History of the Earth

An Integrated and Historical Perspective

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The Grand Canyon, Arizona provides a wealth of information about the geological history of our planet and has stimulated many scientists to investigate how and why such spectacular landscapes develop.

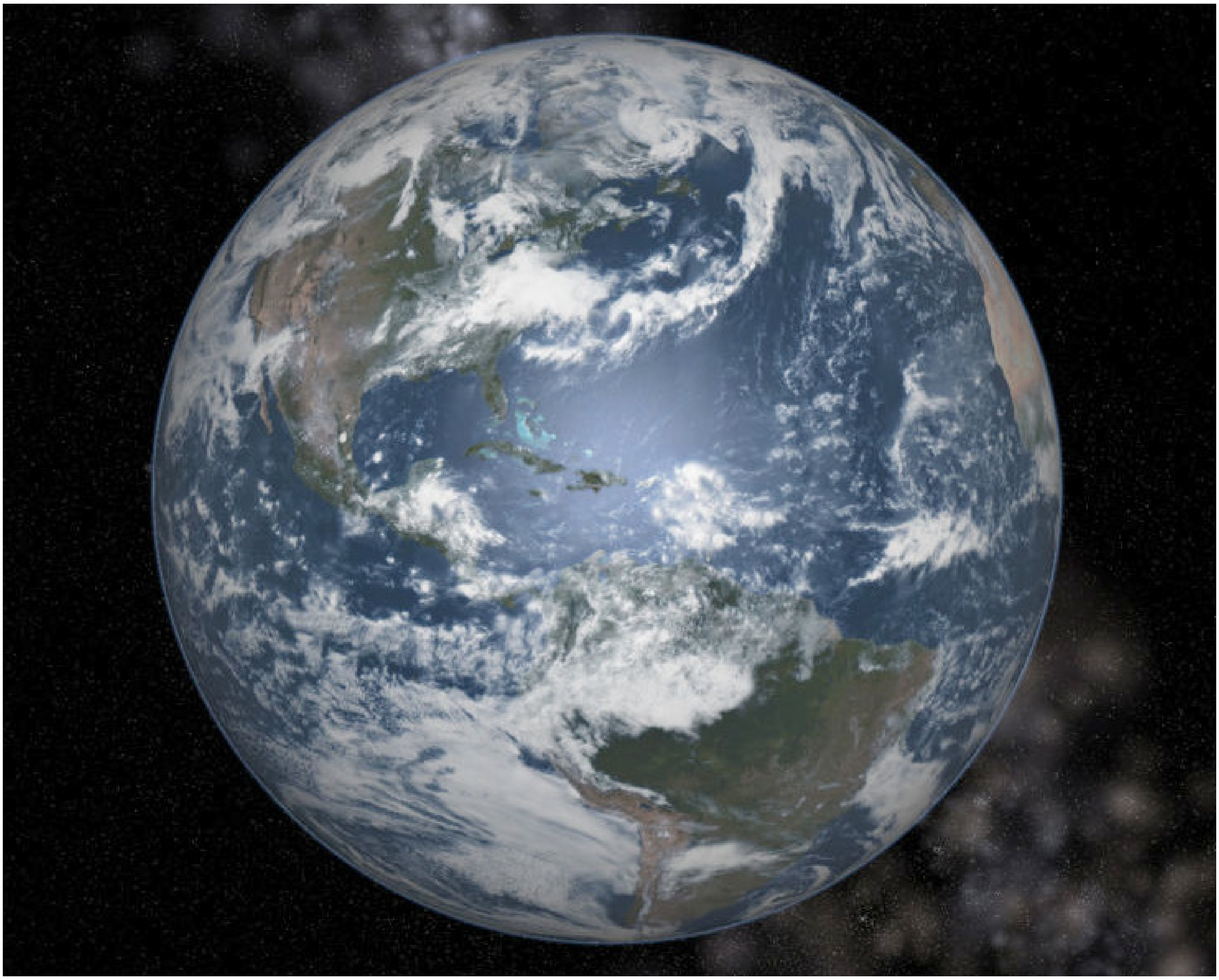
Foreword

Though perhaps well-worn, the cliché that science is like a tree growing up from deep subterranean roots is, none the less, true. Ironically, in today's world where we enjoy the ability to transmit instantaneously huge volumes of data and information, the past remains buried below ground, the special preserve of 'historians of science' and a foreign land where most practicing scientists never tread. Unfortunately, in many universities, there is intense pressure to keep moving forward, to always be in the forefront of science by growing the tree and not looking to its roots. Anything written or thought more than 20 years ago is seldom acknowledged. As a consequence, in the frantic desire to add to knowledge of the workings of the modern world, there is scant attention paid to the past and the pioneers who helped us arrive here. Most of us live and work in a single scientific discipline with little knowledge of the broader narrative.

So where might one start in exploring the roots of science? Who might be interested? How might it be presented in an interesting fashion?

This book is an excellent starting place in an exploration of the deep history and stratigraphy of science. It is a pleasure to read, well written and every page a reminder that we're not as clever as we think, and what we regard as 'fact' has been the product of much trial and error. The entries are short and in a few pages one can quickly review thousands of years of work. It is a book to be dipped into. It does not start at the beginning of science (whenever and whatever that was) but moves around in lively fashion from one topic to another. By so doing, it avoids the sterility of an excessively historical approach focussed on repetition of one date after another, and instead creates an appreciation in the reader of the interrelated nature of 'doing science'. Moreover, you don't need to be a scientist to appreciate this book. The authors have made it very clear that 'Science' is nothing more than formalized enquiry about our natural (and sometimes unnatural) surroundings. The basis of experimentation and testing is simply "I wonder why?" This is something we do every day and is the key to our success as a species, and for our future survival on a habitable planet. This book makes science interesting and appealing, and its authors have done an outstanding job; all scientists should be grateful for the insight it provides into the roots of modern science. It is a perfect place to start mining the past.

Nick and Carolyn Eyles, April 2011



Behold, the earth!

Introduction

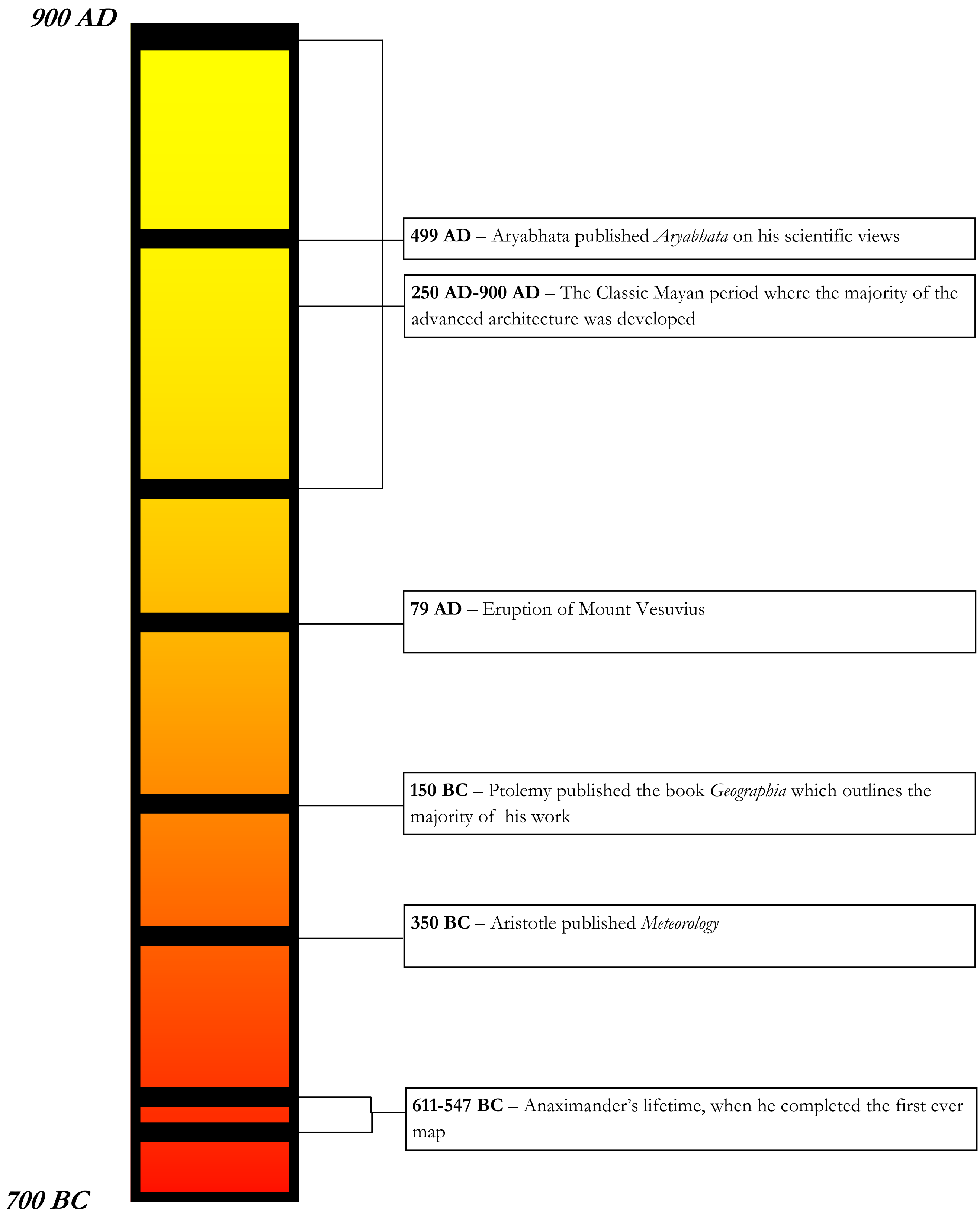
Isaac Newton once wrote, "If I have seen further it is by standing on the shoulders of giants." This sentiment epitomizes the nature of scientific progress. By steadily building upon past discoveries we gain a better understanding of the natural world. Examining the history of scientific thought allows us to understand how both the scientific method and our current knowledge of the world developed.

The aim of this book is to demonstrate the progression of scientific thought and how it relates to our understanding of the history of the Earth. Each chapter is subdivided into sections that examine individuals or ideas important to a particular time period. The book begins with ancient cultures' perspectives of the world, then discusses the development of science during the Renaissance, the exploration and discovery in the 19th century and the technological advances of the 20th century. Also included in the book is a timeline that provides historical context for events and gives an overview of the status of scientific discovery at any given time in history.

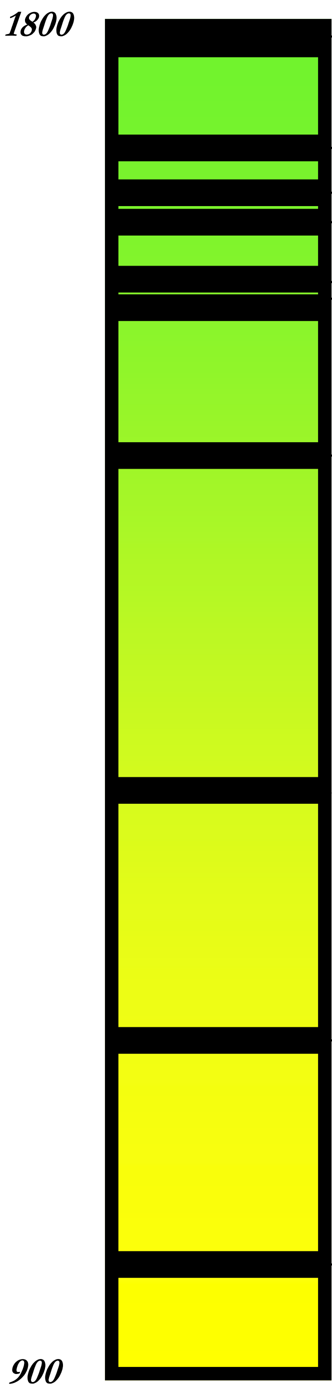
Each historical topic discussed in this book is accompanied by a modern topic outlined in blue. The modern topics each highlight a process or theme from the historical section, and taken together provide a brief yet comprehensive overview of the discipline of earth science. These modern perspectives reinforce the relevance of studying historical discoveries by showing how past discoveries have influenced our present knowledge.

Our integrated approach will provide a fresh perspective on scientific history, and will reveal the truly multidisciplinary nature of earth science.

Ancient Civilizations Timeline



Middle Ages & Renaissance Timeline



1795 – Publication of James Hutton's *Theory of the Earth*

1687 – Publication of Isaac Newton's *Principia*

1669 – Publication of Nicholas Steno's *De Solido intra solidum naturaliter content dissertationis prodromus*

1661 – Publication of Robert Boyle's *The Sceptical Chymist*

1609 – Creation of Thomas Harriot's first map of the moon

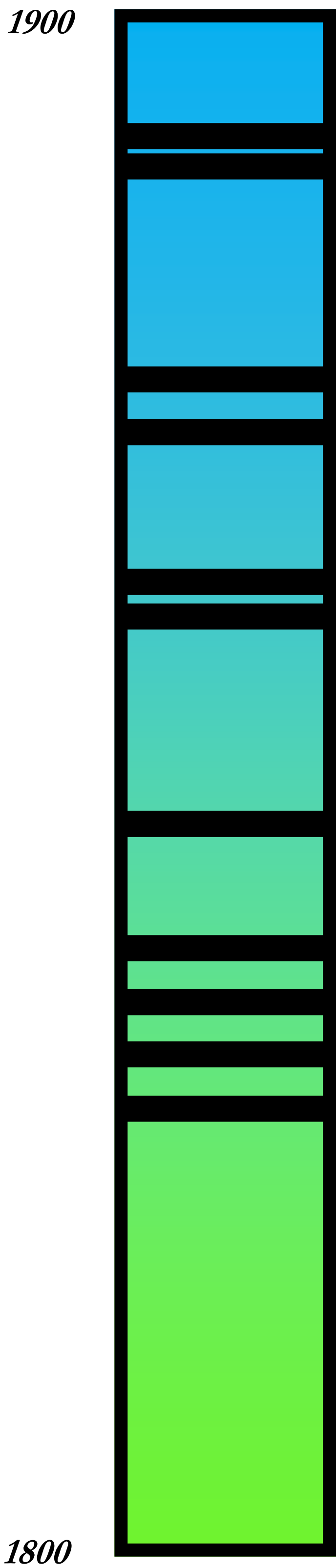
1600 – Publication of William Gilbert's *De Magnete*

1506-1510 – Writing of Da Vinci's collection of scientific papers known as Codex Leicester

1269 – Writing of the first known documents discussing magnetism, by Peter Pergrinus

960-1127 – The Song Dynasty: A period of rapid development in scientific thought in China

19th Century Timeline



1892 – Dr. Gilbert investigated the origin of Canyon Diablo Crater

1891 – The Nobi Earthquake occured, initiating the study of seismology in Japan

1872-1876 – The Challenger Expedition

1862 – Lord Kelvin presented his paper *On the Secular Cooling of the Earth* to the Royal Society of Edinburgh

1859 – Publication of Darwin's *Origin of the Species*

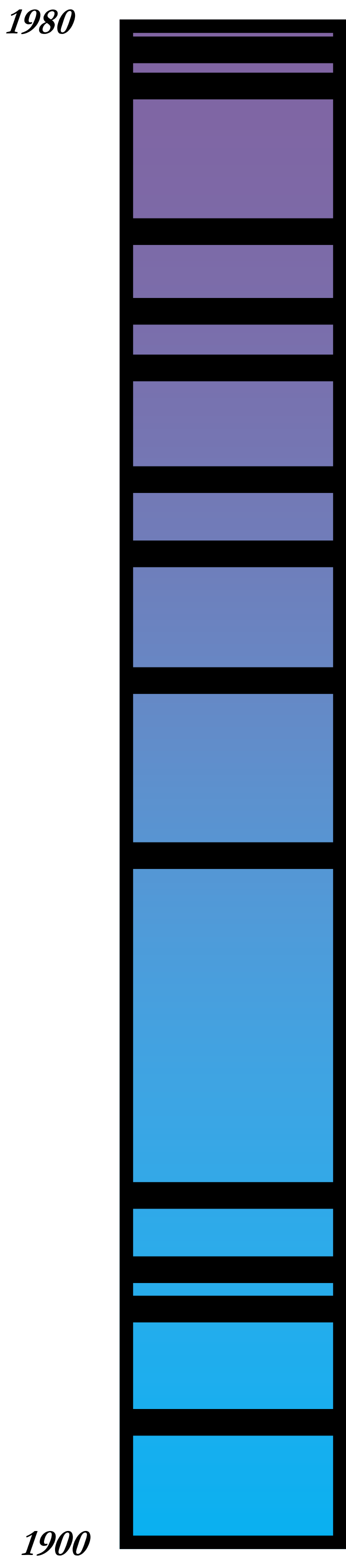
1845 – Beginning of the Northwest Passage Expedition, Sir John Franklin's final journey

1837 – Louis Agassiz presented his paper on glacial theory, known as the *Discourse of Neuchâtel*, at the annual meeting of the Swiss Society of Natural Sciences

1830-1833 – Charles Lyell published *Principles of Geology*, which greatly popularized the doctrine of uniformitarianism

1829 – Louis Agassiz published *Brazilian Fish*

20th Century Timeline



1979 – Discovery of Hydrothermal Vents

1977 – Peter Vail published his breakthrough paper on the global eustasy model, altering the way industry views sequence stratigraphy

1963-1965 – J. Tuzo Wilson published 3 landmark papers on the mechanism for the formation of Hawaiian Islands, the new classification of faults, and the Wilson Cycle

1962 – Harry Hess proposed the Theory of Sea-Floor Spreading

1956-1969 – The earth expansion theory gained momentum and is supported by many earth scientists including L. Egyed and S.W. Carey

1952 – The Miller-Urey Experiment: Synthesis of organic molecules from early Earth atmosphere analogue

1936 – Treibs published an article on his discovery of porphyrin molecules resembling chlorophyll and hemin in oil shale deposits. This discovery provided very strong evidence that petroleum is organic in origin

1914-1945 – The need for topographic maps in WWI and WWII triggers advancement of technology

1918 - First publication of the Köppen Climate Classification System by Wladimir Köppen

1912 – Alfred Wegner proposed Continental Drift Theory

1906 – Svante Arrhenius published *World in the Making*, in which he expressed his view on how the greenhouse effect could affect the human race

Castle Rock in Sedona, Arizona, USA.

History of the Earth

An Integrated and Historical Perspective

Figure 1.1 *A sun dial in the Botanical Garden, New Zealand. The sundial represents one of the few inventions common to several ancient civilizations. It reveals humanity's innate curiosity about the natural world.*

Chapter 1: Science of the Ancient World

The development of science in the ancient world was contingent upon the evolution of both technology and religion.

Although many civilizations were prosperous, some were also isolated causing advances in science to be impeded by a lack of communication and exchange of information. This caused many civilizations to use mythology to account for their observations, while others developed explanations that were more scientific by today's standards. Prejudice between classes meant there was also a lack of information exchange even within civilizations that were not secluded. The lower class were largely uneducated and their ideas were disregarded in favour of those of the presumably more knowledgeable upper class. Additionally, the lack of earlier scientific records disallowed for previously established science to be further developed by future generations.

As technology in the ancient world evolved, some regions were no longer geographically isolated, and the importance of trade in ideas and commodities was realized. The increased variety of observations led to more comprehensive hypotheses and more accurate conclusions. This development of the scientific method was crucial for decreasing the reliance on metaphysical influences to explain natural phenomena. Ancient civilizations simultaneously developed scientific methods resulting in inconsistencies in the conclusions drawn from their techniques. Although the methods evolved differently, they eventually became more representative of the modern scientific method.

Despite the fact that many of the theories about natural phenomena were flawed, the documented work of several ancient civilizations provided a strong basis upon which future advancements in science and technology were made.

Cartography in Ancient Greece

It was around 450 BC when the Greeks made peace with the Persians, allowing the Greek civilization to prosper (Sharaf, 1967; Starr, 1971). During this time, academia thrived. The disciplines of art, drama and philosophy reached great heights, and the work accomplished by the Greeks still remains comparable to the work of today. These advances enabled science to develop in a new way (Sharaf, 1967). The influence of the Greek culture was expanded through colonization and trade, both of which took place in the Eastern Mediterranean region and, later, in the Black Sea. Within the business of trade, the Phoenicians were the Greeks' competition. This competition resulted in greater understanding of the geography of the areas of trade, and caused the intellects of Greece to ponder the nature of the world (Sharaf, 1967).

Figure 1.2 *This map illustrates the location of some ancient Greek colonies and territories in the Archaic period (800-480 BC). Many colonies depicted in the map were home to various Greek intellects mentioned in this section (above).*

What the earth is, and its shape, size, and position relative to the rest of the universe, were common questions among the early Greek thinkers. Unfortunately, the ideas and thoughts of the Greeks would remain only theories as they did not have adequate equipment to experiment and test their hypotheses (Sharaf, 1967). However, the Greek civilization was characterized by a strong spirit of inquiry and natural curiosity (Roberts, 1973). This made them the most influential travellers of the region (Gosch and Stearns, 2008). While they were exploring, the Greeks adapted a new approach for writing about their explorations. This new approach was a very important innovation as they started to observe the geography of the landscapes on which they travelled. This led to the first documented attempts at representing the earth cartographically.

Cartography is the study of creating maps. It is not only considered a science, but a form of art. The art of cartography flourished during the time of ancient Greece. Anaximander of Miletus (611-547 BC) created what has been deemed the first map of the world (Sharaf, 1967; Unwin, 1992). Anaximander's map, though lost, was said to have represented all of the habitable land, or *oikoumene*, known to the Greeks.

Herodotus of Halicarnassus' (484-424 BC) descriptions and writings enable us to know what Anaximander's map looked like (Couprie, 2005). Anaximander theorized that the earth was a section of a cylinder, suspended in nothing, that was not rotating or moving anywhere (Sharaf, 1967). His map was circular and he placed the Mediterranean Sea at the centre (Sharaf, 1967; Couprie, 2005).

Progression of Discoveries and Hypotheses of Greek Intellects

Major advancements in ancient Greek cartography occurred between the time of Pythagoras of Samos (570-495 BC) and Claudius Ptolemaeus (Ptolemy) (AD 90-168). The following provides a brief overview of the important discoveries and theories proposed by these Greek intellects.

