean Discovery Program, 2013a. *About IODP*. [online] Available at: <http://www.iodp.org/about>.
[IODP] International Ocean Discovery Program, 2013b. *Expeditions Schedule*. [online] Available at: <http://www.iodp.org/expeditions>.
Irvine, R.J. and Smith, M.J., 2001. Geophysical exploration for epithermal gold deposits. J*ournal of Geochemical Exploration*, 36(1990), pp. 375–412.
Isaac, N., 1609. *Philosophiae Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy)*. Translated from Latin by Bernard Cohen. Oakland: University of California Press.
Isager, J., 2013. *Pliny on Art and Society: The Elder Pliny's Chapters On The History Of Art*. New York: Routledge. pp. 256–260.
Isidore, n.d. *Etymologiae*. XIII and X ed. p. 4.
Jablonski, D., 1994. Extinctions in the fossil record. *Philosophical Transactions: Biological Sciences*, 344(1307), pp. 11–17.
Jackson, J., 2005. *A World on Fire: A Heretic, an Aristocrat, and the Race to Discover Oxygen*. New York: Penguin Group, pp. 1–12.
Jackson, P.W., 2006. *The Chronologers' Quest: The Search for the Age of the Earth*. New York: Cambridge University Press.
Jaggar, T.A., 1945. Protection of harbors from lava flow. *American Journal of Science*, 234, pp. 333–351.
Jain, S. 2013. *Fundamentals of Physical Geology*. Springer Geology.
James, F.A., 2008. *The Correspondence of Michael Faraday 1855-1860*. Stevenage: Institution of Engineering and Technology.
James, S.R., 1989. Hominid use of fire in the lower and middle Pleistocene. *Current Anthropology,* 30, pp. 1-26
Jarrell, R.A., 2005. Klotz, Otto Julius. *Dictionary of Canadian Biography,* Volume XV.
Jenkins, G.S., 2003. GCM greenhouse and high-obliquity solutions for early Proterozoic glaciation and middle Proterozoic warmth. *Journal of Geophysical Research*, 108(D3), p. 4118.
Jenkins, G., 2004. A Review of Neoproterozoic climate modeling studies. *The Extreme Proterozoic: Geology, Geochemistry, and Climate Geophysical Monograph series,* 146.
Johannes, K., 1609 *Astronomia nova (New Astronomy)*. Translated from Latin by William H. Donahue. Cambridge: Cambridge University Press.
Johnson, W., 1998. Ricochet of non-spinning projectiles, mainly from water. *International Journal of Impact Engineering* 21(1-2), pp. 15–24.
Jones, D. and Dixon, N., 1998. *Geotechnical Engineering of Landfills: Proceedings of the Symposium Held at the Nottingham Trent University Department of Civil and Structural Engineering on 24 September 1998*. London: Thomas Telford, p. 149.
Jones, J. and Dhaliwal, R., 2011. Leonardo da Vinci's earth-shattering insights about geology. The Guardian, [online] 23 November. Available at: <http://www.theguardian.com/artanddesign/jonathanjonesblog/2011/nov/23/leonardo-da-vinci-earth-geology>.
Jones, P.B., Walker, G.D., Harden, R.W. and McDaniels, L.L., 1963. The development of the science of hydrology. *Texas Water Commission*, 63(3), pp. 1-38.
Kahn, C.H., 1994. *Anaximander and the Origins of Greek Cosmology*. Hackett Publishing.
Kaiser, J., 2011. *Grand Canyon: The Complete Guide: Grand Canyon National Park*. Ringgold: Destination Press.
Kak, S.C., 1998. The sun's orbit in the Brahmanas. *Indian Journal of History of Science*, 33, pp. 175–192.
Kamer, C., 2013. Earth Through Time, *Geology 103*. West Virginia University. [online] Available at: <http://pages.geo.wvu.edu/~kammer/g3/1.pdf>.
Kappelman, J., Plummer, T., Bishop, L., Duncan, A. and Appleton, S., 1997. Bovids as indicators of Plio-Pleistocene paleoenvironments in east Africa. *Journal of human evolution*, 32, pp. 229–56.
Karterakis, S., Karney, S., Singh, B. and Guergachi, A., 2007. The hydrologic cycle: A complex history with continuing pedagogical implications. *Water Science & Technology: Water Supply*, 7(1), pp. 23–31.

Kauffman, G.B., 1997. Victor Moritz Goldschmidt (1888–1947): A tribute to the founder of modern geochemistry on the fiftieth anniversary of his death. *Springer*, 2(5), pp. 1–26.
Kaufman, D.S., Schneider, D.P., McKay, N.P., Ammann, C.M., Bradley, R.S., Briffa, K.R., Miller, G.H., Otto-Bliesner, B.L., Overpeck, J.T. and Vinther, B.M., 2009. Recent warming reverses long-term arctic cooling. *Science,* 325(5945), pp. 1236–9.
Keller, S., 1998. Sections and views: visual representation in eighteenth-century earthquake studies. *The British Journal for the History of Science*, 31(1976), pp. 129–159.
Kelley, M.C. and Heelis, R.A., 1989. *The Earth's Ionosphere: Plasma Physics and electrodynamics*. Academic Press.
Kelly, K., 1973. *Garbage: The History and Future of Garbage in America.* New York: Saturday Review Press.
Kemp, M., 2006. *Leonardo da Vinci, The Marvellous Works of Nature and Man*. New York: Oxford University Press Inc. p. 429.
Kettering, C.F., 1947. Biographical memoir of Thomas Midgley Jr. *National Academy of Sciences: Biographical Memoirs,* 24(11).
Khanna, S.N. and Linderoth, S., 1991. Magnetic behavior of clusters of ferromagnetic transition metals. *Physical Review Letters*, 67(6), pp. 742–745.
Kiessling, W. and Claeys, P., 2002. *Geological and biological effects of impact events*. New York: Springer. pp. 83–100.
Kimbel, W.H., Johanson, D.C. and Rak, Y., 1997. Systematic assessment of a maxilla of homo from Hadar, Ethiopia. *American Journal of Physical Anthropology*, 103, pp. 235–262.
King, C., 2012. *An Anthology of Nineteenth-Century American Science Writing*. London: Anthem Press. pp. 219–228.
Kinoshita, M. et al., 2010. NanTroSEIZE stage 3: Plate boundary deep riser: Top hole engineering. *Integrated Ocean Drilling Program Expedition 326 Scientific Prospectus*, 326.
Kirschvink, J., 1992. *The Proterozoic Biosphere: A Multidisciplinary Study.* Cambridge University Press. pp. 51–52.
Kirschvink, J., Gaidos, E., Bertani, E., Beukes, N., Gutzmer, J., Maepa, L. and Steinberger, R., 2000. Paleoproterozoic snowball earth: Extreme climatic and geochemical global change and its biological consequences. *Proceedings of the National Academy of Sciences of the United States of America,* 97(4), p. 1400-1405.
Kjeldsen, P. et al., 2002. Present and long-term composition of MSW landfill leachate: A review. *Critical Reviews in Environmental Science and Technology*, 32(4), pp. 297–336.
Klinghoffer, A.J., 2006. *The Power of Projections: how maps reflect global politics and history*. Westport: Praeger Publishers. pp. 1–3.
Klotz, I., 2013. *Galaxy Hosts 10 Billion "Habitable" Earth-Size Worlds.* Discovery Communications. [online] Available at: <http://news.discovery.com/space/alien-life-exoplanets/galaxy-hosts-10-billion-habitable-earth-size-worlds-131104.htm>.
Knight, J. and Grab, S.W., 2013. Lightning as a geomorphic agent on mountain summits: Evidence from southern Africa. *Geomorphology,* 204, pp. 61-70.
Kolar, C.S. and Lodge, D.M., 2002. Ecological predictions and risk assessment for alien fishes in North America. *Science*, 298(5576), pp. 1233-1236.
Konhauser, K.O., Hamade, T., Raiswell, R., Ferris, G.F., Southam, G. and Canfield, D.E., 2002. Could bacteria have formed the Precambrian banded iron formations? *Geological Society of America*, 30(12), pp. 1079–1082.
Korte, M., 2011. Geomagnetic Field, Secular Variation. In H. Gupta, ed. *Encyclopedia of Solid Earth Geophysics*. Springer Netherlands, p. 394.
Kostylev, V., Todd, B., Fader, G., Courtney, R., Cameron, G. and Pickrill, R., 2001. Benthic habitat mapping on the Scotian Shelf based on multibeam bathymetry, surficial geology and sea floor photographs. *Marine Ecology Progress Series*, 219, pp. 121–137.
Kovarik, W., 1998. Henry Ford, Charles Kettering and the Fuel of the Future. *Automotive History Review,* 32, pp. 7-27.
Kovarik, W., 2005. Ethyl-leaded gasoline: How a classic occupational disease became an international public health disaster. *International Journal of Occupational and Environmental Health,* 11(4), pp. 384-397.
Koyre, A., 1943. Galileo and the scientific revolution of the seventeenth century. *Philosophical Review.* 52(4), pp.333–348.
Krim, H. and Viberg, M., 1996. Two decades of array signal processing research: The parametric approach. *IEEE Signal Processing Magazine*, 13(4), pp. 67–94.
Kruger, R., 1492. *Continuation into Roman and Medieval Thought*. [online] Available at: <http://www.uni-stuttgart.de/romlit/>
Krupp, E.C., 2003. *Echoes of the ancient skies: The astronomy of lost civilizations.* New American Library.
Krupp, E.C., 2012. *Echoes of the ancient skies: The astronomy of lost civilizations*, Courier Dover Publications.