Pythagoras was the first to introduce the idea of a spherical earth (Sharaf, 1967; Unwin, 1992). He also thought that the heavenly bodies, including the earth, revolved around a central fire that sits in the centre of the universe. Since spheres and circles were considered the most perfect form, the heavenly bodies, including the earth, must have been spheres revolving around the central fire in circular paths (Unwin, 1992). Democritus of Abdera (460-370 BC) demonstrated from Anaximander's map that he thought the world was longer from east to west than from north to south (Sharaf, 1967). Herodotus made some of the most important developments in geography.

Herodotus travelled extensively and realized the importance of travel and exploration (Sharaf, 1967; Gosch and Stearns, 2008). He wrote a book in the mid 5th century BC entitled *Histories* about his voyages in which his writing supported Democritus' earlier claim that the world was longer from east to west (Sharaf, 1967; Roberts, 1973). Herodotus was very influential in shaping the mapping and geography in ancient Greece.

Aristotle (384-322 BC) was the first Greek to integrate mathematics and astronomy into geography. This was critical in that it has now allowed for geography to be placed on a par with other sciences in terms of systematic observations (Sharaf, 1967). Aristotle was able to prove that the Earth was a sphere and supported his theory with a contemporary understanding of eclipses. He too thought that the earth was the centre of the universe and that it was a stationary object. He made the important realization that there was correspondence between the southern and northern hemispheres of the earth (Sharaf, 1967).

Alexander the Great (356-323 BC), a pupil of Aristotle, went on great expeditions around the known world. With him, he brought trained civilian staff to keep records of the geographical discoveries. They also documented the ethnicity observed within the various geographic areas. There were also men who travelled with Alexander who paced out distances (Sharaf, 1967, Roberts, 1973). Dicaearchus of Messina (350-285 BC), another pupil of Aristotle, created maps of the Mediterranean and Greece. Unfortunately, not all of his work survived. Dicaearchus recorded the heights of mountains and included the Himalayas on his maps. He also tried to calculate the circumference of the earth (Sharaf, 1967).

Pytheas of Massillia (4th Century BC) voyaged in the northwest while Alexander was exploring the east. He wanted to travel north so that he could fill in what Herodotus did not know about this region (Sharaf, 1967). He kept records of everything that he saw while sailing; however, much of his work was also lost (Roberts, 1973).

A proclamation was made by Aristarchus of Samos (310-230 BC) that the Earth revolved around the Sun, but unfortunately he did not receive any support on this theory due to the geocentric theories proposed by Aristotle and Ptolemy (Sharaf, 1967).

Eratosthenes of Cyrene (275-195 BC) was a librarian in Alexandria, and was one of the greatest scholars there. He calculated the circumference of the earth with astounding accuracy (Sharaf, 1967, Kish, 1978). Finally, Ptolemy was an astronomer who worked in Alexandria. He wrote a compendium of astronomy before switching his focus to geography (Unwin, 1992).

Herodotus of Halicarnassus (484-424 BC)

Herodotus was a Greek historian who travelled over vast areas of known land in order to research for his book, *Histories.* He learned to make detailed observations as he travelled allowing him to produce very complete descriptions of the geographic features he observed. From all of the information that he gathered, Herodotus was able to create an image of the world which was quite accurate. The area of the world that he knew was relatively small which he acknowledged, but of the areas that he did know, he had very complete representations (Roberts, 1973; Gosch and Stearns, 2008). His book and other works are so detailed that a map can be constructed from his elaborate descriptions, both of which provide the most detailed picture of the ancient Greek world. Herodotus' work proved that travel and exploration was important for the Greeks in the pursuit to gain a better understanding of the Earth (Roberts, 1973).

Eratosthenes of Cyrene (275-195 BC)

Eratosthenes calculated the circumference of the earth with extreme accuracy. In fact, he is considered to be the first person to successfully calculate the circumference of the earth, even though many others tried before him (Unwin, 1992). He calculated the circumference to be approximately 40233.6 km – this is only 160 km greater than the circumference of the earth as we know it today. His success lies within the elegant mathematical methods that he used in his calculations (Kish, 1978). Eratosthenes

Figure 1.3 *Eratosthenes of Cyrene (27-195 BC). Eratosthenes was a mathematician and scientist in ancient Greece. In this oil painting by Bernado Strozzi, Eratosthenes can be seen on the left teaching in Alexandria as a librarian (below).*

agreed with Aristotle's thoughts on the spherical shape of the Earth and the movement of other celestial bodies around it. He was the first geographer to work out a system of latitude and longitude which changed the methods of mapping. With all of this, Eratosthenes created the best world map up until his time (Sharaf, 1967).

Ptolemy (AD 90-168)

Due to the advancements in mapping and geography before his time, Ptolemy had great advantages when it came to creating maps of his own. He used the system of latitude and longitude introduced earlier by Eratosthenes. Ptolemy incorporated equal spacing along the northern and southern edges, assigned sequential numbers to the lines of longitude from the west to east, and was able to calculate the maximum length of daylight for each line of latitude. He organized his work around the system of latitude and longitude – this is one of the greatest innovations in cartography (Tuplin and Rihll, 2002). Despite Ptolemy's innovative organization, his work contained some fundamental inaccuracies. When selecting a maximum circumference of the Earth to use in his work, he adopted the value that Posidonius of Apameia (135-51 BC) calculated instead of the more accurate result of Eratosthenes' calculation. This choice remains quite puzzling and ultimately led to inaccurate degrees of longitude. This is because Hipparchus of Nicaea (190-120 BC) had an accurate way of dividing the equator into 360 degrees based upon Eratosthenes' circumference value and other astronomical calculations (Sharaf, 1967; Unwin, 1992).

Ptolemy was the first geographer to introduce the terms meridian and parallel (Sharaf, 1967). He also introduced two types of projections, conical and cylindrical, which allowed for the world to be projected onto a planar surface (Unwin, 1992). With this, he explained how to construct a globe based on its parallels and meridians. These theoretical aspects comprised the first part of Ptolemy's book titled *Geographia*. The second part of the book was devoted to listing the latitudes and longitudes of major features found within regions of the continents. Because of this vast and extensive list, Ptolemy's book formed a basic account of the European world (Unwin, 1992).

The ideas and theories about the science and art of cartography that came from the brilliant minds of the ancient Greek philosophers, geographers, and scientists were able to stimulate the minds of others many years later. Fortunately, these scientists were equipped with the apparatus needed to test the theories posed by the Greeks (Sharaf, 1967).

THE WORLD ACCORDING TO PTOLEMY

Figure 1.4 *The world according to Ptolemy (90-168 AD) as recreated by H.G. Wells (1919). The map illustrates the progress of cartography in ancient Greece (right).*

Geographic Information Systems

A geographic information system (GIS) is a computer program that enables the user to manipulate and display all types of geographically referenced information (ESRI, 2010). GIS is used to assess spatial data in various ways and because of this, relationships, patterns, and trends can be observed and produced in a range of formats including charts, reports, globes, and maps (ESRI, 2010). GIS provides a standard in which geographic information and data can be expressed and understood. Maps created in GIS comply with specific standardized criteria allowing them to be analyzed and understood by all users.

Along with key concepts that make up the discipline of geography, GIS allows for a better understanding of the Earth. Taking *The Geographic Approach* to studying geography provides the opportunity to create geographic knowledge by analyzing and modeling processes derived from measured data of the Earth (ESRI, 2010).

GIS is a means of relating all types of data as long as they have a spatial component (ESRI, 2010). It uses many layers to display all the features of the data and information simultaneously to create a 'big picture' that can be used to uncover and analyze patterns and trends that emerge. GIS is not limited to modelling only current topological and geological features of the Earth; it has also been used to model past and possible future environments of the Earth (ESRI, 2010).

Digital Elevation Models and Terrain Analysis

An example of GIS can is demonstrated through a study done by Alexakis et al on Thessaly, a region located in Central Greece. Today, Thessaly's landscape consists of two major basins and two plains – Larisa and Karditsa. In this study, Alexakis et al. used GIS to explore the reconstruction of the Thessaly landscape during the Neolithic period. (Alexakisa et al., 2010) From this landscape analysis, a model of the settlements and habitation of Thessaly during this period was produced. Stratigraphic data were collected from many boreholes and were processed and analyzed using GIS, geomorphology, remote sensing, and digital elevation models (DEM). With the use of these technologies, an estimate of the amount and distribution of alluvial deposits found in the boreholes was modelled. This was important because alluvial deposits were concentrated in magoules established in the Early Neolithic Period (Alexakisa et al., 2009).

The basins and plains found in Thessaly today, along with the coastline and Lake Karla, were reconstructed to represent Neolithic Thessaly using the technologies mentioned earlier. GIS was used to place the magoules onto the reconstructed landscape which allowed the creation of a map showing where the settlements of Neolithic Thessaly were located (Alexakisa et al., 2010).

This is just one example of how GIS can be used, in conjunction with other technologies, to create a picture of the past Earth.

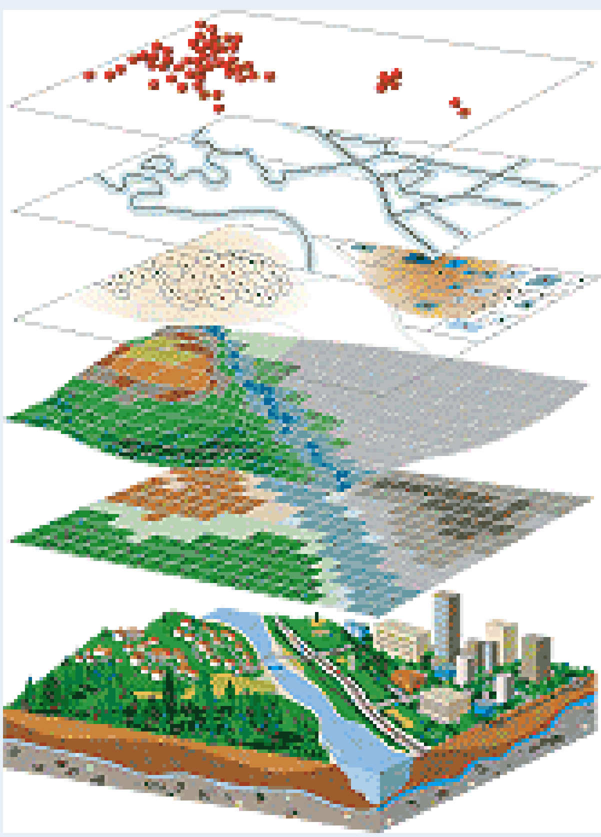


Figure 1.5 *An exaggerated example of how various layers, each displaying a single feature, can be put together to produce a complete picture. This allows for more information to be obtained and for patterns to emerge and become recognizable to the analyst (left).*

Aristotle and the Scientific Method

A Brief Biography of Aristotle

Aristotle (384-322 BC) was an ancient Greek philosopher whose area of study spanned physics, politics, ethics, biology, zoology, music, poetry, logic, and metaphysics (Ross, 2004). Although he cannot be considered an Earth scientist in the same sense as modern researchers who study the Earth, its atmosphere, biosphere, and oceans, Aristotle used his renowned systematic thought processes to describe the world around him (Harper, 2004). Despite making conclusions about the Earth that, based on today's knowledge, have proven to be incorrect, Aristotelian logic provided the basis on which the natural world was studied for over a thousand years after his death (Ross, 2004; Harper, 2004; Oldroyd, 1996).

Aristotle was born in the town of Stagira in the ancient kingdom of Macedon, centered in what is now northern Greece (Harper, 2004). His father was the Macedonian king's physician, one of Aristotle's many relatives who held such a high ranking post. Therefore, Aristotle was raised with the best education available at that time. He was educated and trained as a member of the aristocracy, and later studied at Plato's Academy (Figure 1.21) (Ross, 2004; Harper 2004). Although it is unlikely that the school had any formal doctrine to teach, the most prominent philosophers, Plato (429-347 BC) among them, gave students academic lectures about logic, which would greatly influence Aristotle's scientific studies (Harper, 2004).

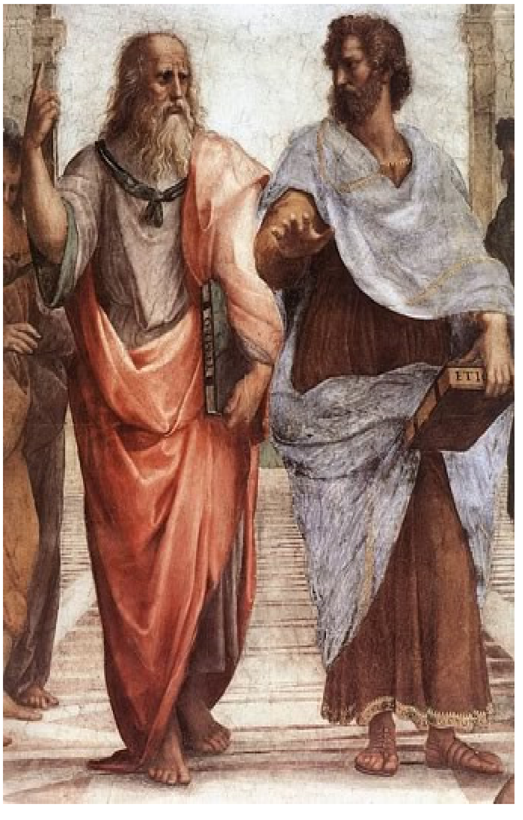


Figure 1.6 *Aristotle and his teacher, Plato, in Raphael's famous painting The School of Athens. Aristotle (on the right) gestures to the earth, signifying his belief in extracting knowledge from experience and observation.*

Aristotle's Method of Discovery

Aristotle, like all scholars of his time, did not perform experiments or strict observations to confirm his theories (Harper, 2004; Webster, 2006; Newman, 1887). Instead, most of his conclusions were drawn from his opinions, based upon the knowledge available to him in ancient Greece (Ross, 2004; Missiakoulis, 2008). His methodology, however, marked a significant step forward, as most previous writers ascribed many natural phenomena to supernatural causes (Harper, 2004). This was, in part, due to ancient Greek mythology which attempted to explain the origin of Earth and its history as a function of divine intervention (Ross, 2004; Madigan, 1988).

Aristotle's Research on Earth's Interior Processes

The method by which Aristotle studied the natural world is perhaps best analyzed using an example. One topic which Aristotle examined extensively was the formation of earthquakes (Oldroyd, 1996; Webster, 2006; Missiakoulis, 2008). Earthquakes were a plague to the Macedonian Empire, often killing hundreds of its civilians because their lack of knowledge about earthquakes led to the inability to adequately prepare for them (Lloyd, 1974). Therefore, the subject was well studied by Aristotle's contemporaries and predecessors.

Before Aristotle's time, the most prominent theory about earthquake formation was postulated by another Greek philosopher, Democritus (460-370 BC) (Webster, 2006). He believed that the Earth was filled with water and that if rain were to be added to this, the force of the excess water attempting to penetrate the surface of the Earth would result in an earthquake. Aristotle assessed this and many other theories and found flaws in each. If Democritus' theory were to be true, for example, Aristotle reasoned that the Earth would have to be sinking in many locations. He also gathered evidence about earthquakes occurring in places that were commonly exposed to neither rain nor drought, further contradicting Democritus' theories (Webster, 2006).

Next, Aristotle formulated a hypothesis of his own. In ancient Greece, the belief was that everything was comprised of one or more of the classical elements: earth, water, air and fire (Harper, 2004; Webster, 2006; Lloyd, 1974). Aristotle, using this belief, extrapolated that every substance had its own natural place. For example, the solid Earth was at the bottom, covered by water which was below air. If any substance was trapped in an unnatural place, it would eventually be forced to return to its natural place (Webster, 2006). In his writings, he justifies this belief system by using a number of observations. For instance, he noted that when solid objects are thrown in the air, they eventually come back down to Earth (Webster, 2006; Missiakoulis, 2008). This theory of knowledge is known as empiricism, wherein one extracts necessary information from sensory experiences, and extends this knowledge to more abstract notions (Ross, 2004). In this way, he extended his experience with gravity to his theory of earthquakes formation: if air were to be trapped underground, it would eventually move upward where air belongs (Webster, 2006). Therefore, Aristotle postulated that earthquakes were the result of violent winds that were trapped in cavities inside the Earth escaping, effectively causing the ground to shake (Webster, 2006; Kolbl-Ebert, 2009).

Lastly, Aristotle attempted to develop a method by which to describe regions and types of weather wherein earthquakes are more likely to strike. He stated that the spring and autumn seasons were probably the time when the severest of earthquakes occur because they are the windiest seasons (Webster, 2006; Kolbl-Ebert, 2009). He also estimated that earthquakes were more likely to happen near large bodies of water because he recognized that water evaporates and transforms into air, which would subsequently seep into the Earth's surface and increase the pressure inside. The limited records on earthquake incidences available to Aristotle at that time indicated to him that his theory was indeed correct (Webster, 2006).

Although modern seismologists know Aristotle's observations led to incorrect conclusions, it is the method by which he performed these studies that was truly revolutionary to the field of Earth science, not his findings (Ross, 2004; Harper, 2004; Oldroyd, 1996; Newman, 1887; Lloyd, 1974). With his unique form of deductive reasoning, Aristotle asked a question, performed background research, tested previous hypotheses by analyzing empirical data (albeit not strictly numerical), and concluded that these theories could not be correct (Ross, 2004; Webster, 2006). He then postulated his own hypothesis based on empiricism. This in itself was a significant advance in science because previously, theories were commonly tested solely against revelation, intuition, and a priori reasoning, rather than against observations of the natural world. Aristotle's method of investigation was a vital precursor to the modern scientific method (Madigan, 1988).

Figure 1.7 *Aristotle tutoring Alexander the Great (below). Alexander's father personally selected Aristotle from a list of many famous philosophers to begin educating his son when Alexander turned 13 years old. In return, the king rebuilt Aristotle's hometown, which he had previous razed.*

The Product of Scientific Thought

By integrating empiricism into his investigations, Aristotle was able to publish Meteorology (350 BC), a treatise comprised of four books that contained his theories about Earth science (Ross, 2004; Webster, 2006, Kolbl-Ebert, 2009). Despite the modern definition of the treatise's name, the scope of Meteorology's contents encompassed much more than the study of weather, but rather geology and earth science in its entirety. The first book in the series is constructed from a combination of studies on weather, such as precipitation, winds, and climate change, and astronomical studies, including his ideas about shooting stars, comets, and the Milky Way. The second book is a study of oceanography with an analysis of seas and their formation, as well as earthquakes, volcanoes, and several weather-related topics. His final books focus more closely on weather and corresponding optical phenomena, such as rainbows and halos (Webster, 2006).

Many theories published in Meteorology, in light of modern research, have been proven false (Harper, 2004; Lloyd, 1974). However, this was primarily due to the limited technology in Aristotle's lifetime. Most of the topics published in Meteorology were processes that required extensive amounts of observation over long periods of time to understand fully. Continuing with Aristotle's research on earthquakes as an analogue, if there were a greater quantity of available records about earthquake incidences in many locations, Aristotle may have identified that his theory was flawed. He would likely refine his theory had he known earthquakes are not a function of weather alterations and are no more likely to occur in one season than others (Plummer et al., 2007). Accessible empirical evidence and the instruments required to derive it were the missing materials in Aristotle's otherwise complete implementation of the modern scientific method (Ross, 2004; Webster, 2006). This is not to suggest that every idea published in Meteorology was later proven to be incorrect. For example, Aristotle was the first documented scientist to recognize that fossils were once living animals, though be believed that they lived inside the sediments that they were discovered in (Webster, 2006; Plummer et al., 2004). Perhaps the idea of his that best agrees with modern science is his theory that Earth's surface is dynamic. He noted that rivers appear to dry up and, because of this, he believed that the seas must also do the same. Therefore, he wrote that the land and the sea change throughout time; that is, land transforms into sea and sea into land in an almost cyclical process (Webster, 2006). He even stated that this process is not observable because it occurs over periods of time much greater than the length of one lifetime (Lloyd, 1974).

Aristotle as a Legend

For most of his life, Aristotle's teachings were revered by the public. This was due in part to the fame of his teacher Plato, who in turn was taught by Socrates (469-399 BC). Both of these Greek philosophers were renowned for their innovation in a myriad of scientific disciplines (Ross, 2004). Furthermore, in his later years, he became the tutor of the new king of Macedonia, Alexander the Great (356-323BC) (Ross, 2004; Lloyd, 1974). Although he lost the king's favour toward the end of his life by providing Alexander with poor information on the geography of his empire, Alexander was greatly influenced by Aristotle. For instance, with Aristotle's advice, Alexander travelled with many scientists who mapped the landscape as they journeyed and interpreted the writings of the civilizations they encountered, ultimately aiding his conquest (Ross, 2004). Despite Alexander's eventual public contempt for Aristotle, the Macedonian king was never able to convince the public to ignore Aristotle's teachings because there was constant conflict between Macedonia and the surrounding empires. Aristotle avoided possible persecution from the Macedonians by escaping to Athens in 323 BC, where he died a respected man (Oldroyd, 1996).

Unfortunately, Aristotle was so well respected that many of his conclusions, even those that scientists now know to be incorrect, remained the highest scientific authority for many centuries to come (Ross, 2004; Harper, 2004). In fact, in the quest to reconcile scientific theories with Christian theology, Aristotelian philosophy was adopted as the official philosophy of the Roman Catholic Church from AD 1100 to AD 1500. Consequently, many scientists in the Middle Ages and the Renaissance were criticized simply because their findings did not coincide with Aristotle's discoveries (Ross, 2004). It is an irony of the history of science that Aristotle's studies, which were likely the first works based on empiricism, ultimately impeded observational science.

From Earthquakes to Planetary Formation

In addition to the surface waves which cause the ground to shake violently, earthquake activity is associated with two types of waves that pass through Earth's interior. These seismic waves are the primary waves (P waves) and secondary waves (S waves), and they are essentially propagating vibrations that transfer energy from the focus below the epicentre outward in all directions (Plummer et al., 2004).

If seismometers are placed on the opposite side of the Earth from where the earthquake originates, they should theoretically detect these S and P waves. However, experiments proved that only P waves can be detected, and because scientists know that P waves can propagate through a liquid while S waves cannot, this indicated that the Earth's inner core must be composed of liquid (Plummer et al., 2004).