Kuhn, T.S., 1957. *The Copernican Revolution: Planetary Astronomy in the Development of Western Thought*. Harvard University Press.

Lagios, E.D., 2010. *Aristotle Theory about Earthquakes*. [online] Available at: <http://www.geophysics.geol.uoa.gr/frame_en/histo/aristotle_en.html>.

Lamb, W.K., 1977. *A History of the Canadian Pacific Railway*. New York: Macmillan Publishing Co.

Lane, N., 2002. *Oxygen: The Molecule That Made the World*. Oxford: Oxford University Press.

Leach, E.W., 1990. The politics of self-presentation: Pliny's "letters" and roman portrait sculpture. *Classical Antiquity*, 9(1), pp. 14–39.

Leakey, M.D. and Harris, J.M., 1989. Laetoli: A Pliocene site in northern Tanzania. *Journal of human evolution*, 18, pp. 173–181.

Leakey, M.D. and Hay, R.L., 1979. Pliocene footprints at Laetoli beds in Laetoli, northern Tanzania. *Nature*, 278, pp. 317–323.

Leakey, M.G., Spoor, F., Dean, M.C., Feibel, C.S., Antón, S.C., Kiarie, C. and Leakey, L.N., 2012. New fossils from Koobi Fora in northern Kenya confirm taxonomic diversity in early homo. *Nature*, 488, pp. 201–4.

Leddra, M., 2010. *Time Matters: Geology's Legacy to Scientific Thought*. Chichester: John Wiley & Sons Inc. pp. 38–46.

Leet, L.D., 1938. *Practical Seismology and Seismic Prospecting*. New York: D. Appleton-Century Company Inc. pp. 3–5, 330–335.

LeVay, S., 2006. *When Science Goes Wrong: Twelve Tales from the Dark Side of Discovery*. Toronto: Penguin Group Inc. pp.45–52.

Levinton, J.S., 2008. The Cambrian explosion: How do we use the evidence? *BioScience,* 58(9).

Lewis, C., 2000. *The Dating Game: One Man's search for the Age of the Earth*. Cambridge: Cambridge University Press.

Lewis, K.W., Aharonson, O., Grotzinger, J.P., Kirk, R.L., McEwen, A.S. and Suer, T.-A., 2008. Quasi-periodic bedding in the sedimentary rock record of Mars. *Science*, 322(5907), pp. 1532–1535.

Lewis, M. and Wigen, K., 1997. *The Myth of the Continents: A Critique of Metageography*. Los Angeles: University of California Press Ltd. pp. 104–123.

Lhwyd, E., 1698. Part of a letter from Mr. Edw. Lhwyd to Dr. Martin Lister, fell. of the coll. of phys. and R.S. concerning several regularly figured stones lately found by him. *Philosophical Transactions of the Royal Society*, 20(243), pp. 279-280.

Lindberg, D.C., 1992. *The Beginnings Of Western Science*. 1st ed. Chicago: The University of Chicago Press.

Lordkipanidze, D., Ponce de León, M.S., Margvelashvili, A., Rak, Y., Rightmire, G.P., Vekua, A. and Zollikofer, C.P.E., 2013. A complete skull from Dmanisi, Georgia, and the evolutionary biology of early homo. *Science*, 342, pp. 326–31.

Lovtrup, S., 1977. *The Phylogeny of Vertebrata*. London: J. Wiley.

Lowenstein, T.K., Timofeeff, M.N., Brennan, S.T., Hardie, L.A. and Demicco, R.V., 2001. Oscillations in Phanerozoic seawater chemistry: Evidence from fluid inclusions. *Science*, 294.

Lucas, Robert E., Jr. 2002. *Lectures on Economic Growth*. Cambridge: Harvard University Press.

Ludvigsen, R. ed., 1996. *Life in Stone: A Natural History of British Columbia's Fossils*. Vancouver: UBC Press.

Lyell, C., 1853. *Principles of Geology: The Modern Changes of Earth and Its Inhabitants*. 9th ed. New York: D. Appleton & Company, pp. 49–52.

Lyell, C., 1970. *Principles of Geology*. Lehre: J. Cramer.

Ma, J., Xu, X., Zhao, C. and Yan, P., 2012. A review of atmospheric chemistry research in China: Photochemical smog, haze pollution, and gas-aerosol interactions. *Advances in Atmospheric Sciences*, 29(5), pp. 1006–1026.

Mack, R.N., Simberloff, D., Lonsdale, W., Evans, H., Clout, M. and Bazzaz, F.A., 2000. Biotic invasions: Causes, epidemiology, global consequences, and control. *Ecological Applications*, 10(3), pp. 689–710.

Mackin, J., 2009. *The Science of Oceanography*. New York: Nova Science Publishers.