As an analogy, consider the fact that a glass lens will refract light, depending on the shape and composition of the lens. In a similar way, Earth's interior bends seismic waves while they propagate through the Earth, and the amount of this refraction as well as the speed at which the wave travels is contingent upon Earth's interior conditions, primarily its density and composition. Therefore, through the use of simple mathematical models, seismic waves have allowed scientists to analyze the interior of the Earth (Figure 1.23) (Plummer et al., 2004).

The data derived from seismic waves, along with data pertaining to Earth's magnetic field, revealed an important trend: the planet's density increases progressively from the crust to the core (Levin, 2009).

When NASA analyzed the seismic wave data from the Moon, they discovered the same density trend. To make sense of this data, scientists proposed a theory known as planetary differentiation, which explains an important process in the formation of the Earth and indeed all planets. The theory states that debris expelled from forming stars begins to accrete around the star to form protoplanets. Next, thermal energy from the impacts and gravitational pressure melt large portions of the celestial object. In these melted zones, it is possible for denser materials to essentially sink toward the centre of the body, while lighter elements will rise toward the surface. When this theory was modelled, researchers also noted that some materials may also differentiate according to their chemical affinities, and are essentially transported by other material to which they were bounded. This theory has allowed scientists to both explain why certain elements are found in specific layers of the Earth, and to approximate the composition of the Earth at inaccessible depths (Levin, 2009).

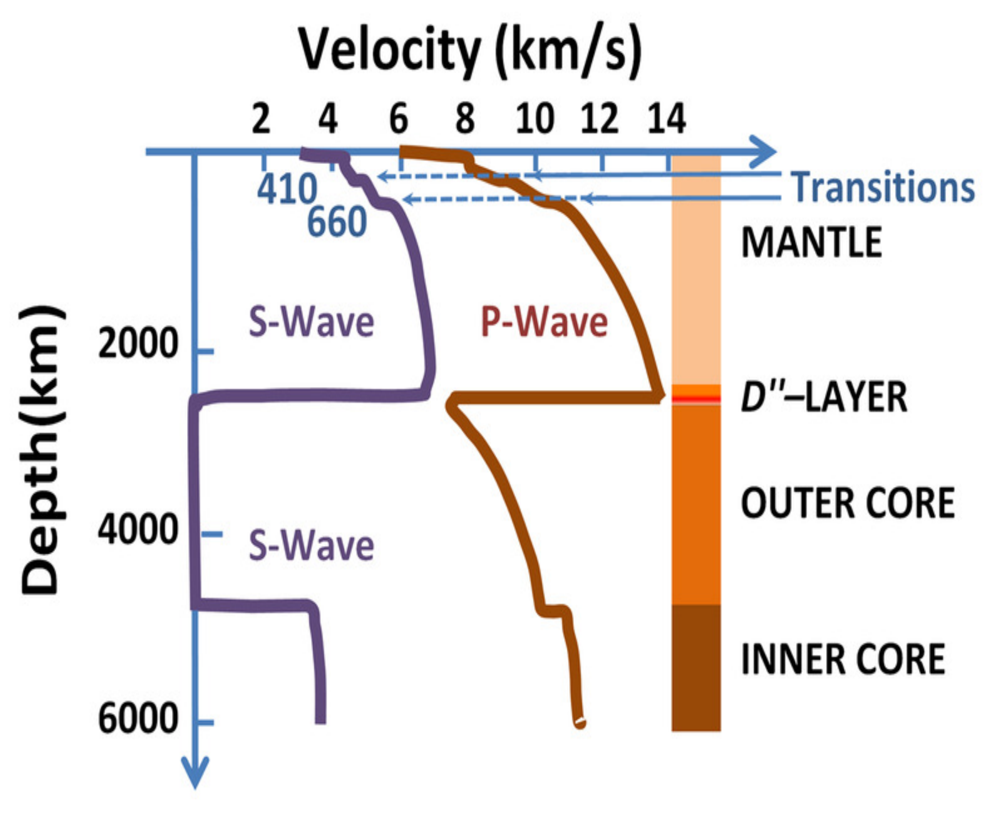


Figure 1.8 *The graph above describes the velocities at which S and P waves propagate through various layers of the Earth. Note that S waves simply cannot travel through the outer core, as it was liquid.*

Scientific Method and Views of the Earth in Ancient India

Indus Valley Beginnings

From the dawn of Indian civilization over 8000 years ago (Minnesota State University, n.d.) to before the arrival of the British Raj in the 18th century, India has seen great scientific advances originate from within her historical borders, often catalyzed by the spread of ideas developed in other places. Located east of ancient Bactria and Persia, and west of China and Japan, India—a major center for trade along land and sea routes to Arabia and the Orient—played an important role in the propagation of ideas in the eastern hemisphere. Further philosophies were brought in by means of religion—Buddhist pilgrims journeyed to the birthplace of their religion in India while Islamic missionaries from Arabia and the Mediterranean sought new converts in the east (Bose et al., 1971). These cross-cultural dialogues spawned by trade and religion ultimately added to scientific inquiry in ancient India—inquiry that is credited with the first use of an artificial reservoir to store water (Rodda and Ubertini, 2004) and the first mention of the number zero in the world.

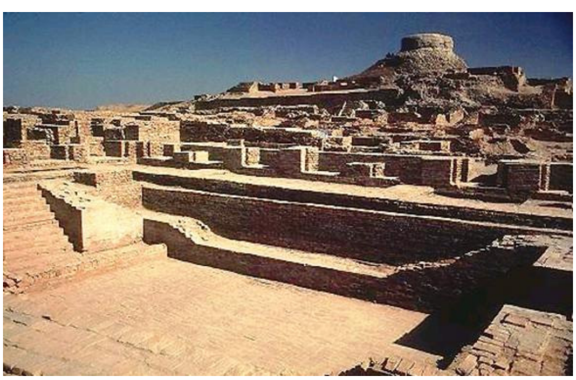


Figure 1.9 *Excavation site of Mohenjo-daro. Large cities in the Indus Valley had elaborate water and sewage systems. Pictured is a great bath in Mohnejo-daro.*

The history of science and technology on the Indian subcontinent can be traced back to the Indus Valley, which was home to a bronze-aged civilization of the same name. Located in present-day Pakistan and parts of western India, the Indus Valley civilization was centered on the cities of Mohenjo-daro and Harappa. The Indus Valley civilization was highly dependent on the local landscape, relying on the Indus River to supply water to an otherwise arid region, and it is therefore not surprising that various ideas about earth history and terrestrial processes were developed. Cities were laid out near rivers and coasts and had elaborate networks of sewage systems connected to public and private baths constructed with precisely placed bricks. These constructs indicate knowledge of fluvial processes and hygiene. Irrigation channels were additionally used to improve farms, and early philosophical works allude to a heliocentric view of the Earth's place in the solar system (Rodda and Ubertini, 2004). It was not until the Vedic period however that these ideas were developed into a more comprehensive understanding of hydrological, geomorphic, and orographic processes.

Although little information about the Indus Valley civilization remains, it is possible that the same planet which the inhabitants of the civilization knew so much about caused the downfall of the civilization. Studies of historical intensity of the geomagnetic field show a link between periods of high intensity and societal changes. Periods of intense geomagnetic fields are thought to have affected climate and caused the North Atlantic to cool, resulting in a more arid Middle East. Peak intensities correspond to political strife and the collapse of many eastern bronze-aged societies including the Indus Valley civilization (Gallet et al., 2006).

Science and Religion in the Vedic Period

The Vedic Period (circa 1300-300 BC) saw scientific thought flourish under the hand of religion. The *Rigveda* and *Puranas* were two of several influential texts composed at this time, and have given historians an insight into life and the beliefs of this time.

The *Rigveda*, a religious text, asserts that the universe is infinite, with the sun in its center so that its rays spread to the heavens passing the earth (Kak, 1998). The *Puranas* discuss the age of the universe, proclaiming that the universe undergoes cycles of creation and destruction that are 8.43 billion years or longer (Kak, 2005). The *Puranas* additionally give an account of how the Earth as it was known then may have formed, tying in knowledge of earthly processes:

"I remember that once upon a time there was nothing on this earth, neither trees and plants, nor even mountains. For a period of eleven thousand years (four million earth years) the earth was covered by lava… Then there arose great mountains, but without any human inhabitants." (Kak, 2005)

It is important to recognize that while these accounts often contained references to demons and other mythological figures, the texts point to an understanding by the Indians of geologic processes over very long time scales. Of course, the difficulty in translating these texts must also be considered. Interpretations of Vedic texts during the Vedic Period may have differed from our interpretation, causing us to misjudge the extent of Vedic knowledge of terrestrial processes.

The idea of measurements and units was of great importance at the time. Use of the unit of length *angulum*, which is approximately equal to 1.763 cm, was first documented around 2000 BC in the Indus Valley. The same length measure was used to at least the Mughal period (AD 1600) before the arrival of Europeans. Precise length scales were important in measuring the earth in ancient India, largely because agriculture was the main source of income, and precise measurements allowed for better revenue-collection system (Balasubramaniam, 2009).

Figure 1.10 *Statue of Aryabhata (born AD 476) at the Inter-University Centre for Astronomy and Astrophysics in Pune, India*

In addition to the *angulum* being used as a unit of length, the Vedas referenced a longer unit *yojanam*. A *yojanam* is equivalent to 16000 *hasta*, which in turn is equivalent to 24, 28, 32, 42, or 52 *angulum*. This discrepancy arises from the 3rd century BC writer Kautilya's work *Arthasastra*. *Arthasastra* contained information on the different measures used at the time, including the *hasta* for which it had several different values, each of which was likely used in different time periods. The Vedas gave a value of 5000 *yojanam* for the circumference of the earth. Interpreting a *hasta* as 28 *angulum*, the Vedas predict that the Earth is 39 491.2 km around, which is within 1.5% of the accepted value of 40 075 km. This fact demonstrates that the ancient Indians not only knew that the planet was spherical, but also possessed a very good understanding of its size (Balasubramaniam, 2009).

Further to knowing the shape and size of the Earth, Indians from the Vedic period possessed a working knowledge of terrestrial processes. Rainfall remained an important feature and physical process in the lives of the ancient Indians, and Vedic scientists recognized the cause of the process as heat from the sun lifting water to the atmosphere. Mythology is intricately mixed into this however, with Parjanya the rain god depicted as a bull roaring down to impregnate plants with his water (Ramanathan, 1993). On his visit to India, the 10th century Persian scholar Al-Biruni also commented on the influence of religion in scientific works from the Vedic period. Al-Biruni noted, among other examples, that the Indian thinkers were well aware of the mechanics behind eclipses, but still bowed down to Brahmin myth in which a demon in the form of a "Head" devours the sun, describing the mythological version before their own scientific interpretation (Bose et al., 1971).

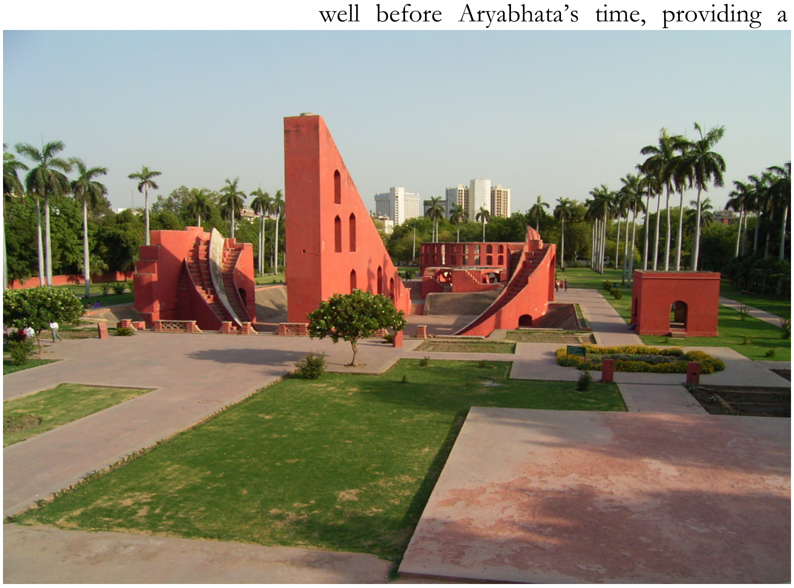
The apparent influence of religion on science can be explained by the notion that science in ancient India sought to describe the myths themselves and questioning myths and rituals rejected the way of life that was intended to be justified. By discussing ideas that were then regarded as being within the domain of the priests and seers (and by extension politicians), scientists risked being dragged into a very political discussion (Chattopadhyaya, 1977). It was not until much later, however, that thinkers freely presented their ideas without alluding to the many religious myths propagated during the Vedic Period.

Science in the 5th Century

The 5th century saw a renaissance for science and mathematics in ancient India. The Gupta dynasty, deemed the "golden age of ancient Indian learning" (Ansari, 1977), was in power, and the famous University of Nalanda was seen as a great center for science. Trade routes flourished with the Middle East, Greece, and Byzantine Rome, bringing in further ideas. It was at this time that one of India's great thinkers, Aryabhata (pictured in Figure 1.32), was born, and it was from this period that India's oldest surviving scientific work, Aryabhatiya, was published.

Unlike other isolated civilizations such as the Maya (see pages 20-23), cross-cultural communication readily occurred between India and other societies. Greek figures such as Pythagoras and Alexander the Great (see pages 4-11) are known to have visited India well before Aryabhata's time, providing a foundation for the future sharing of scientific ideas (Bose et al., 1971). Around this time, Greek influence is apparent in scientific thought. Two works from this time, the Romaka Siddhanta and the Paulisa Siddhanta are among the oldest Indian works in that contain knowledge from the West, their names alluding to foreign influences. The accounts of these works are mentioned in the works of Varahamihara, a 6th century Indian astronomer. Varahamihara's writings also contain references to technical Greek terms and constellation names, indicating Western influence in Indian science (Bose et al., 1971).

Figure 1.11 *Science after Aryabhata: Jantar Mantar, a Mughal-era astronomical observatory in Delhi. A similar observatory is located in Jaipur, several hundred kilometers away.*



Aryabhata (476-550) is credited with being the first in India to develop the idea that the earth rotated on an axis and that eclipses are caused by shadows, in his work Aryabhatiya which he published when he was 23. Astronomy and knowledge of the Earth's place in the universe were held in great esteem at the time, and Aryabhata at one point wrote,

"He who disparages this universally true science of astronomy…loses his good deeds and his long life" (Bose et al., 1971).

Greek and Babylonian astronomical findings were built upon by Aryabhata, and historian P.C. Sengupta suggested that the planetary theory based on Babylonian elements developed by Aryabhata for the Indians can be compared to what Ptolemy did for the Greeks (Bose et al., 1971).

Aryabhata's magnum opus Aryabhatiya is composed of 123 verses divided into four chapters. The first three chapters primarily deal with mathematics, while the last, Gola, deals with astronomical concepts. In Gola, Aryabhata calculated the angular velocity of the earth as approximately 0.25 arc minutes per second, which is very close to the modern value. Aryabhata additionally recognized the different between a sidereal day and a solar day. In Aryabhatiya, he writes,

"The conjunction of the sun and the earth forms the [civil] days; while the rotation of Earth causes the naksatra dina (sidereal days)" (Dutta, 2006).

It is imperative to understand the importance of Aryabhata's contributions to science in India in order to fully understand the development of science in the East. Unlike previous astronomers, his approach to understanding the Earth's place in space was more mathematical than calendric. Rather than focusing on the motions of other celestial bodies with respect to the Earth—the basis of the ancient calendars—Aryabhata, equipped with knowledge discovered by his predecessors and foreign thinkers alike, provided a mathematical model of the motion of the planet. Aryabhata's findings were later exported to the Arabs, who, along with Indian mathematicians, further built upon his findings (Ansari, 1977).

Modern Measurement Techniques in the Earth Sciences

Science has come a long way since thinkers such as Aryabhata proposed lengths for the circumference of the earth. New methods have since been developed that yield answers with greater precision, largely due to the advent of better technology. Rather than using celestial trigonometric calculations to discover attributes of the earth, we are now able to employ satellites and computers to accurately map the planet.

The basic principle in measuring the earth has not changed over time—like the ancients, we can use our knowledge about other related phenomena and apply this knowledge using available technology. As technology develops, precision generally increases, yielding better measurements.

Satellites are an important tool in the earth sciences. Using highly precise satellites, continental drift can be measured, climate data can be acquired, and the world can be mapped. As mentioned before on page 7, GIS is an important tool in cartography. Data from GPS technology, guided by an array of satellites, can be linked together with geographical information systems (GIS) to produce different types of maps of the world (Abler, 2005). Satellite altimetry—the measure of altitude by satellites—has been used produce topographic maps of the world's oceans, for example. By bouncing microwave signals off the ocean floor and measuring the time delay in its return, the depth of the ocean can be ascertained (Fu and Cazenave, 2001).

One application of satellite altimetry is in resource exploration. In mapping sea floors and obtaining gravity data, locations of (for example) hydrocarbon deposits can be established (Bhattacharyya, Verma and Majumdar, 2009). The recently developed technique of finding gravity data—the distribution of the earth's mass—using satellites forms satellite based gravity analysis. NASA's Gravity Recovery and Climate Experiment (GRACE) tracked changes in the Earth's gravity field via two satellites for five years starting in 2002. The highly accurate data's error estimates indicated a 2-cm accuracy in determining height over both land and ocean regions, with a spatial resolution of 400 km (Tapley et al., 2004). Such gravitational data could be used to find deposits of resources by looking for characteristic densities in certain regions, and in determining the mass of the earth to a greater precision, since this takes into account density change. Previous methods of estimating the mass of the earth involve invoking Newton's Universal Law of Gravitation and using the known value of the radius of the Earth to calculate mass. In both cases, knowledge of other phenomena and/or technology was used to provide an answer to the question, with the latter being more precise due to better technology.

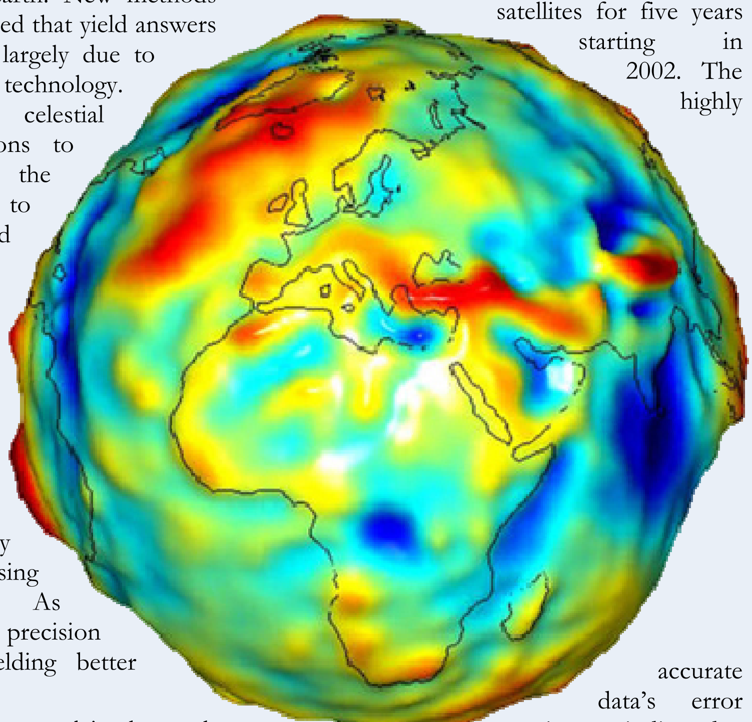


Figure 1.12 *Gravity data compiled by NASA's GRACE mission. GRACE began with the launch of two satellites in 2002.*

Roman Interpretation of Earth Processes in Pompeii

Just 240km south of one of the most prosperous cities of the ancient world, the city of Pompeii lies in the shadows of Vesuvius (Beard, 2008). Pompeii did not play any significant role in Roman history but it will forever be remembered because its fate was quite remarkable.

Ironically, the city of Pompeii was successful for the same reason that it was destroyed: Mount Vesuvius. A prehistoric eruption of the volcano created the landform that the city was built on. When the volcano erupted, lava travelled out from the cone and towards the Sarno River in the southeast. About a quarter mile from the shore, the lava cooled and formed an isolated, extended hill (Leppmann, 1968). As time went by, the cooled lava was covered by humus and greenery creating an inhabitable environment. Around 800 BC the land was settled by the Greeks but was eventually taken over by the Romans during the Samnite war in 420 BC (Corti, 1951).

Figure 1.13 *Ruins of the Temple of Jupiter in the forum of Pompeii with Vesuvius in the background. The temple was destroyed in the earthquake of AD 62 and was still awaiting reconstruction when the city was buried in the eruption of AD 79 (above).*

Its proximity to the Sarno River, which connected to the sea, allowed Pompeii to become an important trading place (Harris, 2007). By 197 BC Pompeii and the nearby town of Herculaneum were the resorts of the wealthy governing Roman class (Corti, 1951). Amphitheatres, temples and baths were constructed creating an oasis for Rome's elite (Leppmann, 1968). However, not all of Pompeii's inhabitants were part of the upper Roman class. Pompeii was attractive to farmers because of the fertile soils that allowed for the wheat to be harvested twice a year (Harris, 2007). The fertility of the soil was a result of the prehistoric volcanic eruptions of Vesuvius. After the eruption that formed the physical foundation of Pompeii, Vesuvius remained inactive for many centuries and the crater closed up (Corti, 1951). When Vesuvius did erupt for the first time in over a millennium, the outcome was devastating.

It was in AD 62 that Vesuvius showed the first signs that it was active once again. The region surrounding Pompeii, including Herculaneum and other small cities, had always experienced small earthquakes. Around midday on 5 February AD 62 a huge earthquake shook the area (Harris, 2007). With the epicentre being in Pompeii, not many of the buildings in the city survived. The Temple of Jupiter was one of the many structures that were destroyed in the giant quake. Collectively, the citizens of Pompeii decided that although the damage was extensive, the benefits of the geology of the area outweighed the dangers (Corti, 1951). Of course, not everyone agreed and some of the inhabitants that were not dependent on the land relocated. The citizens that did remain in the city quickly forgot about the havoc that the mountain looming in the background was capable of causing (Corti, 1951). Sixteen years later, the cities of Pompeii and Herculaneum were soon reminded of the devastating power of the mountain.