Mahajan, G., 2008. *Evaluation and Development of Groundwater*. New Delhi: APH Publishing. p. 317.

Mantell, G., 1825. Notice on the Iguanodon, a newly discovered fossil reptile, from the sandstone of Tilgate Forest, in Sussex. *Philosophical Transactions of the Royal Society of London,* 115, pp. 179–186.

Manten, A., 1966. Historical foundations of chemical geology and geochemistry. *Chemical Geology*, 1, pp. 5–31.

Marini-Bettòlo, G.B., 1986. Chemical events in the atmosphere and their impact on the environment. *Elsevier*, 1986, pp. 227–230.

Martin, D., Briggs, D.E.G. and Parkes, R.J., 2004. Experimental attachment of sediment particles to invertebrate eggs and the preservation of soft-bodied fossils. *Journal of the Geological Society*, 161, pp. 735-738.

Marvin, U., 1973. *Continental Drift: The Evolution of a Concept*. Washington: Smithsonian Institution Press.

Master, S., 2010. Plutonism versus Neptunism at the southern tip of Africa: The debate on the origin of granites at the Cape, 1776–1844. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 100(1-2), pp. 1–13.
Mathez, E.A., 2000. *Earth: Inside and Out*. The New Press. p. 237.
Matsuoka, M., 2013. *Monitor of All-Sky X-ray Image (MAXI).* [online] Available at: <http://www.nasa.gov/mission_pages/station/research/experiments/603.html#overview>.
Matthew, G.F., 1899. Studies on Cambrian faunas: Upper Cambrian fauna of Mount Stephen. *Transactions of the Royal Society of Canada*, 5(4), p. 42.
Matthews, S.W., 1976. What's happening to our climate. *Nat Geog*, 150(5).
Maugeri, L., 2006. *The Age of Oil: The Mythology, History, and Future of the World's Most Controversial Resource.* Westport: Praeger Publishers. pp. 5-18.
Mawson, D., 1949. The late Precambrian ice age and glacial record of the Bibliando dome. *Journal and Proceedings of the Society of New South Wales*, 82, pp. 150–174.
Maxwell, J.C., 2010. *The Scientific Papers of James Clerk Maxwell*. New York: Cambridge University Press.
McCluskey, S.C., 2000. *Astronomies and Cultures in Early Medieval Europe*. New York: Cambridge University Press, p. 252.
McCormmach, R.T.H.E., 2012. *Weighing the World: The Reverend John Michell of Thornhill.* 28th ed. London: Springer.
McDaniel, M., Sprout, E., Bourdreau, D. and Turgeon, A., 2013. *Paleontology*. [online] Available at: <http://education.nationalgeographic.com/education/encyclopedia/paleontology/?ar_a=1>
McGrayne, S. B., 2001. *Prometheans in the Lab: Chemistry and the Making of the Modern World.* Chicago: RR Donnelley & Sons Company. pp. 79-106.
McKay, C., 2000. Thickness of tropical ice and photosynthesis on a snowball Earth. *Geophysical Research letters*, 27(14), pp. 2153–2156.
McLennan, S.M. and Grotzinger, J.P., 2008. *The Martian Surface*. Cambridge: Cambridge University Press. pp. 541–577.
McLennan, S.M., 2010. Geochemical perspectives on the sedimentary rock cycle of Mars. *Goldschmidt Conference Abstracts*, p. A690.
McLeod, K.S., 2000. Our sense of snow: The myth of John Snow in medical geography. *Social Science & Medicine (1982)*, 50(7-8), pp. 923–35.
McMahon, M.A., 1992. Small matters: Benjamin Franklin, Philadelphia, and the progress of cities. *The Pennsylvania Magazine of History and Biography*, CXVI(2), pp. 157–182.
McMullen, K.Y., Poppe, L.J., Twomey, E.R., Danforth,W.W., Haupt, T.A. and Crocker, J.M., 2007. *Sidescan Sonar Imagery, Multibeam Bathymetry, and Surficial Geologic Interpretations of the Sea Floor in Rhode Island Sound, off Sakonnet point, Rhode Island*. [online] Available at: <http://woodshole.er.usgs.gov/pubs/of2007-1150/>.
Melosi, M. V., 2000. *The Sanitary City*. Baltimore: The John Hopkins University Press.
Melosi, M. V., 2005. *Garbage in the Cities (Refuse, Reform and the Environment)*. Pittsburgh: University of Pittsburgh Press.
Meyer, H.W., 1971. *A History of Electricity and Magnetism*. Massachusetts: MIT Press.
Micheels, A. and Montenari, M., 2008. A snowball Earth versus a slushball Earth: Results from Neoproterozoic climate modeling sensitivity experiments. *Geosphere*, 4(2), p. 401.
Midgley, T. and Boyd, T., 1922. The Application of Chemistry to the Conservation of Motor Fuels. *Industrial and Engineering Chemistry,* p. 850.
Milkereit, B., Eaton, D., Salisbury, M., Adam, E. and Bohlen, T., 2003. *3D Seismic Imaging for Mineral Exploration*. [online] Available at: <http://www.geophys.geos.vt.edu/hole/ccss/milkereitCCSS.pdf>.
Miller, D.C., 1937. *Sparks, Lightning, Cosmic Rays*. New York: The Macmillan Company.
Misra, S.B., 1969. Late Precambrian fossils from southeastern Newfoundland. *Geological Society of America*, 80, pp. 2133–2140.
Missiakoulis, S., 2008. Aristotle and earthquake data: A historical note. *International Statistical Review*, 76(1), pp. 130–133.
Mitchell, B., 2013. *Beno Gutenberg.* [online] Available at: <http://honors.agu.org/bowie-lectures/beno-gutenberg-1889-1960/>.
Mohorovicic, A., 1909. Earthquake of 8 October 1909. *Geofizika*, 9.
Moltz, J., 2011. *The Politics of Space Security Strategic Restraint and the Pursuit of National Interests*. 2nd ed. Stanford: Stanford University Press.
Morris, S.C. and Whittington, H.B., 1979. The animals of the Burgess Shale. *Scientific American*, 241(1), pp. 122-135.
Morris, S.C., 1978. Laggania cambria walcott: A composite fossil. *Journal of Paleontology*, 52(1), pp. 126-131.
Morris, S.C., 1999. *The Crucible of Creation: The Burgess Shale and the Rise of Animals.* Oxford: Oxford University Press.