Titus (AD 39-81) had only been emperor for about six weeks when strong earthquakes accompanied by rumbles of distant thunder shook the district on 20 August AD 79 (Corti, 1951). As the earthquakes were frequent in the area, the warning signs were not dwelled upon. 24 August AD 79 was recorded as one of the hottest mornings in Pompeii (Harris, 2007). The civilians went about their business just as they would have any other day. Around midday, the closed crater of Vesuvius was cracked open sending thick, black smoke into the air. As people tried to flee Herculaneum and Pompeii, they faced a sea of mud and lava as ash and lapilli rained down on them from above (Corti, 1951). Herculaneum was much closer to Vesuvius and so was destroyed by the first nuée ardente only 5 minutes after the initial eruption. Volcanic debris blanketed Pompeii until the fourth nuée ardente finally destroyed the city (Berry, 2007). The city that had once been a vacation getaway for the elite was now buried under 6m of volcanic debris (Harris, 2007). It wasn't until the 18th century that the almost perfectly preserved city was rediscovered and the tragedy of the eruption was discovered (Corti, 1951).

Hercules and the Titans

Mythology had a large impact on daily life in Pompeii. The temples, aside from the amphitheatre, were the largest attraction in the city. When the earthquake hit the city in AD 62, the restoration of the temples was the first task to begin (Corti, 1951). The earthquakes and major eruption of AD 79 were primarily viewed as a repercussion of Hercules imprisoning the titans under the base of Vesuvius and so were attributed to the insufficient worship of the gods. The people of Pompeii believed that since the gods supported and protected Rome, they did the same for Pompeii as long as they received the appropriate worship (Beard, 2008).

Figure 1.14 *Vesuvius is depicted as being covered in vines with Bacchus, the god of fertility and wine in the foreground. The snake in the bottom right corner is the genius of Vesuvius and was the local spirit of fertility. This painting may indicate that the people of Pompeii understood Vesuvius to be the source of the fertile soil. Alternatively it may show that they were unaware of its real dangers and that the gods were responsible for their good fortune (left).*

The myth of Hercules implied that upon defeating a monster in Rome, Hercules travelled south to Campania, where Pompeii was located (Wiseman, 2004). Once he arrived, he saw that the Titans were revolting against the gods of Olympus. Hercules was able to defeat the Titans and imprisoned them beneath Vesuvius. After his victory, Hercules founded two cities and named them Herculaneum and Pompeii, after himself and the procession that was held for him (*pompe*) (Wiseman, 2004). Although at the time the two cities were insignificant in the overall Roman myth, it was predicted to be only a matter of time until the Titans rebelled and destroyed the two cities.

The major earthquake of AD 62 along with the other minor earthquakes that occurred frequently was attributed to the conflicts of the Titans. Periodically, they were thought to shake themselves in an attempt to release themselves from their prison, causing the earth below their feet to shake. After the earthquake of AD 62, the people believed that the Titans had almost succeeded in escaping but were prevented by the power of the gods (Corti, 1951). It was after this that the inhabitants of Pompeii believed that the prayers and sacrifices that they were making to the gods were insufficient. To prevent such a disaster from recurring, the number of sacrifices and prayers made were doubled. In order for the gods to be fully pleased, the temples needed to be rebuilt immediately but until they were, temporary temples replaced them (Corti, 1951).

When major earthquakes started again on 20 August AD 79, it was believed that the Titans were stirring once again. Immediately, prayers and sacrifices were increased and it was thought that this would keep them safe from the fury of the Titans (Corti, 1951). On 22 and 23 of August AD 79, the shakes were less severe confirming the belief that the gods had been appeased. As the giant cloud of smoke rose from the new crater of Vesuvius, the Pompeians began to think that the worship of the gods had not been carried out properly (Beard, 2008).

The spot from which the flames and smoke were issuing was the same spot where Hercules had detained the Titans below the earth. In the terror and panic, the people thought that they could see the huge black forms and hear the trumpets of the Titans signalling their readiness for vengeance (Wiseman, 2004). It was clear that the gods were not happy. They had come down to earth to punish humanity by sending the world into chaos and destruction (Corti, 1951). While some people still sought the aid of the gods, others believed that this was their punishment and were being condemned to eternal darkness.

In this sense, the final destruction of Pompeii was self-inflicted by the inhabitants. The Titans were responsible for the devastation that the city had endured up until the eruption because of their anger towards the gods. These beliefs were widely held across the district but still others believed the gods had no part in the destruction of Pompeii.

Pliny the Younger

Very few, if any, of the inhabitants of Pompeii or Herculaneum were able to escape the volcanic eruption but the letters of Pliny the Younger (AD 61-112) to Tacitus (AD 56-120) provide a first hand account of the disaster (Leppmann, 1968).

Pliny the Younger was the nephew of the scientist and scholar Pliny the Elder (AD 23-79), author of the extensive compendium of scientific disciplines, *Natural History* (Berry, 2007). On the day of the eruption, Pliny the Elder was stationed as a commander 30 kilometers away from Pompeii. His desire to study the eruption and his duty to help the evacuation of the city led to his death in the downfall of Pompeii (Berry, 2007).

the area. In one of the many letters, he noted that the earthquakes had become so strong that "it seemed as though everything was being turned upside down." (Berry, 2007).

A Scholar's Perspective

Although one of the most noted scientists at the time, Pliny the Elder was not the only one interested in the power of Vesuvius. The Greek geographer Strabo (63 BC-AD 23) made note of the true nature of Vesuvius before the eruption in AD 79. He was familiar with the geology of Etna and noticed the similarity in the burnt appearance of the rocks. This resemblance allowed for him to conclude that like Etna, Vesuvius had also erupted at one point (De Carolis and Patricelli, 2003). He believed that the area had once been covered in flames but then the fuel gave out so the fire was quenched and therefore Vesuvius was no longer active in the same way as Etna (Leppmann, 1968).

Figure 1.15 *In the painting The Last Day of Pompeii, Karl Briullov depicted the chaos that was unleashed as the city of Pompeii was destroyed by the eruption of Vesuvius (right).*

Tacitus wrote to Pliny the Younger asking about his uncle's death and it is in those letters that we find the detailed scientific observations of the eruption (Berry, 2007). In the letters, Pliny the Younger makes note of every detail of the eruption that he can see from his location 30km away. He uses terminology to explain not only visually what is happening but also the overall sentiment in

Vitruvius, a Roman engineer and architect who lived in the 1st century BC, was also able to identify the true nature of Vesuvius (De Carolis and Patricelli, 2003). He believed that the Pompeian pumice was once another type of stone that was converted because of the fire burning beneath Vesuvius. In order for the rocks to be found so displaced from the mountain, they had to have flowed out of the crater and flooded the countryside (De Carolis and Patricelli, 2003).

Whether an act of the gods or a result of a fire burning underground, the consequences of establishing a city at the base of a volcano was understood by all on 24 August AD 79. The destructive nature of the mountain in the background was shown as an entire city and its inhabitants were frozen in time under six meters of volcanic debris (Harris, 2007).

Volcanism and the Modern Landscape

The Earth as we know it is in constant flux as continental plates move and new landscapes are created. The movement of the plates is not the sole explanation for today's landscape. Volcanoes are often forgotten yet they are some of the most powerful influences on the modern topography.

Hawaii

One of today's top vacation destinations was created by volcanic activity; Hawaii is composed of a series of volcanic islands. A hot mantle plume in the mid Pacific Ocean plate is responsible for creating the Hawaiian Islands (Macdonald, Abbott and Peterson, 1983). When a plate moves over the mantle plume, a volcanic island is formed. As it continues to move, new islands are formed and the old ones are eroded (Macdonald, Abbott and Peterson, 1983). The erosion of old volcanic islands and the creation of new ones have a large impact on the overall landscape of our planet.

Figure 1.16 *The tuff cone Diamonhead as seen on the Hawaiian island of Oahu. The islands of Hawaii were all formed as a result of underwater volcanic activity (left).*

On the Hawaiian Islands themselves, many of the natural landforms that are seen are a direct consequence of past geologic events, or in the case of the big island of Hawaii, current volcanic activities. One example is that of Diamondhead on the island of Oahu (Macdonald, Abbott and Peterson, 1983). The giant tuff cone was believed to have formed from a relatively brief volcanic eruption that lasted for only a few hours because of the symmetry of the crater (Macdonald, Abbott and Peterson, 1983). In addition to Diamondhead, the craters and valleys that are found throughout all of the Hawaiian Islands can be attributed to volcanic activity.

Scotland

Scotland is not usually thought of as an area of strong volcanic activity but a vast majority of the landscape is indeed a result of ancient volcanism. As the plates moved with the formation and break up of supercontinents, Scotland passed over a number of hot mantle plumes aiding in the creation of its mountainous modern day landscape (Upton, 2004).

The Isle of Mull on the west coast of Scotland is one of the many places in the country where the volcanic history is evident. Mountains cover the island as relics of past hot spots on the mantle (Upton, 2004). The island is littered with igneous rocks, ring-dykes and calderas. The escarpments on the island are shaped by steep contacts of ring-dykes and gabbros (Upton, 2004). A number of other islands off the coast of Scotland are also perfect examples of the impact of volcanism on the modern landscape. The islands are covered in cone sheets and hills that act as a reminder of the once active volcanoes (Upton, 2004).

Hawaii and Scotland are only two of the countless examples of volcanism's effect on the modern landscape. Although most of the examples that have been mentioned are ones that occurred millions of years ago, volcanic activity is still present today. The current landscape is being changed as volcanoes across the globe continue to reshape the existing topology and create new landmasses, adding to the overall beauty of our planet.

Ancient Maya

The ancient Maya were an intensely religious people whose faith led them to make incredible scientific advances, particularly in astronomy and mathematics. They created a complex calendar that allowed them to predict astronomical events with remarkable accuracy. Their advanced mathematics enabled them to calculate millions, and was the first ever to use the concept of zero (Laughton, 1998; León-Portilla, 1988)). We are still learning about this culture today through their beautiful art and intricate architecture.

Figure 1.17 *The Mayan Moon Goddess (above). She was one of the many Mayan deities.*

The many cities of the Maya were located in a variety of environments. Mayan civilization stretched across Belize, western Honduras and El Salvador, and the Chiapas and Yucatán peninsula of Mexico. The southern part of this region was particularly well-suited for agriculture and contained a range of volcanoes (Laughton, 1998). Thick tropical rainforest spread across the central Maya, while limestone dominated the northern region. Subterranean streams running through caves provided an excellent source of water in this area (ibid.).

Ancient Maya flourished for nearly three thousand years. The Preclassic period began around 1500 BC when first settlements were small villages. The Classic period extended from around AD 250 until AD 900. It is believed that the Mayans made most of their advances in science and art during this era (Laughton, 1998; Benson, 1967). It was also in this period that villages grew to be major city centers with magnificent temples. The majority of people still lived in thatched huts, but the rulers and upper class were housed in elaborate stone palaces. The Classic period ended in disease, war and land depletion in the lowlands of Maya (ibid.). Cities located here gradually collapsed and were abandoned in the Postclassic period (ca. AD 900 to AD 1500). Highland Mayan cities continued to thrive until the 1500s, when the arrival of the Spanish caused the general downfall of the Maya. Spanish bishop Fray Diego de Landa also destroyed most of the Mayan codices (their "books of knowledge"), claiming they were full of superstition and lies. Only four codices survived (ibid.).

Although highly successful, the Maya was never a unified empire. It was instead made up of many city-states that were often at war with each other. Despite this inherent animosity, the Mayan people shared a common culture. They believed in the same deities and myths, participated in the same rituals, played the same games, built similar structures and used the same time cycles and calendar (Laughton, 1998). It is remarkable that such a divided people could be at the same time so unified.

Deities and Myths

The Mayans believed that before the Earth was created there was only sky and a massive primordial sea. The gods of each of these domains met and decided that they needed people to worship them. Since these worshippers would need somewhere to live, the deities created the Earth (Laughton, 1998). This Earth was square and was bounded above by the celestial realm and below by the underworld (*Xibalba*). A tree at each of the four corners of the earthly realm supported the sky above while the World Tree (*wakahchan*) at the center of the square allowed souls of the dead to move between the three realms. This great tree was rooted in the underworld and extended up through the Earth to spread its branches in the celestial realm (ibid.).

Next, the gods created animals. Dissatisfied with their howls and shrieks, the deities attempted to make humans from mud. These beings spoke only gibberish and quickly melted (ibid.). The gods then created wooden humans. While these creatures spoke and reproduced, they had no soul and therefore could not worship their creators. Angered, the deities sought to destroy the wood people and were able to wipe most of them out (ibid.). The survivors evolved into monkeys, an interesting parallel between Mayan myth and human evolution. Finally, the gods succeeded in making four humans from maize (a staple food of the Maya). These humans quickly learned to worship the gods and to make sacrifices to thank them for the miracle of creation. Ritual sacrifices were an integral part of Mayan culture (ibid.).

The Mayans attributed all natural processes to the gods and considered many celestial bodies to be actual deities. The Moon goddess (Fig. 1.51) was depicted as a young, bare-breasted woman. The Sun (*Kinich Ahan* or "Sun-Face Lord") was portrayed as a fierce, one-toothed being with barbells on either side of his mouth (Laughton, 1998; Longhena, 2000). At sunrise this god was young, but after his journey across the sky he became old and bearded. After sinking below the horizon, it was believed that *Kinich Ahan* entered *Xibalba* as a jaguar to do battle with the terrible gods of this realm. Every morning he would escape to rise into the sky again (ibid.). Because of their association with the Sun god, jaguars were considered sacred by the Maya. Kings wore their pelts in battle, and they were sometimes offered as sacrifices (ibid.).

Venus was another important celestial body to the Maya. This god was depicted as a sinister male, whose appearance was associated with drought, war and hunger. Some people even believed that Venus gave off harmful rays, and covered their windows when it was in the sky (ibid.).

Chac, the god of rain, thunder and lightning, was usually shown as a blue figure with a long, curving nose who carried an axe. He was a beneficial yet vengeful god, as he provided rain for the crops but also caused devastating storms. The sound of *Chac's* axe striking was thought to cause thunder while the sparks created were believed to be lightning (ibid.).

Hun Hunahpu (also called *Wak-Chan-Ahaw* for "Raised-Up-Sky-God") was the maize god. He was shown as a young man with maize growing out of his head and controlled the staple food of the Maya (ibid.).

Interpreting Natural Structures

Mayans believed that everything on Earth had a spiritual aspect. It was thought that mountains housed the souls of ancestors, objects in the sky were deities in the celestial realm, and *Xibalba* was located underground or underwater (Laughton, 1998). The Maya thought that holes exposing subterranean rivers in the north were entrances to the underworld. Mayan art shows people entering the underworld in a sinking canoe (ibid.).

Much of Mayan sculpture and architecture was meant to recreate the natural world. Stone pyramid temples were designed to resemble the sacred mountains, and were used as tombs for rulers. These are found in cities throughout the Mayan region, but were especially popular in the lowlands, where there were no actual mountains (Laughton, 1998; Christie, 2003). Tikal (Fig. 1.52), known as the "city of the dead", has the most impressive pyramid temples. Here,

Figure 1.18 *A stone pyramid temple at Tikal (left). Tikal was known as the "city of the dead" and had some of the most impressive pyramid temples of the Maya.*

tombs were built on top of each other as kings died. These tombs are filled with impressive offerings and stocked full of food and drink to sustain departed rulers during their journey through *Xibalba* (ibid.). In the city of Yaxchilán, pyramid temples are surrounded by tall stone structures called *stelae* or "tree stones". These monuments have the city's history carved into them, and are meant to represent the trees of the rainforest surrounding the city. *Stelae* in the city of Copán are distributed in a manner that corresponds to movement of planets and constellations (ibid.).

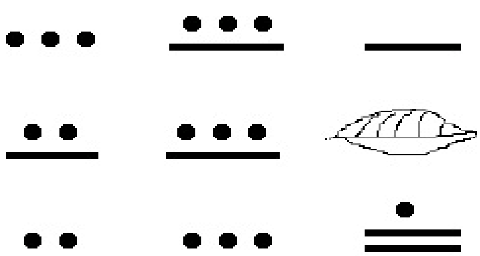


Figure 1.19 *The Mayans had a complex, base twenty system in which numbers were represented with dots, lines and a shell for zero (right). The first column of this diagram is 1342, the second is 3363 and the third is 2011.*

Time Cycles, Mathematics and Codices

The Mayans had a vast knowledge base. They kept extensive records of everything they knew and observed in a type of book called a codex. Information could also be found carved into many of the Mayan stone creations. *Stelae*, for example, were used to record information about rulers and to promote their power (Laughton, 1998; Benson, 1967). The Mayan writing system is made up of hieroglyphs. It is a phonetic system read from left to right. Codices were made of strips of fig bark several feet long folded concertina style. The "pages" of these volumes were filled with pictures and tables to keep track of everything from astronomical cycles to the timing of rituals (ibid.).

In order to construct the complex tables in the codices, astronomer-priests spent a great deal of time observing the motion of celestial bodies. Despite a lack of observational instruments, the celestial cycles described by the Mayans were incredibly accurate. They were able to predict the appearance of Venus in the sky with an error of only 1.92 hours in 481 years, even though the cycle of Venus is not a constant length (Laughton, 1998). This is all the more impressive because it required the astronomer-priests to realize that the Morning Star, visible for the first 260 days of Venus' cycle, and the Evening Star, visible for the second 260 days, were the same entity, namely Venus. Priests used this and many more cycles recorded in the codices to predict the best time for agricultural duties, lunar and solar eclipses, passing of the constellations in their zodiac and many other things, all with stunning accuracy. Kings also planned their battles according to when celestial bodies would appear in the sky (ibid.). Their strict adherence to time cycles demonstrates the Mayan belief that everything was preordained by the deities (ibid.).

The number system of the Maya was very advanced for its time. It was a base twenty system (vigesimal count) in which dots and lines were used to represent different numbers (Fig. 1.53). A single dot represented the number one, two dots the number two, and so on up to four. A horizontal bar was used to represent five, and combinations of these symbols were used to represent the numbers from one to nineteen (Laughton, 1998; León-Portilla, 1988; Benson, 1967). Number notation was a series of rows. The first row represented a number from zero to nineteen, the second a multiple of twenty, the third a multiple of 400 (20 x 20), the fourth a multiple of 8000 (20 x 20 x 20) and so on. This system allowed the Mayans to calculate millions. The Maya were also the first recorded civilization to discover the concept of zero, which they represented with a shell-like picture (ibid.).

By combining their skills in both mathematics and astronomy, the Maya were able to create an extraordinarily accurate calendar. This calendar was actually made up of several interlocking time cycles. The first was a 260 day calendar that combines one of the twenty different day signs with a number from one to thirteen (ibid.). It is thought that this calendar is either astronomically based or derived from the duration of human pregnancy. The second calendar has eighteen months of twenty days each, and one month of five days (called *Uayeb*), which is considered to be a period of bad luck. Together, these first two calendars created a fifty-two year cycle called the Calendar Round (ibid.). The third calendar is called the "Long Count" and it counts the days from the start of the current world age. According to Mayan myth, the world was created on August 13, 3114 BC. Together, these cycles combined to make a calendar far more accurate than any other existing calendar at that time (ibid.).

Geologic Time

Throughout history, cultures and civilizations such as the Maya have devised methods of marking events in time. Geologists have developed their own calendar known as the geologic time scale (Fig. 1.54), which provides us with a tool for studying Earth's physical history. Its use and ongoing construction have helped us to understand how the structures we see today were created (Plummer et al., 2004; Babcock, 2009).

Methods of Dating

Both relative and numerical age dating have been used to construct the geologic time scale (Plummer et al., 2004; Babcock, 2009). Relative dating is based on the principles of stratigraphy. These include original horizontality, lateral continuity, superposition and cross-cutting relationships. The most well-known type of numerical dating is radiometric or isotopic dating (ibid.). The geologic time scale itself is a relative time scale, meaning that its periods are of arbitrary length. Rock units from different areas of the world can be correlated by comparing the types of rocks and fossils they contain (ibid.).

Geologic Time Scale

Plummer et al. (2004) show that the geologic time scale is divided into eons. These are further divided into eras, then periods, then epochs. The Precambrian is split into three eons and dominates the majority of the time scale (87%). The Hadean eon begins when the Earth was formed and ends when the oldest rocks in Canada were created. Single-cell fossils first appear in the Archean eon, while the first fossils of this kind in Canada date back to the Proterozoic eon. The North American Craton also began to form during the Archean eon. The Precambrian ended as the first soft-bodied, multi-cellular organisms were emerging. Fossils preserved as imprints of these organisms are found at Mistaken Point, Newfoundland.

The Phanerozoic eon is split into three eras: the Paleozoic, the Mesozoic and the Cenozoic (new life). At the beginning of the Paleozoic era is the Cambrian explosion of life, during which the first complex life forms (such as the trilobite) developed very rapidly. The first fish developed late in the Cambrian period, while the first land plants came into existence in the Ordovician period. Amphibians evolved from fish during the Devonian period, making them the first land vertebrates. The Paleozoic era ended with the biggest mass extinction recorded, with 95% of species being obliterated. The surviving species evolved into dinosaurs, mammals, flying reptiles and huge marine reptiles in the Mesozoic era. A second mass extinction brought the Mesozoic era to a close, eliminating 75% of species. Mammals, relatively insignificant in the Mesozoic era, flourished in the Cenozoic era. Hominids only developed six million years ago in the late Holocene epoch. On the geologic time scale, humans are a very recent species.

Figure 1.20 *The geologic time scale (below). Geologists have constructed this calendar of Earth's history to help them analyze the structures we see today.*

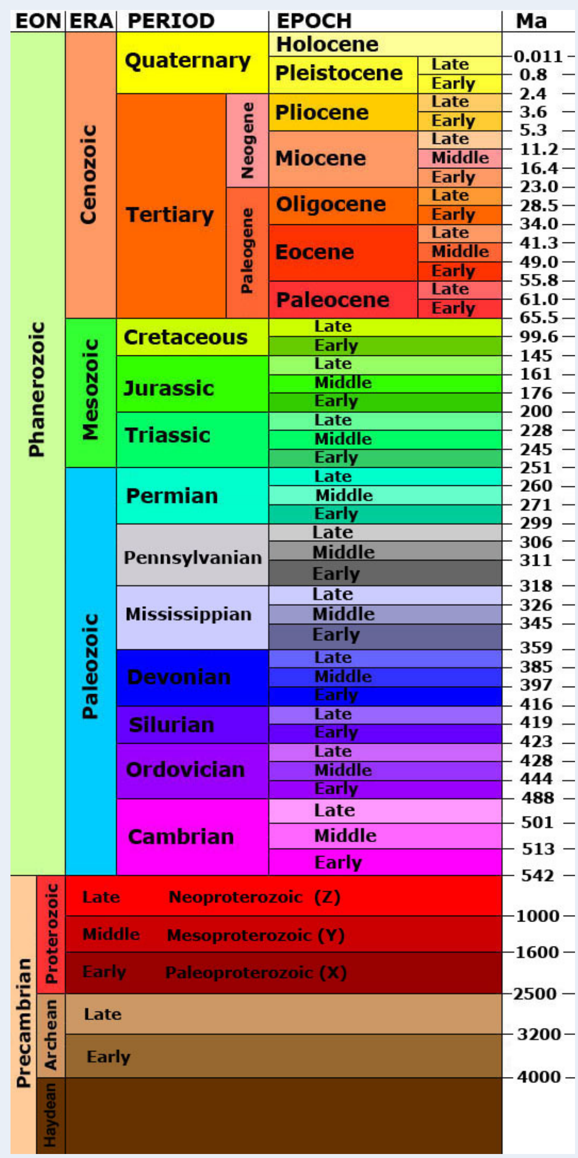


Figure 2.1 *The compass was invented during this time period. It is an example of how scientific thought and technology flourished in this era.*

Chapter 2: A Thousand Years of Thought

From the 9th century until the 18th century, European scientific thought was dominated by religious cosmology. In contrast, Asian scientific thought focused more on qualitative observations, and was not restricted by faith-fueled dogma.

The period in Europe following the dark ages until the end of the eighteenth century witnessed the development of the scientific method, which sought explanations for natural phenomena based on observations, accurate measurements and calculations. The distinct disciplines of modern science were not yet established – they fell collectively under the mantle of natural philosophy – requiring early scientists to have an extensive knowledge base. The life and works of these natural philosophers played a significant role in establishing the foundations of modern science. Many European scientists encountered opposition from religious authorities, which hindered their ability to conduct research and express their ideas. Nevertheless, these men established scientific principles that ushered in the era of modern science.

China: The Song Dynasty

The Song Dynasty of China lasted from 960 to 1279. During this time, scientific thought and technological advancements were booming. Much of the progress at this time had revolutionary effects on the society. But because of the lack of communication between Eastern Asia and the rest of the world, their achievements remained within a limited region. One of the most influential developments was the discovery of printing and the use of bark paper and bamboo paper. Books describing paper-making methods were written, and paper money began to be issued (Jixing, 1983). Further developments in printing included the creation of the first set of clay characters for movable type printing. This technology allowed for some of the earliest printed mathematical texts (Runchuan, 1983). In math, Pascal's triangle was diagrammed at the beginning of the 11th century (Shuchun, 1983). A famous polymath of the Song Dynasty, Shen Kuo (1032-1095) experimented with acoustic properties such as pitch interference, resonance, and sound amplification (Nianzu, 1983). Fixed pivot compasses were discovered, and used in the first recording of compass navigation at sea (Wenzhou, 1983). While science was being developed to improve lives, it was also being used to increase destructive powers. Texts describing gunpowder weapons and gunpowder formulas were complied, and large scale production of gunpowder weapons began to take place. Early flamethrower-type weapons were developed, along with small scale fragmentation bombs (Jiahua, 1983).

Figure 2.2 *Shen Kuo (right) was one of the most influential scientists of the Song dynasty. His investigations spanned all disciplines, and has notable discoveries in many areas of science.*

Various natural anomalies were also explained. Rainbows were understood to be the result of the sun dispersing in rain droplets (Quipeng, 1983). Stone tablets were set up in the Song Dynasty to record water levels of rivers to try to improve predictions for agricultural land during flood seasons (Zhenghai, 1983). In a quest for gold, Chinese alchemists discovered methods of chemically separating different metals and compounds (Kuike, 1983). The earliest record of man-made nickel brass was recorded in the Song dynasty (Tangkun, 1983). In 1116, a classification system was developed to analyze and identify the properties of many minerals based on specific properties like cleavage, colour and crystal form. Records from the Song dynasty describe copper mining at depths of up to 255 meters. Included in these records were descriptions of dangerous gases which the miners tested for by using a long bamboo poles with a lamp on the end. Sophisticated coal mining techniques were also developed, with specific methods to ensure the structural integrity of the mine, to move underground water, and to remove carbon monoxide (Wenheng, 1983). Techniques were also used to harness to the power of the natural world. Silkworm raisers developed grafting techniques to improve the growth of mulberry trees, resulting in higher quality silk from silkworms (Zichun, 1983). Wooden pagodas were built with alterations to reduce torsion or shifts from earthquakes and winds (Hongxun, 1983).

The developments of The Song Dynasty were critical steps in the development of science and technology in China

However, many of these advancements were also historical firsts, marking the Song Dynasty as a major milestone in the development of science throughout history.

Earth Science in the Song Dynasty

Like many areas of science, the earth sciences had major developments during the Song dynasty in China.

Geographical descriptions of the land in the form of observations, as well as map making, boomed in the Song dynasty. In 971, the Emperor ordered that maps of all the provinces within China be compiled. To complete this task, surveys were sent to each village, with instruction on what information to send to the government, namely maps that included roads, mountains, rivers and fields. These maps were collected and then compiled over the course of 39 years, with completion in 1010; the final work consisted of 1566 chapters. A geographer in 1059 named Shan O explored the rivers and lakes of a region in China and mapped them over a time period of 30 years. Shortly after, in 1160, another geographer named Fu Yin made a detailed map of one of the most significant water features of China, the Yellow river. But mapping in the Song dynasty was not solely of provinces and hydrological features. In 1080, a map was made that showed the city of Sian, using a scale of 5 centimetres to 1.6 kilometres (Needham, 1959).

Some of the most impressive maps of the 11th century were two stone maps titled *Map of China and the Barbarian Countries* and *Map of the Tracks of Yu the Great*. These were carved in 1137, with each just under a meter squared in size. Interestingly, although dated within the same year, the techniques used on each map contrast significantly. *Map of China and the Barbarian Countries* has a less definite coast line, ill-defined rivers, and the outlying countries are described in text rather than visually. In contrast, *Map of the Tracks of Yu the Great* has gridlines with a proper scale, a definite coast line, and accurate river systems. Another notable map of the Song Dynasty was created by Shen Kuo. He describes his development of a relief map in his scientific writings *Brush Talks from the Dream Brook*. He built up saw dust, glue, and wax on a wooden base to represent mountains and changes in terrain. When this model was brought back from the field, a fully wooden replica was created (Needham, 1959).

Records from many scholars of the Song Dynasty show the discovery of fossilized organisms. These included conch shells, oyster shells, crab like animals, and snake like animals in rock formations. Both Chu Hsi (1130-1200) and Shen Kuo come to the conclusion that the fossils must have come from ancient oceans, and that the mountains that contained the fossils must have uplifted over time. Shen Kuo further hypothesized that water and wind cause erosional effects on stone, wearing it away into fine particles of sand or mud. Observations of fossilized plants, such as petrified pine trees or petrified bamboo were also recorded, and gave clues to the understanding that environmental conditions change over time (Needham, 1959).

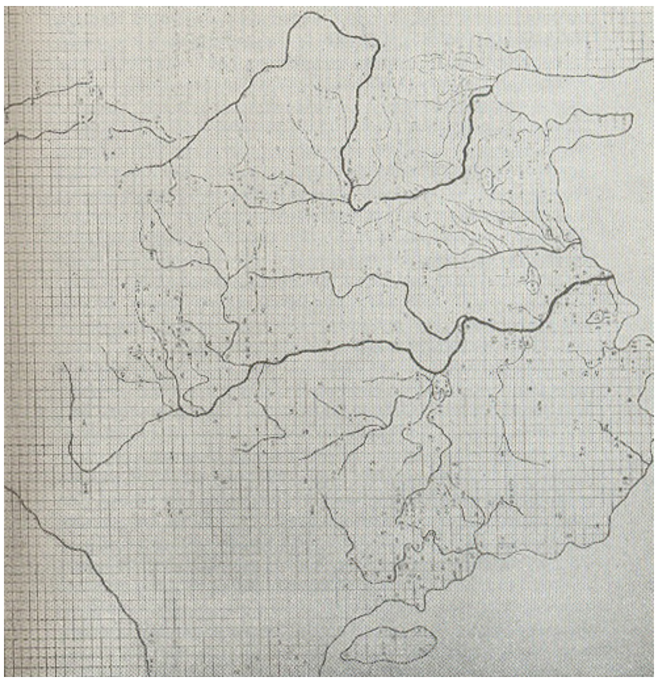


Figure 2.3 *Map of the Tracks of Yu the Great (left) was an example of advanced cartography from the Song Dynasty. This relief map carved into stone has accurate shorelines, rivers, and also uses gridlines with a scale.*

Shen Kuo

Shen Kuo, born in 1032, worked for the Emperor and studied the natural world. His discoveries has a significant influence on the development of science in the Song Dynasty. In his early career, Shen Kuo was able to effectively drain and redirect a number of rivers, which opened up about 40 000 hectares of highly fertile farm land (Holzman, 1958). Shen Kuo's achievements meant that by 1071, he was acting as an administrator of scholarly works, and political advisor, a high ranking secretariat. With this he was able to reform the unproductive Beurau of Astronomy, and direct the construction of a more advanced armillary sphere. Shen continued to work with the Beurau of Astronomy, and developed creative ways to alter water flow to reclaim farmland. In 1072, Shen Kuo apparently took the first topographical measurement in recorded history when he compared the altitude of the capital, Kaifeng, to the altitude a the mouth of the Huai river (Holzman, 1958).

Shen Kuo also made contributions to the development of cartography. In 1074, he was instructed to inspect part of China's boarder. He travelled the site for 20 days and then constructed a topographical map using a wood base, built up with sawdust, glue, and wax. Shen Kuo also made maps of important landscapes as he travelled on diplomatic missions. At the end of his political career in 1088, Shen submitted a map that he had been working for 12 years titled *Shou Ling Tu* or *Map of the empire's prefectures and subprefectures* (Holzman, 1958, p.275). As part of his reward for his work, Shen was allowed to retire to an estate he called Dream brook, near modern day Jiangsu, where he lived until he died in 1095. It was there that Shen Kuo wrote his most influential work, *Brush Talks from the Dream Brook* or *Mengqi bitan*. (Holzman, 1958, p.277). This work contained 30 chapters, 26 of which have survived. The chapters consist of short sections on a wide variety of topics, including astronomy, mathematics, meteorology, medicine, physics, optics, and geology (Holzman, 1958). His achievements in geology are revolutionary discoveries. Shen observed petrified bamboo in the Shaanxi region, where the environment did not allow bamboo to grow; from this he predicted that the environment and landscape had changed throughout time. In his *Mengqi bitan* Shen Kuo says "Is it not that earlier than distant antiquity the land was low and the atmosphere humid, stable for bamboo?" (Holzman, 1958, p.289). Shen also discusses his discovery of fossils in the Taihang mountains, and proposed that the land was previously underneath a sea, and that the land was built up from suspended sediment and mud within the waters. He also made observations of rock formations in south-eastern Zhejiang found within deep valleys. His explanation reveals an understanding of erosion, as he says that "it is just that great waters have swirled about in the valley, taking away all the sand and earth and leaving only great rocks standing out high and solitary" (Holzman, 1958, pp. 289-290).

Figure 2.4 *The Taihang mountains (right) were where Shen Kuo discovered fossilized fauna from ancient seas.*

Shen Kuo's recordings also discuss other important observations in the natural sciences. He describes the action of a compass, and the opposite nature of north and south charges. He proposed a solar calendar of 365 days with 12 months (5 Greater months of 31 days and 7 Lesser months of 30 days). Shen also hypothesized that the moon does not produce its own light, but reflects the light from the sun. From this, he explains that the sun and moon must be spherical, resulting in the phases of the moon (Holzman, 1958).

Shen Kuo's position in the government allowed him the time and resources to explore the many disciplines that he did. Shen Kuo's work is hard to classify, as much of his work was not classically scientific, since he rarely provided any method to explain the phenomena he saw. As a result, Shen Kuo's major recording of observations seems to be a collection of unrelated topics and he develops no general theories. However, his works is thoroughly scientific in his consistent, objective observation, relatively unfiltered by external influences. It seems his curiosity in the workings of the world drove his discovery, as opposed to notoriety or political gain (Pregadio, 2008).

Geomorphology

Geomorphology is the study of the earth's surface and the forces that work to change these features over time (Tinkler, 1985). On a global scale, the largest geomorphological factor is the movement of tectonic plates. Over the course of millions of years, the interations of plate movements has lead to the uplifting of mountain ranges, creation of volcanic belts, and sea floor subduction among many other features. Tectonic plate subduction also plays and important role in the creation of metamorphic rocks and minerals formed under high pressures an tempertaures. On the surface of these plates, large erosion surfaces produce great volumes of transported sediment. These changes in weight cause isostatic adjustment of the tectonic plate and this isostatic adjustment of the plate causes significant changes in the elevation of the earth's crust. Within these depressions bodies of water or fluvial systems often develop. These hydrological systems create some of the most noticeable features on the earth's surface (Tinkler, 1985).

Rivers meander and create winding waterways. Over thousands of years, rivers widen and can carve out valleys. The result of fluvial erosion is that river systems are also an extremely important vehicle for sediment transportation. Sedimentary rock formations are often created by sediment deposition in hydrological environments in a number of energy conditions. Larger bodies of water, like lakes and oceans erode shorelines and deposit sediments and their bases (Tinkler, 1985).

Not just liquid water changes the surface of the earth. Glaciers cause many geomorphological effects. Their weight often causes isostatic movement the translational movement of the glacier causes significant erosion, causing huge volumes of volumes of sediment to travel with them with them. Formations from bullet shaped rocks, to boulder fields, to whole moraines are created as a result of glaciers' erosional powers (Tinkler, 1985).

Wind, like water, also erodes sufaces over long periods of time and can act as a transporter. for sediment

Over time, the power of geomorphological movements has continually chnaged the the surface of the earth, but the realtive balance between erosion and deposition means that the cycle has continued for billions of years (Tinkler, 1985).

Figure 2.5 *A boulder field (below) is the result of the erosional and depositional powers of glaciers.*

Early Geomagnetism

Magnetic theory has developed greatly since the first recorded reference to the lodestone's ability to attract iron in the 6th century B.C.E., but there is still much that is unknown about magnetism. The lodestone was pivotal in developing magnetic science, and until geomagnetism became quantitative in the 18th and 19th centuries, lodestone, geomagnetism and magnetism were synonymous (Wasilewski, 1977). Early pioneers in this science documented all the properties of loadstone but never came to a conclusion as to why these events occur. Two prominent early western scientists that studied the behaviour of lodestone and magnets were Peter Peregrinus (fl. 1269) and William Gilbert (1544-1600). It is important to note that while Europe was in the midst of the Dark Ages, the Orient was flourishing with scientific thought. The invention of the compass is credited to Chinese scientist, Shen Kuo, a significant number of years before the emergence of the compass in the West (Roller, 1959). While Gilbert and Peregrinus were not the first to investigate magnetism, they were the first to write about it in the Western world. Their works were highly circulated, and as such are an excellent representation of the state of knowledge on this subject at the time, thus providing an accurate portrayal of the Western history of geomagnetism (Roller, 1959).

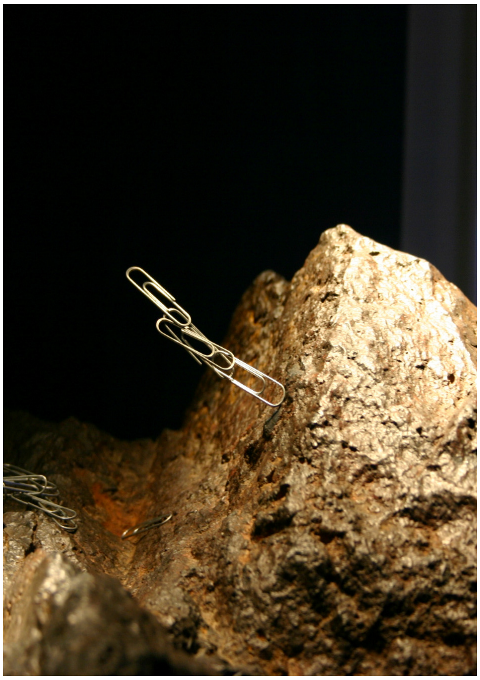


Figure 2.6 *Lodestone, a naturally magnetised rock, exhibiting its magnetic properties (right).*

Origin of the Lodestone

The origin of the lodestone is essential in understanding the history of magnetism, as it was lodestone that induced the magnetic phenomena under inspection. Early research into magnetism was centered on observing how objects react in the presence of lodestone and how lodestones interact with each other. Lodestone is a type of rock that contains high quantities of the mineral magnetite, Fe_3O_4 (Wasilewski, 1977). Magnetite is a natural magnet, thus the presence of magnetite in lodestone causes it to be naturally magnetized (Wasilewski, 1977). The first recorded mention of lodestone is credited to Thales of Miletus (624-546 B.C.E.) recorded by Aristotle (384-322 B.C.E.) (Roller, 1959).

"Thales, too, to judge from what is recorded about him seems to have held soul to be a motive force, since he said that the stone has a soul in it because it moves the iron." (Smith, 1931, p.405)

While this is the first mention of lodestone, the reference to the stone was secondary as Aristotle's was writing about soul; there were no claims of natural phenomena. It was not until Peregrinus' letter that magnetism was written about in the manner of scientific discovery. Still, due to many passing references in primeval documents, it is accepted that knowledge concerning lodestone and its properties was common in ancient times (Roller, 1959).

Peter Peregrinus

Peregrinus' letter is significant in the history of magnetism as it is the earliest Western recording of lodestone and its effect on iron (Roller, 1959; Zilsel, 1941). Peregrinus broke his letter into two Parts. Part I is a compilation of all that was known about lodestones up until that time. It is an extensive list that goes through all the properties and behaviours of lodestone as it interacts with iron and other lodestones (Roller, 1959). The extensive amount of information in this part indicates that Peregrinus did not invent or discover these ideas, but that they were common knowledge among people who studied the stones. Part I is written in a very modern fashion, similar to a person taking qualitative observations of basic magnetic phenomena:

"The poles of the lodestone may be found by: laying bits of iron wire on the stone, and drawing lines along the length of the wire, for the lines will converge to the poles; they may be also be identified as the points of greatest force exerted on iron; they are also the points at which a bit of iron wire stands perpendicular to the surface of the stone."(Roller, 1959, p.40)

Part I of Peregrinus' letter also defined and clarified many terms. For example, he introduced the term *magnetic poles* and the concept of *polarity* into the study of magnetism. It is for these reasons that the Part I of this letter is significant in the history of magnetism (Zilsel, 1941).

Part II of Peregrinus letter went on to explain three magnetic instruments. The first described a lodestone floating in a wooden box with a semicircle surrounding the box perpendicular to the water. The semicircle is subdivided to take measurements like an alidade. This instrument essentially combines a compass and an alidade. Peregrinus described a method for measuring the azimuth of celestial bodies using this instrument (Roller, 1959).

The second instrument described by Peregrinus was a fully pivoting dry mounted needle. This is significant because until now compasses consisted of a magnet floating on water, which could not be used for sea navigation (Kreutz, 1973). Peregrinus described a vertical wire that mounted a horizontal magnetized iron wire (Roller, 1959). This was all encased in a container with a transparent top divided into 360 parts. It was only after this technology developed could the compass be used as an effective navigation tool for ships (Kreutz, 1973). The last instrument that was described in Part II was a magnetic perpetual motion machine. There is obvious reason to believe that Peregrinus never constructed this apparatus due to the impossibility of perpetual motion (Roller, 1959).

Peregrinus' work was essential to Gilbert because no other text was available on this subject. It was not until Gilbert published his book some 300 years later that new foundational information about magnetism was circulated (Wasilewski, 1977; Zilsel, 1941).

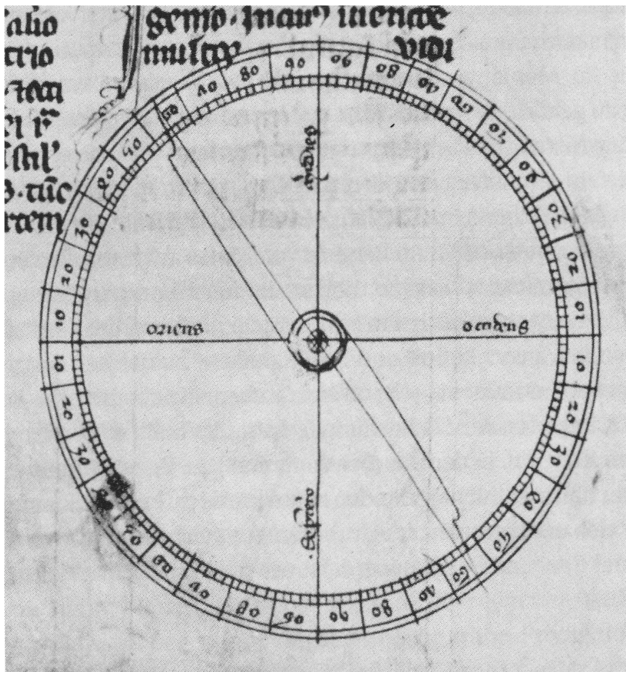


Figure 2.7 *A sketch from the second part of Peregrinus' letter (left) showing his design for a fully pivoting, dry mounted needle.*

William Gilbert

Gilbert is best known for publishing his six-part book *De Magnete*, wherein he first makes the distinction between magnetism and the amber effect (Zilsel, 1941). The amber effect is the observation that when amber is heated or rubbed it has the ability to attract certain materials, whereas lodestone is only observed to attract iron (Roller, 1959). It was Gilbert who first compiled a list of materials that amber could and could not attract (Roller, 1959). We know today that the reason for this attraction is the static electricity created when the amber is rubbed or heated, and not magnetism. Due to this discovery Gilbert is credited with the distinction between electricity and magnetism. Gilbert created a new branch of physics called electricity, and because of this he is known as the "father of modern electricity" (Zilsel, 1941; Gilbert, 1958; Roller, 1959).