Morris, S.C., 2006. Darwin's dilemma: The realities of the Cambrian "explosion." *Philosophical Transactions of the Royal Society of London*, 361.
Mumford, I., 1971. Lithography, photography and photozincography in English map production before 1870. *The Cartographic Journal,* 9(1), pp. 30-36.
Murozumi, M., Chow, T. J. and Patterson, C., 1969. Chemical concentration of pollutant lead aerosols, terrestrial dusts, and sea salts in Greenland and Antarctic snow strata. *Geochimica et Cosmochimica Acta,* 33(10), pp. 1247-1294.
Murphy, S. and Kiran, B.R., 2012. Mystery of fossils: A review. *International Journal of Recent Scientific Research*, 3(11), pp. 901–907.
Murray, G., 2003. *Five Stages of Greek Religion*. Courier Dover Publications. p. 240.
Musso, T.B., 2010. Assessment of smectite-rich claystones from Northpatagonia for their use as liner materials in landfills. *Applied Clay Science*, 48(3), pp. 438 – 445.
Musson, R.M.W., 2013. A history of British seismology. *Bulletin of Earthquake Engineering*, 11(3), pp. 715–861.
Mutch, T.A., Arvidson, R.E., Head, J.W.I., Jones, K.L. and Saunders, R.S., 1976. *The Geology of Mars*. New Jersey: Princeton University Press. pp. 1–400.
Nader, J.J., 2009. Darcy's law and the differential equation of motion. *Géotechnique,* 59(6), pp. 551-552.
Nakamura, H., 1962. *East Asia in Old Maps*. Tokyo: Kasai Publishing and Printing Co.
Narasimhan, T.N., 2009. Groundwater: From mystery to management. *Environmental Research Letters*, 4(3), p. 035002.
Narbonne, G.M. and Gehling, J.G., 2003. Life after snowball: The oldest complex Ediacaran fossils. *Geology,* 31(1), pp. 27–30.
NASA, 2013. *Mars Exploration Rovers*. [online] Available at: <http://marsrovers.jpl.nasa.gov/overview/>.
National Defence University, 1978. *Climate Change to the Year 2000: A Survey of Expert Opinion*. Minnesota: The University of Minnesota.
National Geographic, 2013. *The Development of Agriculture: The Genographic Project.* [online] Available at: <https://genographic.nationalgeographic.com/development-of-agriculture/>
[NOAA] National Oceanic and Atmospheric Administration, 2013. *Mapping the Ocean Floor: Bathymetry*. [online] Available at: <http://oceanexplorer.noaa.gov/edu/curriculum/section2.pdf>.
National Park Service, 2013. *Frederick Law Olmsted National Historic Site*. [online] Available at: <http://www.nps.gov/frla/index.htm>.
Navarro-Gonzalez, R., 2007. Paleoecology reconstruction from trapped gases in a fulgurite from the late Pleistocene of the Libyan Desert. *Geology*, 35, pp. 171-174.
Neal, H.A. and Schubel, J.R., 1987. *Solid Waste Management and the Environment: The Mounting Garbage and Trash Crisis*. Englewood Cliffs: Prentice-Hall.
Needham, J., 1964. *The Development of Iron and Steel Technology in China.* Cambridge: W. Heffer & Sons.
Needham, J., 1974. Astronomy in ancient and medieval China. *Philosophical Transactions for the Royal Society of London. Series A, Mathematical and Physical Sciences*, pp. 67–82.
Nei, M. and Roychoudhury, A.K., 1974. Genetic variation within and between the three major races of man, Caucasoids, Negroids, and Mongoloids. *American Journal of Human Genetics*, 24, pp. 421–43.
Nelson, G., 1978. Ontogeny, phylogeny, paleontology, and the biogenetic law. *Systematic Zoology*, 27, pp. 324-345.
Neugebauer, O., 1975. *A History of Ancient Mathematical Astronomy.* 2nd ed. Springer. pp. 320–321.
New York Times, 1925. Ethyl Gasoline Defended. *New York Times*, 6 April, p. 23.
New York Times, 1925. Ford Predicts Fuel from Vegetation. *New York Times*, 20 September, p. 24.
Ni, Y., 2012. Geochemical characteristics of biogenic gases in China. *International Journal of Coal Geology*, 113(3), pp. 76 – 87.
Nield, T., 2007. *Supercontinent: Ten Billion Years in the Life of Our Planet*. Massachusetts: Harvard University Press.
Norman, D., 2005. *Dinosaurs A Very Short Introduction.* Oxford: Oxford University Press.
Numbers, R.L. and Lindberg, D.C. eds., 1986. *God and Nature: Historical Essays on the Encounter between Christianity and Science*. Berkeley: University of California Press.
O'Leary, M., 1988. *BioScience: Carbon Isotopes in Photosynthesis*. 38th ed. University of California Press. pp. 328–336.
Ockham, W., Ratisbona, A., Bade, J. and Treschel, J., 1495. *Quaestiones et decisiones in quattuor libros Sententiarum Petri Lombardi.* Lyon: Jean Treschel.
Oeser, E., 1992. *Historical earthquake theories from Aristotle to Kant*. Wien: Geologische Bundesanstalt.
Okunova, T. V., Giruts, M. V., Erdnieva, O.G., Koshelev, V.N. and Gordadze, G.N., 2010. Comparative characterization of the distribution of biomarker hydrocarbons in the chemical transformation products of oxygen-containing precursors of petroleum. *Solid Fuel Chemistry*, 44(5), pp. 351–363.
Oldham, R.D., 1906. The constitution of the interior of the Earth, as revealed by earthquakes. *Quarterly Journal of the Geological Society*, 62(1-4), pp. 456–475.

Oldham, R.D., 1914. Letters to editor: The constitution of the interior of the Earth as revealed by earthquakes. *Nature*, 92, pp. 684–685.

Opinion. U.S. Government Printing Office, p. 109.

Oreskes, N., 2003. *Plate Tectonics: An Insider's History of the Modern Theory of the Earth*. Boulder: Westview Press. p. 424.

Oswalt, T.D. and McLean, I.S. eds., 2013. *Planets, Stars and Stellar Systems Vol 1: Telescopes and Instrumentation*. Springer Netherlands. pp. 361–429.

Oweis, I.S. and Khera, R.P., 1990. *Geotechnology of Waste Management*. London: Butterworths.

Owen, R., 1842. Report on British Fossil Reptiles: Part II. *Report of the Eleventh Meeting of the British Association for the Advancement of Science, held at Plymouth*, pp. 66-204.

Owen, T. and Pilbeam, E., 1992. *Ordnance Survey: Map Makers to Britain since 1971*. London: HMSO.

Pacyna, J. and Hov, Ø., 2002. Sea to air transport of trace gases in the coastal zone: A literature review. *Regional Environmental Change*, 2(4), pp. 185–200.

Palmason, G., 1975. Geophysical Methods in Geothermal Exploration. *Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, U.S.A.*

Palmer, D., 2005. Earth Time John Wiley & Sons Ltd., ed., West Sussex, England.

Palmerino, C.R., 2008. Galileo through french eyes. *Metascience*, 17(1), pp. 111–115.

Paneth, N., 2004. Assessing the contributions of John Snow to epidemiology. *Epidemiology*, 15(5), pp. 514–516.

Parker, A., 2003. *In the Blink of an Eye: How Vision Sparked the Big Bang of Evolution*. New York: Perseus Publishing.

Parsons, P. M., 2004. *The Great Dinosaur Controversy A Guide to the Debates*. Santa Barbara: ABC-CLIO Inc.

Partington, J.R., 1960. *A History of Greek Fire and Gunpowder*. JHU Press. p. 381.

Paterson, N.R. and Bosschart, R., 1987. Airborne Geophysical Exploration for Ground Water. *Groundwater*, 25(1), pp. 41-50.

Patrick, R., 1987. *Groundwater Contamination in the United States*. 2nd ed. Philadelphia: University of Pennsylvania Press.

Pedersen, O., 2011. *A Survey of the Almagest*. Springer.

Perrin, C.E., 1986. Documents and translations: Lavoisier's thoughts on calcination and combustion, 1772-1773. *Isis*, 77(4), pp. 657–666.

Perrini, P., Lanzino, G. and Parenti, G.F., 2010. Niels Stensen (1638-1686): Scientist, neuroanatomist, and saint. *Neurosurgery*, 67(1), pp. 3–9; discussion 9.

Peters, S.E. and Gaines, R.R., 2012. Formation of the "Great Unconformity" as a trigger for the Cambrian explosion. *Nature*, 484, pp. 363-366.

Petersen, J.K., 2012. *Handbook of Surveillance Technologies*. 3rd ed. CRC Press. p. 1040.

Peterson, T.C., Connolley, W.M. and Fleck, J., 2008. The myth of the 1970s global cooling scientific consensus. *Bulletin of the American Meteorological Society*, 89(9), pp. 1325–1337.

Phillips, J., 2003. *Memoirs of William Smith*. Chippenham: The Bath Royal Literary and Scientific Institution.

Pingree, D., 1978. History of mathematical astronomy in India. *Dictionary of Scientific Biography*, 15(1), pp. 533–633.

Pirkle, J. L. et al., 1994. The decline in blood lead levels in the United States. *The National Health and Nutrition Examination Surveys,* 272(4), pp. 284-291

Plant, J., Smith, D., Smith, B. and Williams, L., 2001. Environmental geochemistry at the global scale. *Applied Geochemistry*, 16(11), pp. 1291–1308.

Plato, 360 BCE. *Plato's Cosmology: The Timaeus of Plato*. Kessinger Publishing. p. 396.

Playfair, J., 1956. *Illustrations of the Huttonian Theory of the Earth*. Urbana: University of Illinois Press.

Plot, R., 1677. *The Natural History of Oxford-shire, being an essay towards the Natural History of England*. Oxford: L. Lichfield for C. Brome.

Plummer, C.C., McGeary, D., Carlson, D., Eyles, N. and Eyles, C., 2007. *Physical Geology & the Environment*. McGraw-Hill Ryerson. p. 592.

Popp, M. and Oxelman, B., 2001. Inferring the history of the polyploid silene aegaea (Caryophyllaceae) using plastid and homoeologous nuclear DNA sequences. *Molecular Phylogenetics and Evolution*, 20(3), pp. 474–481.

Power, A., 2006. A mirror for every age: The reputation of Roger Bacon. *The English Historical Review*, 121(492), pp. 657–692.

Price, D.J., 1969. Contra-Copernicus: A critical re-estimation of the mathematical planetary theory of Ptolemy, Copernicus, and Kepler. Critical problems in the history of science, pp. 197–218.

Priestley, J., 1755. *The History and Present State of Electricity*. London: Johnson.

Priestley, J., 1774. *Experiments And Observations On Different Kinds Of Air*. London. p. 362.

Priestley, J., 1970. *Lectures Of Experimental Philosophy*. Reprint ed. New York: Kraus Reprint Company. p. 180.

Ptolemy, 130 CE. Geographia.

Purvis, A., 1995. A composite estimate of primate phylogeny. *Philosophical Transactions of the Royal Society of London*, 348(1326), pp. 405–421.
Purvis, A., Gittleman, G. L. and Brooks, T., 2005. *Phylogeny and Conservation.* Cambridge: Cambridge University Press.
R. Schöne, B. et al., 2013. Chemical labelling of oyster shells used for time-calibrated high-resolution Mg/Ca ratios: A tool for estimation of past seasonal temperature variations. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 373, pp. 66–74.
Radice, B., 1960. *The Letters of the Younger Pliny*. New York: Penguin Classics. pp. 240–264.
Rakov, V.A. and Uman, M.A., 2003. *Lightning: Physics and Effects.* New York: Cambridge University Press.
Ramstein, G. et al., 2004. A " snowball Earth " climate triggered by continental break-up through changes in runoff. *Letters to Nature,* 541(1966), pp. 303–306.
Rappaport, R., 2011. *Studies on Eighteenth-Century Geology*. Aldershot: Ashgate Publishing Limited.
Raymond, P.E., 1935. *Leanchoilia* and other mid-Cambrian Arthropoda. *Bulletin of the Museum of Comparative Zoology*, 76, pp. 205-230.
Regal, B., 2004. *Human evolution: A guide to the debates*. Santa Barbara: ABC-CLIO.
Reid, H., 1915. Constitution of the interior of the Earth as indicated by seismological investigations. *Proceedings of the American Philosophical Society*, 54(219), pp. 290–297.
Reynolds, J.M., 2011. *An Introduction to Applied and Environmental Geophysics*. Hoboken: John Wiley & Sons.
Richardson, E., 2011. *Thomas Jaggar: Biographical Information*. [online] Available at: <https://www.e-education.psu.edu/earth520/content/l2_p28.html>
Richardson, E., n.d. *A German Seismologist: Earth 520: Plate Tectonics and People: Foundations of Solid Earth Science*. [online] Available at: <https://www.e-education.psu.edu/earth520/node/1778>.
Richmond, B.G., Begun, D.R. and Strait, D.S., 2001. Origin of human bipedalism: The knuckle-walking hypothesis revisited. *Yearbook of Physical Anthropology*, 105, pp. 70–105.
Rightmire, G.P., 2004. Brain size and encephalization in early to mid-Pleistocene homo. *American Journal of Physical Anthropology*, 124, pp. 109–23.
Ringwood, A.E., 1955. The principles governing trace element distribution during magmatic crystallization. *Geochimica et Cosmochimica Acts*, 7, pp. 189–202.
Robin, G. de Q., 1977. Ice cores and climatic change. *Philosophical Transactions of the Royal Society of London. B, Biological Sciences*, 280(972), pp. 143–168.
Robinson, A., 1982. *Early Thematic Mapping in the History of Cartography*. Chicago: University of Chicago Press. pp. 30–32.
Robison, R.A., 1991. *The Early Evolution of Metazoa and the Significance of Problematic Taxa*. Cambridge: Cambridge University Press. pp. 77-98.
Rogers, J.H., 1998. Origins of the ancient constellations: I. The Mesopotamian traditions. *Journal of the British Astronomical Association*. [online].
Rosa, D., 1995. The relation between the synodic and sidereal rotation period of the sun d. rosa. (1974), pp. 393–398.
Rozwadowski, H.M., 2005. *Fathoming the Ocean: The Discovery and Exploration of the Deep Sea*. President and Fellows of Harvard College. pp. 3–35.
Rubinoff, D. and Holland, B., 2005. Between two extremes: Mitochondrial DNA is neither the panacea nor the nemesis of phylogenetic and taxonomic inference. *Systematic Biology*, 54(6), pp. 952–961.
Rudwick, M.J.S., 1985. *The Meaning of Fossils.* 2nd ed. The University of Chicago Press.
Rudwick, M., 1997. *Georges Cuvier, Fossil Bones, and Geological Catastrophes*. Chicago: University of Chicago Press.
Rudwick, M.J., 2007. *Bursting the Limits of Time: The Reconstruction of Geohistory in the Age of Revolution*. Chicago: The University of Chicago Press. pp. 207–220.
Rudwick, M.J.S., 1976a. Life's Revolutions. In: *The Meaning of Fossils*. 2nd ed. New York: Neale Watson Academic Publications Inc. pp. 101–163.
Rudwick, M.J.S., 1976b. Natural Antiquities. In: *The Meaning of Fossils*. 2nd ed. New York: Neale Watson Academic Publications Inc. pp. 49–100.
Rudwick, M.J.S., 1976c. Uniformity and Progress. In: *The Meaning of Fossils*. 2nd ed. New York: Neale Watson Academic Publications Inc. pp. 164–217.
Rudwick, M.J.S., 2008. *Georges Cuvier, Fossil Bones, and Geological Catastrophes: New Translations and Interpretations of the Primary Texts*. University of Chicago Press. p. 318.
Rudwick, M.J.S., 2009. *Geology and Religion: A History of Harmony and Hostility*. London: The Geological Society of London. pp. 103–110.
Rushby, A.J., Claire, M.W., Osborn, H. and Watson, A.J., 2013. Habitable zone lifetimes of exoplanet around main sequence stars. *Astrobiology*, 13(9), pp. 833–849.
Russell, J.L., 1995. What was the crime of Galileo? *Annals of science,* 52(4), pp. 403–410.
Sackmann, I.J., Boothroyd, A.I. and Kraemer, K.E., 1993. Our Sun. III. Present and future. *The Astrophysical Journal*, 418, p. 457.