Gilbert was, in every way, an experimental physicist (Roller, 1959). At this time no theory existed about electricity or magnetism so it was not possible for Gilbert to theoretically deduce what should happen, then carry out an experiment to see if he was correct. For example, when he was compiling his list of materials that were attracted to amber, he had no idea which material would or would not be attracted. Gilbert simply observed the results and attempted the reasoning afterwards, a style of research that has gone out of fashion in modern times.

Figure 2.8 *William Gilbert (right), an influential physicist who made fundamental conclusions about the Earth's magnetic properties.*

In addition to the amber effect and electricity, within his book Gilbert discussed many other things that he observed, researched, or hypothesized. One of the more notable scientific principles discussed was Gilbert's explanation of the five magnetic movements (Gilbert, 1958). Within *De Magnete* Gilbert referred to Aristotle's idea that only two movements existed:

"Aristotle admits only two simple movements of his elements exist – from the centre and toward the centre; light objects upward and heavy objects downward: so that on Earth there is but one motion of all its parts toward the centre of the world."(Gilbert, 1958, p.72)

Almost immediately following this reiteration of Aristotle's thought, Gilbert goes on to explain the five movements observed by magnets, magnet being the broad term to include lodestone, but also, artificially magnetized materials, such as iron needles. The first was *coition*, or similarly, *attraction*. This explained the attractive movement of two magnets, or a magnet and another material, towards each other (Gilbert, 1958). Gilbert used the term coition to differentiate between the attractive forces of a magnet versus the attractive force of amber (Roller, 1959). This distinction between attraction and coition is the first separation of thought between electricity and magnetism. Gilbert defined coition as the force between two magnets, while attractions was the force created by charged amber.

Along with coition, magnets also had *direction* (Gilbert, 1958). It is now well known that lodestones and artificial magnets, when moving freely, align towards the Earths poles. The cause of this movement was thought to be large lodestone mountain ranges that attracted the magnets, but through Gilberts work it was proven that the Earth is a giant magnet itself, and as such magnets on Earth align themselves accordingly (Gilbert, 1958).

There also exists *variation* depending on one's location on Earth. Variation from the meridian was observed in Gilbert's time but the reason for this was unknown (Gilbert, 1958). We understand today that this variation is due to the inconsistent strength of the Earth's magnetic field in different locations around the globe. It was also noted that the needle of a compass might dip below the horizon, this is known as *inclination* (Gilbert, 1958). These two movements, inclination and variation, were issues for early compass makers (Kreutz, 1973). To combat variation compasses would actually be comprised of multiple magnetized needles that when combined aligned with the meridian. To counteract inclination a weight was place at the opposite end to balance the needle (Kreutz, 1973).

The last movement observed by magnetic bodies is *rotation*. This observation by Gilbert was perhaps the most significant to the study of earth science. Gilbert noted that when a lodestone was made perfectly spherical magnetized needled would rotate to align itself with the magnetic field of the sphere (Gilbert, 1958). Gilbert used these spherical lodestones extensively when trying to understand the Earth's magnetism. He called these spheres *terrellas*, meaning "little Earths" as it was Gilbert's belief, and a correct one, that the Earth is a giant magnet (Roller, 1959). He used the terrella as a representative of the Earth when proving that the Earth is a magnet. He demonstrated how a compass reacts at different location around the terrella, and how this paralleled a compass' reaction around the globe (Roller, 1959).

Gilbert built his research around trying to understand these five magnetic movements. The first book of *De Magnete* introduced what was known about magnets, and each subsequent book dealt with one of coition, direction, variation, inclination, or rotation. By trying to understand and explain these movements Gilbert was able to develop a theory for magnetism, and hypothesize about the origins of Earth's magnetic field. In doing this he greatly contributed to the evolution of geomagnetism, and earth science as a whole.

How Geomagnetism Influenced the Theory of Plate Tectonics

Geomagnetism, as we understand today, is produced by the opposite rotations of the Earth's inner and outer cores. This internal spinning produces the magnetic field that assigns a magnetic signature to newly forming rocks while they solidify. This magnetic signature is specific to the period and location that the rock was formed. This concept is foundational for the study of paleomagnetism.

This understanding of paleomagnetism, combined with the works of Alfred Wegener, Harry Hammond Hess, and Fredrick Vine and Drummond Matthews in the early 1960s, lead to a huge breakthrough in the verification of continental movement. As with every other scientific concept, it was not the work of a single scientist that provided the justification for the theory of plate tectonics. While it is commonly known that Wegener contributed the idea of continental drift to the theory of plate tectonics (Schwarzbach, 1989), it was not solely Wegener who proved this theory.

In 1962 a huge breakthrough occurred in the understanding of seafloor spreading. This was the year that Harry H. Hess published his very influential paper *The History of Ocean Basins*. In this paper Hess proposed a mechanism for seafloor spreading (Hess, 1962). By explaining sea floor spreading Hess was able to provide the driving force that was missing in Wegener's theory for continental drift (Schwarzbach, 1989).

Hess came to this conclusion due to the work of Vine and Matthews. After WWII there were immense advancements in marine technology, which benefited the study of the ocean floor greatly. From this Vine and Matthews were able to note magnetic anomalies along the sea floor (Vine, 1963). They observed bands, or strips, of rock that had the same magnetic signature - i.e. the minerals within the rock all had the same magnetic orientation (Vine, 1963). Furthermore, they saw that magnetic bands were symmetrical on either side of the mid-ocean rift, and that the lateral size of each band roughly correlated with the magnetic reversal events of the Earth (Vine, 1963). They concluded that the magnetic signatures must have been assigned to the rocks as they were being formed, and as such, new ocean crust must have been forming.

It was the findings of Vine and Matthews that Hess was able to build upon. From this Wegener was able to prove the theories that he proposed. Together these developments led to the modern understanding of geomagnetism and the validation of the theory of plate tectonics.

Leonardo da Vinci's Codex Leicester

Perhaps best known for his painting of the *Mona Lisa*, Italian polymath Leonardo da Vinci (1452-1519) also made a number of scientific discoveries in his time. Besides being an artist, da Vinci was also a profound scientist, engineer, and inventor. As an acute observer, it appears that Leonardo da Vinci was fascinated by almost everything around him. Many of da Vinci's innovative thoughts and observations were drawn and documented throughout his once enigmatic notebooks. This content, now deciphered and revealed to the general public, provides insight to one of history's greatest minds.

Figure 2.9 *Leonardo da Vinci (1452-1519). A self portrait (above) of the Italian artist, scientist, and engineer, drawn in 1512.*

Da Vinci lived in a time when the world was thought to be composed of concentric spheres of earth, water, air, and fire. Gravity was not yet well understood and many still believed that the Earth was located in the centre of the universe. While he accepted most of these premises, da Vinci held strongly to direct study as he attempted to learn about the functions of nature. His goal was to address the following four key themes within his notebooks: the science of painting, architecture, the elements of mechanics, and general human anatomy. Eventually added to this list were his studies of botany, geology, flight, hydrology, and many other areas of interest. The Renaissance man intended to combine all of his investigations in order to produce a new and unified view of the world. What differed da Vinci from many of the great scientists who followed him, including Newton and Galileo was his integration of art into scientific observations (Desmond and Pedretti, 2000).

The Codex Leicester

Of da Vinci's comprehensive array of notebooks, the Codex Leicester remains one of his most renowned pieces of work. Written between 1506 and 1510, the Codex Leicester, originally known as the Codex Hammer, is now owned by William H. Gates III in the United States. The manuscript is displayed on loose, double-sided sheets of linen paper, and comprises a total of seventy-two pages. In it are da Vinci's thoughts and observations recorded in his signature mirror style writing, as well as more than three hundred pen and ink sketches, drawings, and diagrams that illustrate both his imagined and real experiments.

The Codex Leicester is an exhibition of da Vinci's transcendent brilliance. It explores a wide variety of topics including astronomy, geology, and hydrodynamics. Da Vinci made observations and presented theories regarding the nature of rivers and seas, the structure of the Earth, and the properties of water, rocks, fossils, and even celestial light (Fairbrother and Ishikawa, 1997).

For da Vinci, art and science were inseparable. Both, he believed, were based primarily on insightful observation which was amplified by his great ability to see detail. Furthermore, many of da Vinci's influences were mutually associated with his art and scientific studies. This remains evident among many examples in which traces of da Vinci's scientific research appear in his paintings and drawings. In particular, the scenes of nature depicted in the backgrounds of many of da Vinci's most famous paintings echo the scientific themes of water, the sky, and the Earth that were examined in the Codex Leicester and his other notebooks.

Although the movement and properties of water serve as the main focus of the Codex Leicester, studies on the subjects of geology, astronomy and important notes regarding the composition and nature of the body of the earth were also included. For instance, the codex provides an explanation for the origin of fossils and their existence near mountains. Other topics include the flow of water in rivers and oceans, adjusting to the presence of different obstacles, and the resulting effects of erosion. In addition, da Vinci was able to explain accurately the luminosity of the moon, thus describing the phenomenon of planetshine well before the theory was widely accepted and proven (Desmond and Pedretti, 2000).

The Nature of Water

Da Vinci considered water to be the most visible and dynamic element of nature. Therefore, he felt that a deep understanding of water would help with a greater understanding of all of nature. Da Vinci constantly studied water. Among his remarkable observations and illustrations recorded in the Codex Leicester, he demonstrated the many ways in which water can move. Focusing largely on the flow of water around obstacles, he discussed both its impact and rebound movements. Da Vinci compared the flow of water to the flow of air, and even correctly compared water waves to those of sound and light. He was particularly interested in vortices and the erosive power of water, and thus observed and sketched many of his findings regarding these properties.

In the Codex Leicester, da Vinci depicts flowing water as it encounters an obstacle in its path. He was able to observe how the heavier water lying at the bottom of a stream comes upon the obstacle first and rises up, crashing into the lighter water on top and forcing it outwards to form vortices. The vortices in da Vinci's drawings are not unlike the spiralling curls of hair or the leaves of plants that often appear in his paintings, illustrating his belief in the connection between all natural forms and the true power of nature. He also provides a sketch of water gushing forward through the gates of a lock, noting how it always erodes the bottom of one side more than the other. Ahead of his time, da Vinci anticipated the modern science of hydrodynamics and correctly recognized some of the fundamental properties of fluids, which are now known as density, viscosity, compressibility, surface tension and adhesion (Keller, 1999).

Furthermore, Leonardo da Vinci keenly observed the dynamics and transport of water and suspended particles by rivers originating in the mountains and continuing through the plains to the sea, where sediments were deposited on the sea floor. He correctly formulated the idea that a fast-moving river, or one that travels on a steep slope, can transport larger particles than a slow-moving river, or one that has a significantly shallower slope. Da Vinci also investigated the possible conditions that may cause a river to meander. With impressive intellect, he discovered that when compared to those in the plains, river courses are more stable in the mountains, where deposited sediments can continuously impede the flow of water. Through his proficient studies, da Vinci was able to engineer pile drivers for use in constructing dams, describe how to divert rivers, and suggest ways to build weirs, locks, bridges and canals that minimized erosion and sediment deposits (Desmond and Pedretti, 2000).

The Body of the Earth

Figure 2.32 illustrates da Vinci's global theory. He believed that the centre of the earth could be modeled by a cavern filled with water. This water within the Earth would constantly rise to the surface and flow through a system of subterranean veins, which da Vinci later compared to the blood veins in a human body. He thought that these subterranean waters would cause erosion to the earth's interior, resulting in the collapse of these enormous internal caverns. Water would then fill the sunken area and this movement would cause the relative centres of gravity of the earth and the water to be constantly changing. The surface of the "sphere" of the liquid sea would remain at a constant level, while the earth protruded to different heights and places. Thus, the landforms and bodies of water observed above ground would be undergoing radical transformations over time. From this idea, da Vinci developed his hypothesis on the origin of land masses and mountains (Pizzorusso, 1996).

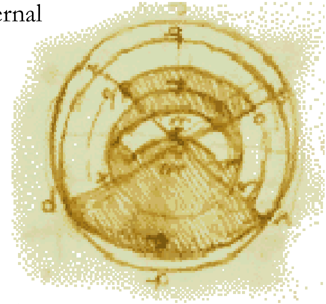


Figure 2.10 *Da Vinci's drawing of the earth filled with water flowing through subterranean veins (above). From the Codex Leicester, Sheet 1B, folio 36r. Drawn between 1506 and 1510.*

Da Vinci formulated that the spherical shape of the earth was maintained because such a shape is adopted by all elements around their own centre of gravity. Since he believed that the earth was not a solid mass, and rather a globe of water-filled caverns, he suggested that the continuous rise and fall of these caverns upon themselves was involved in the formation of mountains. As the caverns collapsed, the heavy matter was pulled towards the centre of the earth and the light pushed towards the surface, where it formed new mountains and landmasses. Thus, in the dynamic formation and reformation of the elements of the earth, da Vinci believed that a perfect state of equilibrium was maintained (Fairbrother and Ishikawa, 1997).

The Origin of Fossils

Just as da Vinci believed water to be the most visible and dynamic element of nature, he felt that mountains were the most visible manifestation of the formation of the earth. During an expedition to the mountains dividing France and Italy, da Vinci made observations about the environment on a range of mountain peaks which he later mentioned in the Codex Leicester. Da Vinci found and recorded layers of fossils in these mountains which were located very high above sea level. These findings provided the basis for his theory on the origin and formation of the landscape as well as that of the fossils (Baucon, 2010b).

At the time, prevailing views suggested that such fossils either "grew" in the rocks, like mineral crystals, or had been swept from the sea by the Biblical Deluge. Da Vinci, however, noted that fossils were too heavy to float, which meant that they could not have been carried to high ground by flood waters. Da Vinci also reasoned that such fragile fossil shells could not have been swept so far inland and survived intact. Furthermore, observing that in certain places there was more than one layer of fossils, he concluded that such phenomena could not be the result of a single event, but rather evidence of a repeated action on the part of nature. This led to the theory that the landscape was formed by continuous and repeated flooding and the erosive powers of water.

Through further observation, da Vinci also discovered that groups of different fossil shells found together resembled the living groups assembled in coastal waters. Moreover, although the plate tectonic theory was not yet suggested, Leonardo believed that mountains had previously formed sea beds, which were gradually lifted until they formed mountains. For all these reasons, Leonardo correctly concluded that the fossils came from animals which once inhabited an ancient sea that covered the land (Baucon, 2010a).

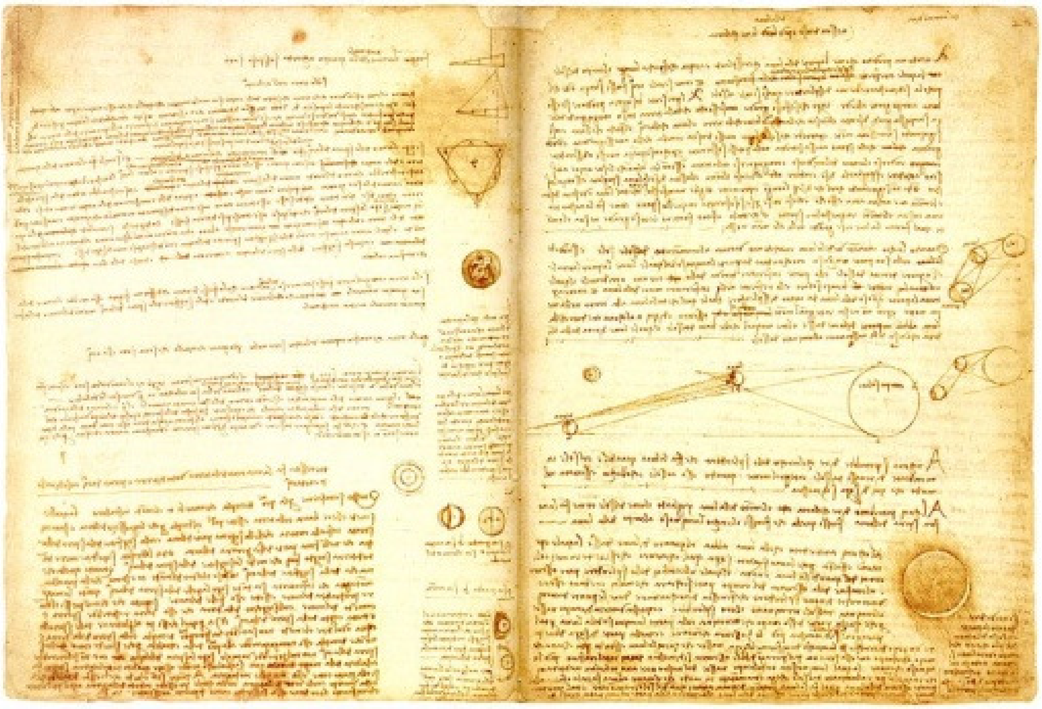


Figure 2.11 *A couple of pages from Leonardo da Vinci's Codex Leicester (right). Fol.35v (on the left) and Fol.2r (on the right). Written between 1506 and 1510.*

The Shine of the Moon

For thousands of years, humans marvelled at the luminosity of the moon at night. As an artist, Leonardo da Vinci had an excellent understanding of light and shadow, and this was reflected in his scientific work. Da Vinci's observations of the moon in its crescent stage led him to one of the most important scientific discoveries in the Codex Leicester. Indeed, da Vinci is credited with the first correct explanation of why the crescent moon in the dark night sky shows a gentle glow across its unilluminated parts. He was able to arrive at this idea through a series of intellectual and logical thoughts. It appeared to da Vinci that the reflectivity of the Earth's and the Moon's surfaces and the continually changing relative positions of the Earth, Moon, and Sun may be greatly associated to the mysterious shine of the moon. At first, da Vinci hypothesized that the moon reflected light because it was covered with water. After many nights of diligent observations, and many sketches within his notebooks, however, Leonardo da Vinci perceptively deduced that sunlight can reflect from the Earth and illuminate the unlit portion of the crescent Moon. Hence, he stated that rays of light from the sun reflected from the Earth's oceans act as a secondary light source and cause the pale light of the moon that we perceive from Earth (Reaves, 1987). Needless to say, da Vinci's findings have left a mark on the history of science and the Earth.

Earth's Interior Structure

Today, we know that the Earth's interior consists of rock and metal that can be divided into four main layers as depicted in Figure 2.34: the core which can be further subdivided into the inner and outer core, the lower mantle, the upper mantle, and finally the crust of the Earth. This information is based on studies of the paths and characteristics of earthquake waves travelling through the Earth, as well as experiments on surface minerals and rocks at high pressure and temperature. Geological observation of surface rocks and studies of the Earth's motions in the Solar System, its gravity and magnetic fields, and the flow of heat from inside the Earth have further enhanced knowledge of Earth's interior structure.

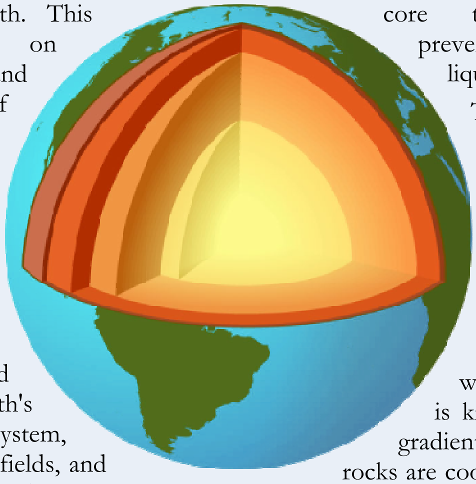


Figure 2.12 *A diagram representation of the modern day understanding of the Earth's interior structure (left). The four layers depicted are: the core, lower mantle, upper mantle, and crust.*

The Layers of Earth

Earth's core, comprising of inner and outer regions, is believed to be composed mainly of an iron and nickel alloy. Researchers have assumed this knowledge based on calculations of its density – roughly 12.95 g/cm^3 at the inner core and 11.05 g/cm^3 at the outer core – and the fact that many meteorites (which are thought to be portions of the interior of a planetary body) are iron-nickel alloys. The core is earth's source of internal heat as it contains radioactive materials which release heat as they break down into more stable substances.

While its temperature is higher than that of the outer core, the inner core is known to be a solid while the outer core remains a liquid. This is due to the tremendous pressure produced by the weight of the overlying rocks, which causes the atoms of the inner core to crowd together, preventing it from becoming a liquid.

The mantle, on the other hand is thought to be composed mainly of olivine-rich rock. The temperature of the mantle is lowest at the upper mantle immediately beneath the crust and increases with depth, creating what is known as the geothermal gradient. In the upper mantle, rocks are cool and brittle, while those in the lower mantle are hot and soft.

The Earth's crust can also be subdivided into two categories: thin oceanic crust that underlies the ocean basins and thicker continental crust that underlies the continents. The oceanic crust is composed mainly of basalt while the thicker continental crust is made primarily of granite. As the density of the thick continental crust is much lower than the mantle, it can "float" above the upper mantle's surface (Poirier, 2000).

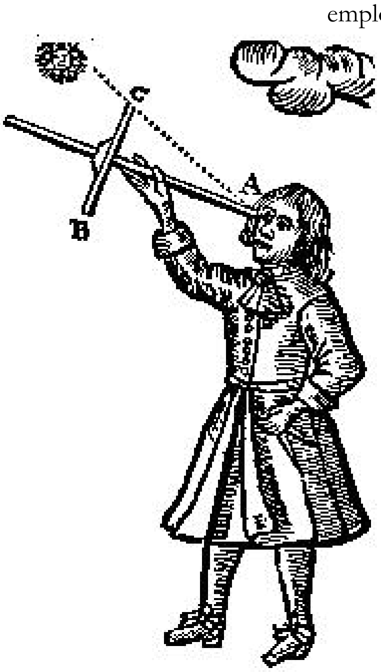
Thomas Harriot

An Elizabethan scientist who studied problems from a multitude of disciplines, Thomas Harriot (1560-1621) had a fascinating life worth examining from a scientific as well as a political perspective. Although famous scientists such as Johannes Kepler (1571-1630) and René Descartes (1596-1650) sought his advice, Harriot's name is not frequently recognized because he did not publish the majority of his findings (Rukeyser, 1970). Alongside his work in linguistics, optics, algebra, geometry, binary notation and atomic theory, Harriot occupied himself with studies related to investigating the earth, including astronomy, surveying, prospecting, and navigation (Shirley, 1983).