Sagemann, J., Bale, S.J., Briggs, D.E.G. and Parkes, R.J., 1999. Controls on the formation of authigenic minerals in association with decaying organic matter: An experimental approach. *Geochimica et Cosmochimica Acta*, 63, pp. 1083-1095
Sarewitz, D., 2004. How science makes environmental controversies worse. *Environmental Science & Policy*, 7(5), pp. 385–403.
Schieber, J., 2007. *Milankovitch Cycles and Glaciation.* [online] Available at: <http://www.indiana.edu/~geol105/images/gaia_chapter_4/milankovitch.htm>
Schmitt, M., 2013. *From Taxonomy to Phylogenetics-Life and Work of Willi Hennig.* Leiden: Brill.
Schopf, J.M., 1975. Modes of fossil preservation. *Review of Palaeobotany and Palynology*, 20, pp. 27-53.
Schrag, D.P. and Hoffman, P.F., 2001. Life, geology and snowball Earth. *Nature,* 409(6818), p. 306.
Schroeder, W., 2000. *Some Aspects in Emil Wiechert*. [online] Available at: <http://verplant.org/history-geophysics/Wiechert.htm>.
Schulte, P. et al., 2010. The Chicxulub asteroid impact and mass extinction at the Cretaceous-Paleogene boundary. *Science,* 327(5970), pp. 1214–8.
Schwarzbach, M., 1980. *Alfred Wegener: The Father of Continental Drift.* Madison: Science Tech Inc. p. 241.
Segall, P., 1997. New insights into old earthquakes. *Nature,* 388, pp. 122–123.
Seitz, F., 2005. Henry Cavendish: The catalyst for the chemical revolution. *Notes and Records of the Royal Society*, 59(2), pp. 175–199.
Seyfullah, L., 2012. Fossil Focus: Using Plant Fossils to Understand Past Climates and Environments. *Palaeontology Online*, 2(7), pp. 1–8.
Seymour, W.A., 1980. *A history of the Ordnance Survey*. London: Dawson.
Shephard, D.A.E., 1995. *John Snow: Anaesthetist to a Queen and Epidemiologist to a Nation*. Cornwall: York Point Publishing.
Sherman, C.C., 1933. Theories on the nutrition of plants from Aristotle to Liebig. *Yale Journal of Biology and Medicine*, 6(1), p. 18.
Sigurdsson, H., Houghton, B., Rymer, H., Stix, J. and McNutt, S., 1999. *Encyclopedia of Volcanoes*. New York: Academic Press. pp. 1343–1350.
Silverberg, R., 1969. *Wonders of Ancient Chinese Science.* 1st ed. New York: Hawthorn Books Inc.
Simkiss, K., 1977. Biomineralization and detoxification. *Calcified Tissue Research*, 24, pp. 199–200.
Simpson, G.G., 1961. *Principles of Animal Taxonomy*. New York: Columbia University Press.
Simpson, G.G., Pittendrigh, C.S. and Tiffany, L.H., 1957. *Life: An Introduction to Biology*. New York: Harcourt, Brace, Co. pp. 741–742.
Singham, M. and Copernicus, N., 2007. The Copernican myths. *Physics Today*, 60(12), p. 48.
Skilling, H.H., 1948. *Exploring Electricity - Man's Unfinished Quest*. New York: Ronald Press Company.
Slotten, H.R., 1994. *Patronage, Practice, and the Culture of American Science: Alexander Dallas Bache and the U. S. Coast Survey*. Cambridge: Cambridge University Press. p. 228.
Smil, V., 1983. *Biomass energies*. New York: Plenum Press.
Smith, D.L., 1964. The evolution of the ovule. *Cambridge Philosophical Society*, 39, pp. 137-159.
Smith, J., 2005. *Frank A. Perret*. [online] Available at: <https://library.gl.ciw.edu/GLHistory/perret.html>.
Smith, M.J., Goodchild, M.F. and Longley, P.A., 2007. *Geospatial Analysis: A Comprehensive Guide to Principles, Techniques and Software Tools*. 2nd ed. Leicester: Troubador Publishing.
Smith, P.M. and Harper, D.A.T., 2013. Causes of the Cambrian explosion. *Science*, 341(6152), pp. 1355-1356.
Snow, J., 1855. *On the Mode of Communication of Cholera*. London: John Churchill.
Snowden, F., n.d. Contagionism versus Anticontagionism. *HIST 234: Epidemics in Western Society since 1600.* Yale University. [online] Available at <http://oyc.yale.edu/history/hist-234/lecture-13>.
Speidel, D.H., 2013. *Mineralogic Phase Rule.* [online] Available at: <http://www.springerreference.com/docs/html/chapterdbid/3544.html>.
Springer, 2007. *Springer Handbook of Acoustics*. New York: Springer Science+Business Media. p. 1182.
Stankiewicz, B.A., Briggs, D.E.G., Michels, R., Collinson, M.E., Flannery, M.B. and Evershed, R.P., 2000. An alternative origin of aliphatic polymer in Kerogen. *Geology*, 28, pp. 559-562.
Stanley, S.M., 2009. *Earth System History.* 3rd ed. New York: W.H. Freeman Company.
Stanley, S.M., Kennett, J.P., Knoll, A.H., Askin, R.A., Barron, E.J., Berry, W.B., Christophel, D.C., Dimichele, W.A., Flower, B.P., Kauffman, E.G., Keller, G., Ruddiman, W.F., Spicer, R.A., Webb, D.S. and Webb, T., 1995. *Effects of Past Global Change on Life*. Washington D.C.: National Academy Press.
Stares, P.B., 1985. *The Militarization of Space: U.S. Policy, 1945-1984*. Ithaca: Cornell University Press.
Stasik, M., Byczkowska, Z., Szendzikowski, S. and Fiedorczuk, Z., 1969. Acute tetraethyl lead poisoning. *Arch Toxikol,* 24(4), pp. 289-291.
Steno, N. and Winter, J.G., 1968. *The Prodromus of Nicolaus Steno's Dissertation Concerning a Solid Body Enclosed by Process of Nature Within a Solid.* New York: Hafner Pub. Co.

Stevens, P.F., 1980. Evolutionary polarity of character states. *Annual Review of Ecology, Evolution, and Systematics*, 11, pp. 333-358.
Stillman, M., 1957. *Understanding Maps: Charting the Land, Sea, and Sky*. 1st ed. New York: Whittlesey House. p. 29.
Stuart, E., 1981. *Biographical Dictionary of American Mayors in 1820-1980*. Westport: Greenwood Press. p. 349.
Swaine, D.J., 1988. Victor Moritz Goldschmidt's contributions to coal science. *Fuel*, 67(6), pp. 877–879.
Swaine, D.J., 1998. Why trace elements are important. *Fuel Processing Technology*, 65-66, pp. 21–33.
Sweeny, A., 2010. *Black Bonanza: Canada's Oil Sands and the Race to Secure North America's Energy Future.* Mississauga: John Wiley & Sons. pp. 23-51.
Swenson, S., 2002. Methods for inferring regional surface-mass anomalies from gravity recovery and climate experiment (GRACE) measurements of time-variable gravity. *Journal of Geophysical Research*, 107(B9), p. 2193.
Taieb, M., Johanson, D.C., Coppens, Y. and Aronson, J.L., 1976. Geological and paleontological background of Hadar hominid site, Afar, Ethiopia. *Nature*, 260, pp. 289–293.
Talbert, Richard J.A. and Unger, R.W.ed., 2008. *Cartography in Antiquity and the Middle Ages: Fresh Perspectives, New Methods*. Leiden: Brill.
Tapley, B.D., 2004. The gravity recovery and climate experiment: Mission overview and early results. *Geophysical Research Letters*, 31(9), p. L09607.
Tattersall, I., 2008. An evolutionary framework for the acquisition of symbolic cognition by Homo sapiens. *Comparative Cognition & Behavior Reviews*, 3, pp. 99–114.
Tattersall, I., 2009. *The Fossil Trail*. 2nd ed. New York: Oxford University Press.
Tesla, N., 1977. *My Inventions*. Zagreb: Skolska knjiga Publishing Enterprise and Belgrade: Nikola Tesla Museum.
The Geological Society, 2007. *Goldschmidt in Britain*. [online] Available at: <https://www.geolsoc.org.uk/Geoscientist/Archive/March-2007/Goldschmidt-in-Britain>.
Tharp, M., 1982. *The Ocean Floor*. New York: John Wiley & Sons, Ltd. pp. 19–31.
The Bible: The Message Study Bible, 2012. Colorado Springs: NavPress.
The Geologic Society of London. T.G., 2007. *Four Centuries of Geologic Travel: The Search for Knowledge on Foot, Bicycle, Sledge, and Camel*. 28th ed. London: The Geological Society of London. pp. 4–28.
Thompson, J., 1974. Maya astronomy. *Philosophical Transactions of the Royal Society of London. Series A. Mathematical and Physical Sciences,* 276(1257), pp. 83–98.
Thomsen, E., 2009. Niels Stensen—Steno, in the world of collections and museums. *Geological Society of America Memoirs*, 203, pp. 75–91.
Thomson, W., 1882. The tides. *The Harvard Classics*, 53.
Thurston, H., 1993. *Early Astronomy*. New York: Springer. p. 118.
Tilley, C., 2013. Victor Moritz Goldschmidt. 1888-1947. *The Royal Society*, 6(17), pp. 51–66.
Tolstoy, I.C., 1981. *James Clerk Maxwell: A Biography*. Edinburgh: Canongate.
Ptolemy., AD 2 c. *Almagest*. Translated and annotated by G.J. Toomer. Princeton N.J: Princeton University Press.
Tucker, T., 2003. *Bolt of Fate-Benjamin Franklin and His Fabulous Kite*. New York: PublicAffairs.
Turner, D.M., 1927. *Makers of Science: Electricity & Magnetism*. London: Oxford University Press.
Turner, S., 1832. *The British Critic, Quarterly Theological Review, and Ecclesiastical Record*. London: C. & J. Rivington, and J. Mawman. pp. 64–87.
Tyce, R.C., 1968. Deep seafloor mapping systems-A review. *Marine Technology Society Journal*, 20(4), pp. 4-16
United Nations Environment Program, 2011. *Phase-out of Leaded Petrol Brings Huge Health and Cost Benefits – UN–Backed Study*. [online] Available at: <http://www.un.org/apps/news/story.asp?NewsID=40226&Cr=pollutant&Cr1=#.UsiIcfRDuSo>..
University of California Museum of Paleontology, 2013. *Plate Tectonics the Rocky History of an Idea.* [online] Available at: <http://www.ucmp.berkeley.edu/geology/techist.html>
University of Glasgow, 2013. *Sir William Thomson Baron Kelvin of Largs*. [online] Available at: <http://www.universitystory.gla.ac.uk/biography/?id=WH0025&type=P>.
US Department of Commerce, 2013a. *Technology: Observation Tools: SONAR*. National Oceanic and Atmospheric Administration. [online] Available at: <http://oceanexplorer.noaa.gov/technology/tools/sonar/sonar.html>.
US Department of Commerce, 2013b. *What is sonar?* National Oceanic and Atmospheric Administration. [online] Available at: <http://oceanservice.noaa.gov/facts/sonar.html>.
Velicogna, I., 2002. A method for separating Antarctic postglacial rebound and ice mass balance using future ICESat geoscience laser altimeter system, gravity recovery and climate experiment, and GPS satellite data. *Journal of Geophysical Research*, 107(B10), p. 2263.
Vénec-Peyré, M.T., 2004. Beyond frontiers and time: The scientific and cultural heritage of Alcide d'Orbigny (1802–1857). *Marine Micropaleontology*, 50(1-2), pp. 149–159.