Biography

Harriot's life and studies began at Oxford, but he moved to London at the age of twenty. There, he met Sir Walter Raleigh (1552-1618), who hired him to facilitate expeditions to North America (Stevens, 1972). Harriot eventually joined Raleigh on one of these voyages to navigate, document the voyage, and learn and translate Algonquin (Shirley, 1983). Harriot remained employed with Raleigh for nearly two decades, managing Raleigh's finances and solving various mathematical problems pertinent to Raleigh's work (Shirley, 1974). When Raleigh was persecuted for atheism, an accusation that eventually led to his execution, Harriot entered service of Henry Percy, Earl of Northumberland (1564-1632) (Shirley, 1974). Harriot acted initially as Percy's accountant and lawyer, but was later encouraged to focus strictly on a scientific and mathematical investigation of the natural world (Shirley, 1974). Percy was eventually imprisoned in the tower of London with Raleigh for his suspected involvement in the gunpowder plot to destroy parliament and assassinate the King (Stevens, 1972). Harriot, despite having been acquitted of charges of atheism, also took up residence in the tower to join Raleigh and Percy (Rukeyser 1970). For his work before and during these years, Harriot earned the respect of mathematicians and scientists in Britain and Continental Europe, who often cited him as an authority on mathematics, navigation, optics, and astronomy (Shirley, 1983).

Figure 2.13 *Demonstration of the use of a cross staff. The user slides the bar BC along the pole, so that B is level with the horizon and C coincides with the object of interest. The angle is read off the pole where it is intersected by the bar.*



Harriot eventually developed skin cancer on his face. On his deathbed, he lamented that he had not published any of his works in mathematics or other areas (Stevens, 1972). He charged a pupil, Nathaniel Torporley (1564-1632), with the task of developing his mathematical notes on algebra into a book to be published posthumously (Shirley, 1974). However, Torporley discovered Harriot's writings on atomic theory, with which he strongly disagreed as a member of the clergy, so did not edit or publish his teacher's work (Shirley, 1974). Instead, Harriot's *Artis Analyticae Praxis* was edited and published by other mathematicians unfamiliar with many of his more abstract conjectures, and consequently the book contains but a portion of Harriot's algebraic work, which itself represents only a fraction of his work in mathematics and science (Stevens, 1972). Indeed, the majority of Harriot's accomplishments were unknown until the rediscovery of his documents in 1784, more than 150 years after his death (Stevens, 1972).

Navigation and Surveying

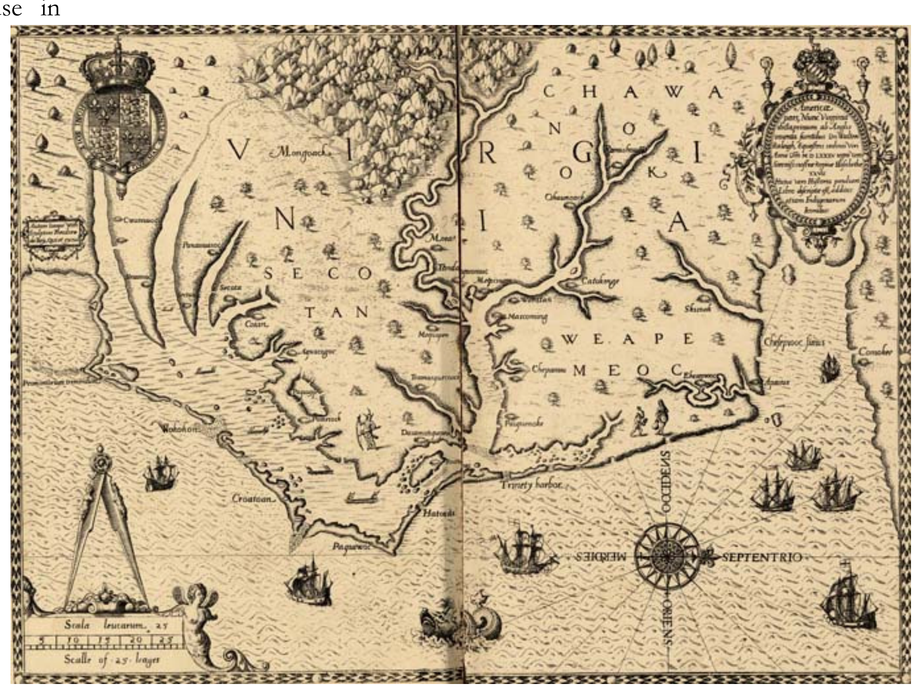
With the rediscovery of his work, Harriot was recognized as one of the greatest mathematicians and physicists of his time (Shirley, 1983). Of particular interest are his contributions to earth science, of which there are several. From very early in his career, working under Raleigh's service, Harriot applied his mathematical knowledge and abilities to the task of navigation (Shirley, 1983). Britain was just beginning to engage in exploration and extensive sea expeditions, and current techniques for ocean navigation were inaccurate and unreliable (Shirley, 1983). Harriot was responsible for teaching Raleigh's captains the basics of marine navigation and wrote a book to this effect, *Arcticon* (Shirley 1983).

The essential navigational tools were a cross staff to measure latitude and a compass to measure direction (Shirley, 1983). The cross staff, shown in figure 2.51, was used to determine the angle between the sun and the horizon at noon, when the sun reaches its zenith (Shirley, 1983). Latitude can be determined by comparing this value to those in carefully calculated tables that relate the sun's zenith and the date to latitude (Shirley, 1983). Harriot built an extremely precise cross staff and recorded new measurements to develop more accurate tables for calculating latitude (Shirley, 1983). Harriot also worked to improve the cross staff itself, suggesting modifications to its construction and use that improved accuracy and safety (Shirley, 1983). He then invented a new device, the back-staff, which did not require users to look directly at the sun, potentially damaging their eyes (Shirley, 1983). Latitude could also be obtained by using a cross staff to take measurements of the North Star, Polaris, but this technique had fallen out of favour among mariners in the 16th century due to inaccuracy (Shirley, 1974) Harriot recognized that these inaccuracies could be largely attributed to the fact that Polaris' location is not fixed relative to the Earth (Shirley, 1974). The tables used in Harriot's time with measurements of Polaris had been calculated centuries previously, when the star was in a different position, and could no longer provide an accurate indication of latitude. Although Harriot calculated updated values for tables to use when measuring the North Star, he discouraged their use in favour of recordings of the sun (Shirley, 1974).

The compass, although frequently used and well understood (see pp. 30-33), presented difficulties when traversing the Atlantic (Moran, 1999). Due to the position of the magnetic north pole in Northern Canada, the declination (the angle between true north and magnetic north) changed considerably when crossing the Atlantic (Moran, 1999). Ships' compasses were calibrated to point north when installed on the vessel, so that they would accurately predict direction in the vicinity of their home port. However, they could be dangerously inaccurate in locations distant from their site of construction (Moran, 1999). Harriot developed a new method of calibrating compasses based on the directions of sunrise and sunset, which are compared to a table to give declination (Shirley 1983). Harriot calculated the values for this table, and measured local declination throughout his expedition to North America for easy reference (Shirley, 1983). The navigational tables constructed by Harriot are extremely significant. Tables like these formed the foundation of Elizabethan navigation, ships' captains lacking the expertise to perform the necessary calculations themselves (Moran 1999).

Harriot was also involved in surveying and mapmaking, a task to which he brought his customary mathematical approach. He made a detailed map of Virginia on Raleigh's 1585 expedition to North America, shown in figure 2.52. His tools consisted simply of a compass to measure direction and a cross staff to measure angles, which he relied on to triangulate the positions of features (Moran, 1999). While in Virginia, Harriot also wrote the first English book to describe the New World, in which he includes information about the terrain, the natives, and a list of natural resources (Hariot, 1893). In addition to listing vegetation and wildlife, Harriot describes the locations and properties of various ore deposits, including those of iron, copper, and other valuable minerals (Hariot, 1893). This surveying and prospecting work helped fuel British interest in colonizing the Americas in later centuries (Shirley, 1983).

Figure 2.14 *Harriot's detailed map of Virginia, surveyed and drawn in 1585-1586. North is to the right in this depiction (below).*



Astronomical Observations

Harriot's work in navigation and mapping furthered the Elizabethan understanding of the Earth, while his work in astronomy furthered understanding of the solar system. Copernicus (1473-1543) had recently published his heliocentric model of the universe, and there was general confusion regarding the organization of stellar bodies. Harriot conducted the first precise measurements of a comet's trajectory in 1607, when he used a cross-staff to record details of the motion of what would later be named Comet Halley (Chapman, 1995). The comet piqued Harriot's interest in astronomy, and his data was of sufficient quality to be used more than 200 years later when precisely calculating Comet Halley's trajectory (Chapman, 1995).

Having acquired a 6x magnification telescope in 1609, Harriot made the first telescopic observations of the moon (Chapman, 1995). As this was a few months before Galileo (1564-1642) acquired a telescope, Harriot became the first person to draw an astronomical illustration with the aid of a telescope (Shirley, 1983). Harriot built and improved many of his own telescopes with magnifications up to 50x and resolutions better than those of Galileo's telescopes (Shirley, 1974). These superior instruments, coupled with Harriot's cartographic background, allowed him to produce an accurate map of the moon's surface, shown for comparison with a modern image of the moon in figure 2.53 (Pumfrey, 2009). Harriot, like many others, falsely interpreted the moon's dark maria as seas and the lighter portions as land (Chapman, 1999). Harriot not only examined Earth's moon, but also studied the four largest moons of Jupiter after their discovery by Galileo (Chapman, 1999). He made calculations concerning their orbits around Jupiter, including some not attempted by Galileo (Stanley, 1983).

The astronomical recordings for which Harriot is best known are those of the sun and sunspots (Chapman, 1999). He observed them near sunrise through a 10x telescope, often with a cover of mist to protect his vision (Chapman, 1999). Harriot made more than 200 observations of sunspots and analyzed their formation, dissipation, and movement on the surface of the sun

(Chapman, 1999). In particular, he studied their motion as the sun rotated, calculating the sun's period to be 27 days (Shirley, 1974). As one of the earliest telescope users, Thomas Harriot contributed immensely to our current understanding of the solar system; as a navigator and surveyor, he enabled future expeditions and provided the foundational skills upon which many future discoveries were made.

History of the Moon

In 1610, with an early telescope, Thomas Harriot drew a map of the moon (figure 2.53), showing distinct light and dark patches on its surface. Today, most of what is known about the moon comes from surface observations, as there has been no deep drilling below its surface (Wilhelms, 1993). Because the moon lacks liquid water, an atmosphere, active volcanoes, or tectonic processes, there is little to change the surface of the moon. It is thus able to preserve a record of all impacts with meteorites of various sizes, while craters and their ejecta on Earth are soon eroded by weathering or tectonic processes (Guest and Greeley, 1977). As a result, the moon is our best source of information regarding the rate of terrestrial bombardment throughout Earth history. This analysis reveals decreasing levels of bombardment since the Earth's formation, but with isolated episodes of increased impact frequency, the most recent of which corresponds closely with the rapid increase in diversity of life on Earth (Koeberl, 2006; Culler et al., 2000).

Formation of the Moon

The moon has orbited the Earth for the past 4.5 billion years, as it was formed very early in the Earth's history (Wilhelms, 1993). Any theory of moon formation must be able to explain the very high angular momentum of the Earth-moon system, the low density of the moon, and the relative sizes of Earth and the moon. Many theories were suggested to explain the origins of the moon, but the only model able to meet all requirements is that of the giant impact hypothesis, which is now generally accepted by scientists (Canup, 2004). This theory involves a large body colliding with the mostly molten Earth at an oblique angle. The majority of the colliding body would have been incorporated into the Earth, but a large portion of the Earth would have splashed out, accreting to form the moon (Canup, 2004). The ejecta would be primarily from the outer, less dense layers of the already differentiated Earth, explaining the lower iron and nickel content of the moon as compared to the Earth (Wiekzorec, et al., 2006).

Subsequent Evolution

The ejecta coalesced into a spherical body and then differentiated into layers based on density (Canup, 2004). By 4 billion years ago, the moon's crust had crystallized, but large impacts occasionally penetrated the crust to form deep basins. These filled with basaltic magma, producing the moon's dark maria (Wilhelms, 1993). This extensive magmatic flooding lasted one billion years, and minimal volcanic activity occurred until 800 million years ago. Since then, the moon has been geologically inactive, its current structure being largely static (Wilhelms, 1993). The moon is asymmetrical, with its centre of gravity shifted slightly towards Earth, and much more extensive maria on the Earth-facing side (Wiekzorec et al., 2006). Its surface is covered by a basaltic crust 50 km thick that is only rarely exposed at the surface. Seismic data indicate that the crust is underlain by a mostly solid mantle, whose 1200 km are separated into three distinct layers. The small core is about 750 km across and, like the Earth's, consists of a molten outer core and a solid inner core (Wiekzorec et al., 2006).

The moon is slowly receding from the earth, drawing energy away through daily tides. It has thus decreased the Earth's period of rotation (day length) by reducing the Earth's rotational kinetic energy (Coughenour et al., 2009). This is significant because it means that tides were once much stronger, and that day length and tidal period are not constant. This has profound implications for organisms and sediment deposition in coastal paleo-ecosystems (Coughenour et al., 2009).

Figure 2.15 *Harriot's lunar map drawn in 1610 shown with a modern image of the Moon, illustrating Harriot's accuracy and precision in his observations (opposite).*

Nicolaus Steno and the Universal Deluge

"And the waters prevailed exceedingly upon the earth; and all the high mountains that were under the whole heaven were covered." –Genesis 7:19, American Standard Version

No single volume has been more influential in guiding the attitudes of the Judeo-Christian world than the bible. For centuries, Scripture has dictated the attitudes of countless people in areas as diverse as diet, work habit and societal law. Throughout most of Christianity's history, the Church demanded a stringent, literal interpretation of the bible, and Judeo-Christian society regarded biblical accounts as fact, relying on Scripture to explain natural phenomena such as geological structures (Steno and Winter, 1968). There was no substantial evidence to contradict a literal understanding, so minimal conflict arose. In the 2nd century, a Christian author named Tertullian formally hypothesized that fossils were the remains of animals that had perished during the flood detailed in the book of Genesis (Cohn, 1996). Scholars, including Leonardo da Vinci (1452-1519), later put alternative theories forward, but through the Renaissance the biblical explanation, corroborated by the word of God, was never eclipsed. The Church ensured that reigning theories were biblically grounded, and those who spoke against the theories were accused of heresy, a crime punishable by death. Finally, in the middle of the 17th century, Nicolaus Steno satisfied the Church by offering a new mechanistic view of the diluvial origin of fossils which provided the theory with the scientific confirmation that it needed (Steno and Winter, 1968).

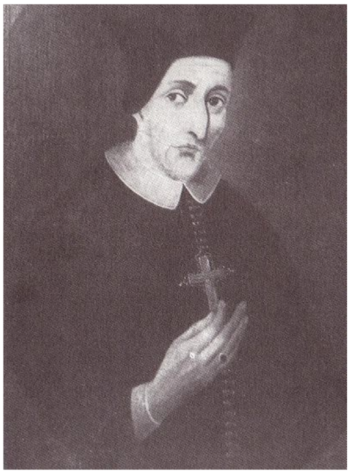


Figure 2.16 *A portrait of Nicolaus Steno (above), early stratigrapher, 1638-1686.*

Nicolaus Steno (1638-1686)

The 'science' of the universal deluge finds its roots with Nicolaus Steno, a devout Catholic well trained in the arts of language, mathematics and medicine. Steno's early life was devoted to anatomy, and he was appointed physician to Grand Duke Ferdinand II of Tuscany (Steno and Winter, 1968). Steno's interest in geology was sparked after he was asked to dissect the head of a shark, an opportunity he was afforded through his affiliation with the Florencian Accademia del Cimento (Academy for Experimentation; other notable members included Francesco Redi, 1626-1697, and Giovanni Borelli, 1608-1679). Steno realized the similarity between the shark's teeth and the strange glossopetrae (tongue-stones) that had been found embedded in rock. The common assumption was that rocks produced the glossopetrae, which were credited with medicinal and magical powers. Steno argued that the glossopetrae were the teeth of long dead sharks, and he was thus motivated to undertake excavations in Tuscany and document his findings (Cohn, 1996). Steno titled his work *The Prodromus of Nicolaus Steno's Dissertation Concerning a Solid Body Enclosed by a Process of Nature Within a Solid* and he addressed it to the Grand Duke Ferdinand II. *Prodromus* means "the forerunner", for his dissertation was intended to precede a work that was never written. It is important to note that although Steno's observations and analyses were very far ranging, only those deemed most relevant to his opinions on the diluvial origin of natural phenomena will be discussed here.

The Prodromus: Fossils

Steno's dissertation begins with an assurance that "the finishing touch shall soon be put on this investigation […] of the inquiry concerning sea objects found at a distance from the sea" (Steno and Winter, 1968, p.209) (for all further quotations from *The Prodromus* only the page number will be provided). Steno first substantiates his estimation of the origin of the glossopetrae. He writes "if a solid body is enclosed on all sides by another solid body, of the two bodies that one first became hard which, in the mutual contact, expresses on its own surface the properties of the other surface" (p.218). By this logic, because the glossopetrae are found inside of the rocks, they must have existed even before the rock itself. Steno continues, stating that "even if the number of teeth [found in lumps of earth] favors [sic] attributing [the glossopetrae's] production to the earth, yet the structure of these same teeth, the abundance in each animal, the earth resembling the bottom of the sea, and the other sea objects found in the same place, all alike support [that the area was once covered in water]" (p.257). Having verified that any area where "marine objects are found" was once covered in water, Steno points out that there is no record of any flood in the area, with the exception of the "universal deluge, four thousand years, more or less before [his] time" (p.258). He admits that some might question the credibility of parts of an animal's body, such as sharks' teeth, "withstanding the ravishes of so many years", but he resolves this issue by explaining that, depending "wholly upon the diversity of the soil", it is indeed possible for parts of an animal to be discovered four thousand years after its death (p.258). He concludes his argument with the evidence that he has "noticed many […] sandy strata which preserved whole all that was entrusted to them" (p.258).

Figure 2.17 *Steno's sketch of shark's head (left) which led him to his decoding of the glossopetrae.*

Next, Steno moves on to demonstrate that "the formation of many molluscs found [in his time] must be referred to times coincident with the universal deluge" (p.258). He asserts that the remnants of the oldest walls of the ancient city of Volterra (it predated Rome) contain "striated shells", which proves that any shells found in stones during his time "had already been formed at the time when the walls of Volterra were being built" (p.259). Steno dissuades his readers from believing that the shells were always made of rock, explaining that in the hill upon which Volterra was built there are strata where it is possible to find molluscs that are even older but have "suffered no change at all" (p.259). Steno is certain that some process must have caused the intact molluscs to transform into rock. He proceeds to calculate that the molluscs are considerably older than the city of Rome. This puts the estimate at well over "two thousand four hundred and twenty years" and so Steno asserts that one may "easily go back to the very times of the universal deluge" when determining the origin of the body of water responsible for the mollusc deposits (p.259). While on the subject of fossils, Steno deters those who might suppose "that the earth which had been carried over into houses over process of time changed into wood". He is certain that "plants inscribed upon stones" were imprinted in stone that had "not yet laid aside the character of a fluid" (pp.261-262).

The Prodromus: Other Geological Formations

Steno also credits the flood with shaping other geological formations. For example, he believes that "a return passage had to be opened for the waters into the deeper parts of the earth", and so deep valleys were formed (p.267). He substantiates this theory with the fact that "in places far from the sea are seen deep valleys filled with many marine deposits" (p.267). Steno is unable to answer the question of "whether the entire sea presently receded" because "the history of nations regarding the first ages after the deluge is […] thought to be full of myths". This view is ironic, considering that today, most academics believe that the book Steno considered to be infallible is itself full of myths (p.267). Steno must then account for the evolution of Earth's features in the short period of four thousand years. He does so by explaining that since "marvels" such as "fires bursting forth from the earth" and "overflowing rivers" have been reported yearly, it is perfectly reasonable to assume that these violent catastrophes could have shaped the Earth's surface (p.269).

The Church's Role

Throughout *The Prodromus* Steno proposes new mechanisms for the formation of geological structures. The book was, however, approved for publication by the Church because Steno's mechanisms still substantiated the Biblical accounts and did not prove "contrary to the Catholic Faith or to good morals" (p. 271). In fact, Steno was very careful to ensue that he "admit[ted] nothing opposed to Scripture, or reason" (p.267). Steno's conviction of the Bible's divinity played a dual role: it both ensured that his research would be considered harmless enough for publication, and prevented him from even considering that the Earth was older than James Ussher (1581-1656) had suggested. It is important to remember that although Steno was not the first to propose the idea that fossils may be the remnants of extant species, he was the first to gain the acceptance of the Church. The foundation of scientific progress is the ability of academics to build upon ideas proposed by their predecessors, and for the first time there existed an accessible, comprehensive manuscript on stratigraphy and fossil origin that would guide scientists for years to come.

Figure 2.18 *The Deluge, Toward its Close: Joshua Shaw's rendition of the drowned humans and animals from the Genesis Flood (right).*

Reception of Steno's Research

Although Steno's explanations were not entirely correct, he is still lauded for his work. Thomas Huxley (1825-1895), a fierce proponent of Charles Darwin (1809-1882), wrote in 1882 that "the principles of investigation thus excellently stated and illustrated by Steno in 1669, are those which have, consciously or unconsciously, guided the researches of palaeontologists ever since" (Huxley, 1882, p.168).