Verhoogen, J., 1965. Paleomagnetism. *Science*, 147(3661), pp. 1060-61.
Verjee, F., 2010. *Geographic Information Systems: Exploring Humanitarian Applications of Spatial Analysis.* Saarbrucken: Lambert Academic Publishing.
Verschuur, G.L., 1993. *Hidden Attraction: The Mystery and History of Magnetism.* Oxford: Oxford University Press.
Volland, H., 1984. *Atmospheric Electrodynamics*. Berlin: Springer Verlag.
Wakasa, S.A., Seisuke, N., Hiroyuki, S. and Yukinori, M., 2012. Does lightning destroy rocks?: Results from a laboratory lightning experiment using an impulse high-current generator. *Geology*, 161, pp. 110-114.
Walcott, C.D., 1911. Cambrian geology and paleontology II. *Smithsonian Miscellaneous Collections*, 57(2), pp. 17-68.
Walker, G., 2003. *Snowball Earth: The Story of the Great Global Catastrophe that Spawned Life as we know it.* New York: Crown Publisher. pp. 231–245.
Weart, S.R., 2010. The idea of anthropogenic global climate change in the 20th century. *Wiley Interdisciplinary Reviews: Climate Change*, 1(1), pp. 67–81.
Wedepohl, K.H., 1996. The importance of the pioneering work by V.M Goldschmidt for modern geochemistry. *Naturwissenschaften,* 83, pp. 165–171.
Wegener, A., 1966. *The Origins of Continents and Oceans.* New York: Dover Publications. p. 246.
Weintraub, B. and Shamoon, S., 1991. Victor Moritz Goldschmidt (1888-1947): Father of modern geochemistry and of crystal chemistry. *Israel Chemistry Society*, pp. 42–46.
Weisstein, E.W., 2007. *Kelvin, Lord William Thomson (1824-1907).* [online] Available at: <http://scienceworld.wolfram.com/biography/Kelvin.html>.
West Laurel Hill Cemetery, 2008. *Rudolph Hering.* [online] Available at: <http://www.webcemeteries.com/memorials/Life-History.asp>.
Westlake, K., 1995. *Landfill Waste Pollution and Control.* Chichester: Albion Pub. p. 144.
Wheeler, P., 1993. Human ancestors walked tall, stayed cool. *Natural History*, (102), pp. 65–7.
White, R.J. and Ghez, A.M., 2001. Observational constraints on the formation and evolution of binary stars. *The Astrophysical Journal*, 556, pp. 265-295.
Whiteaves, J.F., 1892. Illustrations of seven species of fossils from the Cambrian, Cambro-Silurian, and Devonian rocks of Canada. *Canadian Record of Science*, 5, pp. 205-206.
Whittington, H.B., 1980. The significance of the fauna of the Burgess Shale, Middle Cambrian, British Columbia. *Proceedings of the Geologists' Association*, 91(3), pp. 127-148.
Whittington, H.B., 1985. *The Burgess Shale.* New Haven: Published in association with the Geological Survey of Canada by Yale University Press. p. 151.
Wightman, W., 2003. *Application of Geophysical Methods to Highway Related Problems.* US Department of Transportation. [online] Available at: <http://www.cflhd.gov/resources/geotechnical/>.
Will, G., 2009. Dark green doomsayers. *Washington Post*, 15 Feb. p. B07.
Williams, A., 1973. The secretion and structural evolution of the shell in thecideidine brachiopods. *Philosophical Transactions of the Royal Society of London*, 264, pp. 439-478.
Williams, C. and Nield, T., 2007. Pangea, the comeback. *NewScientist*, (2626), pp. 36–40.
Williams, D.M. and Pollard, D., 2003. Extraordinary climates of Earth-like planets: Three-dimensional climate simulations at extreme obliquity. *International Journal of Astrobiology*, 2(1), pp. 1–19.
Williams, D.R., 2004. *Earth Fact Sheet.* [online] Available at: <http://nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html>
Williams, G.D., 2006. Greco-Roman seismology and seneca on earthquakes in natural questions 6. *Journal of Roman Studies*, 96, pp. 124-146.
Williams, G.E., 2008. Proterozoic (pre-Ediacaran) glaciation and the high obliquity, low-latitude ice, strong seasonality (HOLIST) hypothesis: Principles and tests. *Earth-Science Reviews*, 87, pp. 61–93.
Williams, J.G., 1994. Contributions to the Earth's obliquity rate, precession, and nutation. T*he Astronomical Journal*, 108, pp. 711–724.
Willoughby, P.R., 2007. *The Evolution of Modern Humans in Africa*. New York: AltaMira Press.
Wilson, F., 1999. *The Logic And Methodology Of Science In Early Modern Thought*. Toronto: University of Toronto Press.
Wilson, J., 1882. *Report of the Class of 1857 in Harvard College: Prepared for the Twenty-fifth Anniversary of its Graduation.* Cambridge: Samtocrsttg Press.
Wilson, J., 2013. *Apollo Program.* [online] Available at: <http://www.nasa.gov/mission_pages/apollo/missions/index.html#.Up_UUsRDt4c>.
Wisniak, J., 2004. Phlogiston: The rise and fall of a theory. *Indian Journal of Chemical Technology*, 11(5), pp. 732–743.

Whittington, H.B. and Briggs, D.E.G., 1985. The largest Cambrian animal, *Anomalocaris*, Burgess Shale, British Columbia. *Philosophical Transactions of the Royal Society Biological Sciences*, 309(1141), pp. 569-609.
Wollast, R. and Chou, L., 2001. The carbon cycle at the ocean margin in the northern Gulf of Biscay. *Deep Sea Research Part II*, 48(14), pp. 3265–3293.
Wood, A. and Ellyard, D., 2005. *Who Discovered What When*. Sydney: New Holland Publishers Pty Ltd. pp. 1774–1783.
Woodcock, L.V., 2005. Phlogiston theory and chemical revolutions. *Bulletin for the History of Chemistry*, 30(2), pp. 63–69
Woodroffe, R., 1998. Edge effects and the extinction of populations inside protected areas. *Science*, 280(5372), pp. 2126–2128.
Woodward, D. and Lewis, G.M. eds., 1998. *The History of Cartography Vol. 2, Book 3: Cartography in the Traditional African, American, Arctic, Australian, and Pacific Societies*. Chicago: University of Chicago Press. pp. 301–326.
Wright, H.E. and Miller, R.F., 1990. Robert Foulis: New Brunswick Inventor, Entrepreneur and Geologist. *Geoscience Canada (Geology Today),* 17(2), pp. 101-104.
Wyllie, P.J., 1997. Hutton and Hall on theory and experiments: The view after 2 centuries. *Episode,* 21(1), pp. 3–10.
Yamada, H., Tamura, K., Watanabe, Y., Iyi, N. and Morimoto, K., 2011. Geomaterials: Their application to environmental remediation. *Science and Technology of Advanced Materials*, 12(6), pp. 1-13.
Yochelson, E.L., 1967. *Charles Doolittle Walcott 1850-1927*. Washington: National Academy of Sciences.
Yoshida, M. and Santosh, M., 2011. Future supercontinent assembled in the northern hemisphere. *Terra Nova*, 23(5), pp. 333-338.
Young, D. and Stearley, R., 2008a. Investigation of the Earth in the Seventeenth Century. *The Bible, Rocks, and Time: Geological Evidence for the Age of the Earth*. Illinois: InterVarsity Press. pp. 47–70.
Young, D. and Stearley, R., 2008b. The Emergence of Modern Geology. *The Bible, Rocks, and Time: Geological Evidence for the Age of the Earth*. Illinois: InterVarsity Press. pp. 71–100.
Young, D., 1982. *Christianity and the Age of the Earth*. Michigan: The Zondervan Corporation. pp. 27–40.
Zalasiewicz, J. and Williams, M., 2012. *The Goldilocks Planet*. New York: Oxford University Press.
Zeleznik, F.J. and Mcbride, B.J., 2011. *Modeling the Internal Combustion Engine*: *NASA Reference Publication*. [online] Available at: <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19850011423_1985011423.pdf>.
Zlotnicki, V., Bettadpur, S., Landerer, F.W. and Watkins, M.M., 2013. *Earth System Monitoring*. New York: Springer Science+Business Media. p. 123.

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p.99 *Predicted supercontinents*. New Scientist, Williams, C., 2007.

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