The Fall of Diluvialism

The Genesis flood continued to remain a mainstream explanation for Earth's natural phenomena throughout the rest of the seventeenth and eighteenth centuries. A minority of geologists always contested the diluvial origin of earth's formations, but the majority did not approve of their controversial work. James Hutton (1726-1797) is an example of a geologist who could not fathom the "vestige of a beginning" of the earth (for more information on Hutton see pages 54-57), but his work was not well-received; as contemporary Richard Kirwan (1733-1812) stated, Hutton's beliefs were "fatal [to religion and morality" (Kirwan, 1799). Kirwan himself wrote extensively on geology, and his views were far more orthodox. To the universal deluge he attributed the barrenness of the Gobi desert and the fossilized remains of animals and plants found in Siberia (Kirwan 1799).

Geologist Johann Gottlob Lehmann (1719-1767) referenced the Genesis flood in his explanations of mountain formation, claiming that the Flood had caused impressions of flora and fauna to be left in the mountains (Cohn, 1996). It was not until the middle of the 19th century that academics began to accept that the processes which had been attributed to a universal deluge had actually been caused by less catastrophic events such as glaciation. Today, diluvialism has become a theory generally restricted to the academia of fundamentalist Christians.

Diagenesis of Calcium Carbonate Fossils

Contrary to the belief of 17th century Europeans, fossils can be millions of years old, and the mineralogical structure of a fossil often changes. Depending on the fossil's environment, its composition can undergo significant modifications. Biogenic remains that are situated near the sediment-water interface experience chemical alteration through a process called diagenesis (Martin, 1999). Elements that contribute to the original mineralogy of skeletal elements are recycled back into the biogeochemical cycle, and replaced with other material. Skeletal elements of living organisms can be made of calcium phosphate, silica, or calcium carbonate, only the last of which will be discussed here. The exact composition of a skeleton is dependent upon both the type of organism and the environmental conditions in which it lived (Donovan, 1991). The term diagenesis encompasses all processes that affect a sediment and its fossils until the sediment undergoes metamorphism (Donovan, 1991).

Figure 2.19 *Small aragonite crystals (left) growing from an earlier generation of larger aragonite crystals. Fossilized skeletal elements composed of aragonite that lie at the sediment-water interface may undergo diagenesis.*

The Process of Diagenesis

When fossilized skeletal elements are composed of calcium carbonate, the calcium carbonate will either form aragonite or calcite. Calcium carbonate in the form of aragonite is poorly preserved in the geological record because it is typically converted into calcite through diagenesis (Donovan, 1991). There are two ways that this conversion from aragonite to calcite occurs. The first method of conversion is through wholesale dissolution, where the aragonite dissolves but leaves an impression of its shape in a well-cemented host sediment (Donovan, 1991). Calcite precipitate eventually fills the mould (the calcite precipitate is formed from an excess of carbonate ion produced by carbon dioxide dissolved in seawater) (Martin, 1999). The second method of conversion, called calcitization, eliminates the wholesale dissolution; instead, aragonite dissolves on one side of a thin film, and it is replaced by calcite that precipitates on the other side of the film (Donovan, 1991). This second method leaves small amounts of aragonite amongst the calcite crystals (Donovan, 1991).

Fossils that are originally composed of calcium carbonate in the form of calcite are much better preserved in the fossil record. Calcite can be subdivided into two types, high-magnesium calcite and low magnesium calcite, of which the former dissolves much more easily. During diagenesis of high-magnesium calcite, the magnesium ions are replaced with diagenetic low-magnesium calcite (Donovan, 1991). The composition of low-magnesium calcite material is rarely altered by diagenesis.

Significance

The type of diagenesis that occurs is dependent upon the mineralogical environment of a fossil. As such, knowledge of diagenetic processes is necessary for ascertaining the chemistry of ancient waters and the microstructure of extinct species (Martin, 1999). A comprehensive understanding of diagenetic processes is therefore invaluable in piecing together a picture of how different environments have changed over time.

Western Europe in the Renaissance: A Revolution in Landscape Perception

The ability of modern society to understand observed phenomena using established scientific theories is often taken for granted. To appreciate such a feat, it is important to remember that before a branch of science can take form, a notion or concept of the entities within that field must be developed within the mind. That is, a universal principle or perspective must be associated with the observables. Geology, or the science of landscape, is no exception. The conceptualization of landscape necessarily preceded the science of landscape, and it was in Western Europe – at the start of Renaissance – that this reformation of spacial thought began.

Revolution in Spacial Organization

The beginning of the Renaissance was marked by the rediscovery of Arabic and Greek geometry in Western Europe (Rosenberg, 2009). This had a profound effect on how nature was viewed and also inspired society to incorporate geometric organization and structure into nearly every aspect of life. The same underlying geometric principles could be seen in the transformation of land ownership, distribution of wealth, navigation, mapping, and the depiction of nature in Renaissance art (Cosgrove, 1985).

The primary shift in perspective throughout the Renaissance was from a microcosm-macrocosm view to classification based on structural similarities and differences. The former view was based on the idea that resemblances existed throughout the cosmos. For instance, the human body was viewed as an analogy for the cosmos, wherein rocks could be paralleled to bones, and veins to rivers. This differs from the later perspective, which arose in the end of the sixteenth century and was essentially the beginning of what is now known as taxonomy – classification based on geometric structure and form (Field, 2004). This organizational approach formed the basis of thought during the 17th and 18th centuries and caused further reform in societal structure and lifestyle. For example, the concept of double-entry bookkeeping was developed during the Renaissance and reflected the use of a taxonomic classification strategy. In this case, statistics concerning the exchange of goods were classified into categories such as liabilities, assets, incomes, and expenses. Credited as the first to formally write about double entry bookkeeping was Italian mathematician Luca Pacioli, who was aided by contributions from Leonardo da Vinci and Nicholas Copernicus (Rosenberg, 2009).

Geometry and Landscape Art

Perhaps the most vivid representation of changing spacial awareness was that seen in the landscape paintings of Renaissance and Baroque artists. In fact, the term "landscape" and the resulting idea of "landscape art" originated during the Renaissance as a result of Western European preoccupation with geometry (Cosgrove, 1985). In terms of painting, geometric perspective was created by the use of construction lines and points, as well as several optic tools designed to aid the portrayal of an image in agreement with basic geometric properties. Among the instruments used were concave mirrors, convex lenses and camera obscuras (Camerota, 2005). Taken together these efforts served to produce an impression of depth, distance and spacial continuity upon a two dimensional canvas.

The avid interest in incorporating geometry into landscape paintings originated among Italian Renaissance artists (Wittkower, 1960). Among them was Lodovico Cigoli, who wrote about several advanced techniques used to achieve correct perception in his treatise Prospettiva Pratica (Kemp, 1991). Adopting the ideas of Italian mathematician Guidobaldo del Monte, Cigoli describes a method for determining the vanishing point in an image in order to establish a realistic sense of depth. Also described in his publication is the use of "perspectographs" (Kemp, 1991). Such devices were becoming increasingly popular among artists who strived to achieve a proper geometric representation of their subject. The basic motive of these instruments was to transfer

points and outlines of an object onto a canvass so as to represent them in their proper geometric relations as viewed from a particular point (Wittkower, 1960). In this way, the instruments being created were based on the concept of 'linear perspective' which relied on the principle of intersection of the visual pyramid (Anderson, 2007).

Regarded by Renaissance artists as an axiom in the science of painting, the visual pyramid maintained that a group of light rays converge precisely onto a single point in the eye (Camerota, 2005). Within his treatise, Cigoli also discussed his understanding of the visual processes of the eye. In contrast to the ancient viewpoint, in which the eye is seen as "mirror" of the emotions, Cigoli drew parallels between the workings of the eye and a camera obscura. All of these correlations he based on Aristotelian optics, which were reintroduced into the West by the translated writings of Islamic philosopher Alhazen (Kemp, 1991). Cigoli's friendship with Galileo also contributed to the formulation of his theory. At the time, Galileo had introduced the telescope, and attributed its ability to transcribe distant images to the mechanism of the camera obscura. Cigoli extrapolated the same principles to the eye, wherein he paralleled the mechanism of forming images in the eye to that seen in a camera obscura. (Camerota, 2005).

It is easy to overlook the fact that a geometric idea of landscape did not always exist. Prior to the Renaissance, individual features were portrayed as separate objects and thus "landscape" was not a view but rather an accumulation of isolated features. Furthermore, space was not understood to be a measureable entity (Rosenberg, 2009). These ideas are plainly visible when comparing medieval art pieces to those reconstructed in the Renaissance, as seen in Figure 2.71 below. Both paintings portray the story of St. John at Patmos, a small Greek island in the Aegean Sea. The first portrayal, painted somewhere between 1350-1370 by French artist Jean de Mandeville, exemplifies the limited spacial perspective of the Medieval ages. The painting features what appears to be a river flowing both uphill and downhill, even though it was understood to represent the sea surrounding the island. Such a portrayal effectively shows the lack of continuity in spacial perception by including the strip of water as a design element rather than an integrated component of the landscape. The art piece in Figure 1.27 painted by Tobias Verhaecht in 1598, provides striking evidence of the revolution in spacial awareness during the Renaissance.

Figures 2.20 and 2.21

A comparison illustrating the changing notion of landscape Portrayal of St. John at Patmos (left) painted by Master Jean de Mandeville of France between 1350-1370. A Renaissance adaptation (below) painted by Tobias Verhaecht in 1598.

A geometric perspective allows for the depiction of depth and distance within the painting and thus the landscape appears continuous as an integration of structures.

This is the critical difference; incorporation of geometry makes landscape the subject of a painting rather than simply a background onto which a collection of objects are arranged.

From Anatomy to the Natural Landscape

Of particular relevance to the perception of form in geology was the novel way in which the anatomy of the human body was being perceived during the Renaissance. Instead of being viewed as simply a sum of its individual parts, the entire organism was seen as a material object of integrated parts and functions (Rosenberg, 2009). In other words, structure and function were now thought to be continuous across the organism such that the structure and function of one organ could not be viewed as existing in isolation (Field, 2004). The most important consequence of this kind of thought was the ability to conceptualize how a system could change over time. It is highly likely that this reform in understanding the anatomy of the human body was later applied to landscape perception. Once landscape was conceived as a material object of integrated parts and functions, its evolution, too, could be defined (Rosenberg, 2009). This progression of thought was perhaps best seen in the publications of Nicolas Steno, whose later works in establishing the fundamental ideas of geology were likely influenced by his previous work as an anatomist. Also relying on the same concepts was Leonardo da Vinci whose work in anatomy similarly had a large basis in geometry. Quotes from the publications of both Steno and da Vinci explicitly express their appreciation and dependence on geometry when describing anatomical form. Furthermore, several landscape paintings by da Vinci show evidence of anthropomorphic features in which elements of nature are depicted using components of the human form as an outline. Thus, in the work of both polymaths, geometric construction of the human body preceded the application of the same concepts to the natural landscape (Rosenberg, 2009).

Comparing Western Europe to China

The avid use of Greek geometry in reforming all aspects of Western life, including that of scientific thought and perspective, stood in stark contrast to the indifference of such ideas in China. China did not develop an interest in the geometric visualization of space until the 1800s (Rosenberg, 2009). This was largely due to a cultural and religious preference for formlessness rather than spacial structure. Appraisal for the absence of form was even stated explicitly in Buddhist sutra and was thus integral to the daily lives of Buddhists (Summers, 2000).

Apart from cultural divergence, it is also useful to compare mathematical perspectives in China to those prevalent in Europe during the Renaissance. Dominating Western mathematics was Euclidean geometry, which best exhibited the logic and notion of rationality and deduction developed by the ancient Greeks. In China, *The Nine Chapters on Art of Mathematics* is often regarded as the Chinese counterpart to the treatise Euclid's *Elements* (Dauben 1998). Comparing these works reveals a very different approach to the handling and application of mathematical ideas between the two societies. The presentation of concepts in Euclid's *Elements* begins with a statement of abstract idealized definitions and axioms followed by theorems and their proofs. The format of *The Nine Chapters*, conversely, is more that of a handbook containing problems followed by algorithms for solving them (Dauben 1998). Thus, instead of pursuing abstract and logical generalizations, Chinese mathematics was primarily concerned with practical problems. Such a perception of mathematics, with its problem-based form, could account for the absence of its incorporation into art, lifestyle or general spacial awareness.

In retrospect, this contrast between the East and West makes the importance of Arabic and Greek geometry in the development of modern geology, and modern science in general, clear. Although China made several valuable contributions to geology even before the Renaissance, it was in Western Europe that the science of geology was established as we know it today.

Principles of Geology

Nicolas Steno's early work in anatomy provided him with an invaluable grasp on the spacial relationships of organs within the body. This application of geometric perspective is something he reverently promoted in his early publications (Rosenberg, 2009). It is very likely that this appreciation for spacial relationships formed a basis with which he eventually devised foundational geologic concepts.

Nicolas Steno was the first to formally recognize the importance of horizontal layering of rock, also known as stratification. He devised three principles encompassing the universal properties he observed, and it is from these principles – superposition, original horizontality, and original lateral continuity – that stratigraphy was born. Stratigraphy, the science of layered rocks, addresses properties such as texture, composition and arrangement of strata (Levin, 2006).

Figure 2.22 *An outcrop showing features which can be interpreted using the principles of geology. Assuming that the strata have not been overturned, layers at the bottom are oldest and become progressively younger going upward. A slight incline of the bed suggests deformation by tectonic activity.*

Principle of Superposition

The principle of superposition states that in an undisturbed sequence of strata, the oldest layer is at the bottom and layers successively higher are increasingly younger in age (Levin, 2006). Although simple in its premise, this principle effectively describes how the position of strata in a sequence can allude to the relative geologic age of the sedimentary layer and the fossils it contains. However, caution must be taken when applying this principle to areas of previous tectonic activity. In such cases, layers appear tilted and may even be overturned. Correct interpretation can then be achieved though the detection of geopetal structures, such as footprints or fossil impressions, which assist in revealing the correct orientation of the strata (Levin, 2006).

Principle of Original Horizontality

This principle states that sediment is deposited in layers that are originally horizontal and parallel to the surface of the Earth (Levin, 2006). Thus, this principle can be used to infer whether a stratum has undergone alteration or if it exists as it did upon original deposition. For instance, steeply inclined strata would suggest tectonic activity after deposition (Figure 2.72).

Principle of Original Lateral Continuity

The principle of original lateral continuity states that strata extend continuously in all directions when deposited and terminate either by thinning out or by encountering a barrier to sedimentation (Levin, 2006). Thus, the entire distributional area of a sedimentary unit can be mapped out. In particular, if lateral continuity is not seen within a section of the expected distributional area, one can infer that faulting or erosion took place there, causing a disruption in the distributional area.

Although seemingly intuitive, Steno's principles initiated the science of rock layers, or stratigraphy. Included later, in the 18th and 19th centuries, were the principles of uniformitarianism and the principles of cross-cutting relationships and included fragments. These were formulated by James Hutton and Charles Lyell respectively. Taken together, these geologic principles are foundational rules in what is now a very involved quest of unravelling the entire geologic record through the correlation of rock units.

Alchemy in 17th Century Europe

European science, known as Natural Philosophy at the time, was in a state of rapid growth and change during the 17th century. The previous century marked the beginning of the Scientific Revolution which was instigated by the publication of Nicolaus Copernicus' heliocentric model of the solar system in 1543 and continued by the work of Galileo (1564-1642) and Johannes Kepler (1571-1630) (Gleick, 2003). New developments were also occurring in medicine and anatomy at the time, led by William Harvey, who correctly described the workings of the circulatory system in 1628 (Rezende, 2006). Despite these advances, the modern fields of science had not yet developed, many of them being considerably hindered by outdated theories. Two such disciplines in the middle of the 17th century were chemistry and geology. The modern definition of chemistry did not yet exist, and its practitioners were struggling to gain acceptance as natural philosophers. Geology was even less developed and existed almost solely in relation to mineral mining. Its largest influence was George Bauer's *De Re Metallica* published in 1556 (Rezende, 2006). However over the next century both chemistry and geology would grow into important scientific fields, due in part to a shared heritage: alchemy.

Figure 2.23 *Sir Isaac Newton, 1702 (above). Newton is better known for his invention of calculus and classical mechanics, however, he devoted far more time to alchemical studies than mathematics or physics.*

A Brief History of Alchemy

Alchemy had existed in various forms for centuries, dating all the way back to the Hellenistic period. After the fall of Rome in the 5th century, the centre of alchemical study had shifted to the Arabic-speaking world, where it was developed by Jabir ibn Hayyan (721-815) and other alchemists (Rezende, 2006). It was through these Arab influences as well as the renewed study of ancient Greek manuscripts that European alchemy developed and became extensively practiced in the medieval ages. By the 17th century, alchemy was in its prime in Europe (Dobbs, 1991). Some of the greatest minds of the time were devoting considerable attention to the field. Of special note are Robert Boyle (1627-1691) and Isaac Newton (1642-1727), the former the father of modern chemistry and formulator of Boyle's Law, the latter the developer of calculus and classical mechanics (Gleick, 2003; Hunter, 1994).

Alchemy has often carried a negative connotation in modern thought, which has resulted in Boyle and Newton's involvement with the practice being severely downplayed. In fact, Boyle's alchemical studies spanned 40 years, and Newton devoted over a million words to the subject (Gleick, 2003; Hunter, 1994). However, both men were influential – though perhaps not completely intentionally – in developing a clear distinction between the occult alchemy that persisted into the 18th and 19th centuries and modern chemistry that became a respected discipline of Natural Philosophy. In addition, their work with metals and theories on the particle theory of matter built the foundation for the geological advancements of the following century.

Alchemical Beliefs in the 17th Century

The beliefs and theories associated with alchemy in the second half of the 1600s are difficult to rationalize in the light of modern science. However, to appreciate the work of Boyle and Newton in changing alchemical practices and developing chemistry, it is essential to understand the alchemical beliefs under which they worked. The primary goals of alchemy for centuries had been to discover the Philosopher's Stone and the Elixir of Life (Dobbs, 1990). The former was the mystical substance that would turn base metals into gold while the latter was the mixture that would confer eternal life. While seemingly two unrelated goals, they were actually highly intertwined in alchemical theory. It was believed that nature existed under three kingdoms: animal, vegetable and mineral, and that each one required some sort of animating spirit (Dobbs, 1990). For humans this was the soul, while for minerals it was an animating force that gave different minerals their properties. Newton termed it the vegetable force, illustrating the philosophical link between the kingdoms in alchemical thought. The transmutation of a base metal into gold was seen as the greatest purification possible in matter and was analogous to the purification of the human soul, which would give eternal life. At the time, it was believed that the discovery of one would lead to the discovery of the other (Dobbs, 1990).

Such reasoning was a result of the alchemist's understanding of the world's composition. It relied on the classical Greek theory of the elements – air, water, fire, earth and ether – that made up all matter in the universe and gave them their distinctive properties (Dobbs, 1990). In addition, the more recent idea of the *tria prima*, introduced by the 16th century alchemist Paracelsus, was also widely accepted. The *tria prima*, comprising Mercury, Sulphur and Salt, were physical and spiritual properties of matter, as oppose to the elemental definitions they hold today. The behaviours of compounds and mixtures were explained by the proportional presence of these properties. Sulphur for example denoted the "expansive force" of dissolution or evaporation (Hunter, 1994).

Figure 2.24 *The Shannon Portrait of the Hon. Robert Boyle, F.R.S., 1689 (left). 1689. Boyle did more than any other man of his time in removing alchemical influences from chemistry, yet he remained a devoted alchemist to his death.*

Alchemists believed that transmutation was possible through a reorganization of these basic properties and components of matter. Using an analogy of nature, alchemists proposed that the first step in transmutation was the degradation of organized forms into chaos, known as putrefaction, following which the generation of new forms was possible (Gleick, 2003). The decay of plant and animal bodies which eventually resulted in new forms of life, such as new vegetation, was taken as evidence of this. After putrefaction the desired product could be produced by adding the appropriate components and suffusing them with the vegetable force. This last step was usually attempted using quicksilver (mercury) since it was believed to contain the spirit that animated matter (Gleick, 2003).

It was in such a world that Boyle and Newton conducted their alchemical studies. Both men were great collectors of alchemical works and were well versed in alchemical theory. However, through their own experiments and association with other disciplines of Natural Philosophy – Boyle in chemistry and Newton in mathematics and physics – they came to reject many common alchemical beliefs and began to introduce new ideas into the practice.

The Scientific Significance of Alchemical Work

In 1661 Boyle published *The Sceptical Chymist* which contained many important ideas for the progression of chemistry into an accepted discipline of science while removing many alchemical influences (Hunter, 1994). In it, Boyle argued against the alchemical belief that matter was composed of the five Greek elements, and he rejected the notion of the *tria prima*. Instead Boyle presented the idea that all natural phenomena could be explained by the combination of small discrete particles, termed atoms, into mixed bodies (Hunter, 1994). In response to the alchemical tradition of secretive and obtuse writing and broad, ill defined definitions, Boyle also argued for the use of standardized and unambiguous language to describe chemical processes and mixtures (Hunter, 1994). Perhaps most importantly, Boyle called for theoretical explanations to explain experimental phenomena, in contrast to the alchemical practice of experimenting to try and prove pre-existing theories (Hunter, 1994). Despite these important ideas, Boyle still clung to some alchemical doctrines, the most notable of which was the ability to change base metals into gold. Even so, Boyle's thinking led him to believe that if all matter was made of the same atoms, there should be a way to transform one metal into another, which was in sharp contrast to the belief of his time that the Philosopher's Stone was dependent on spiritual forces (Hunter, 1994).

Like most Natural Philosophers, Isaac Newton (15 years Boyle's junior) also adhered to the atomic theory of matter. However, there was a difference of opinion on the precise definition of matter. Mechanical philosophy, a discipline established by René Descartes earlier in the century, held that the mechanical actions of the natural world could only occur through direct contact (Gleick, 2003). This was also the view expounded by the Royal Society – of which Newton would later became President – which was striving to create a science free of occult influences and mysterious forces acting at a distance. Newton disagreed. He rejected mechanical philosophy for the way it offered a different mechanical explanation for every phenomenon. In particular Newton disliked their theory of hooked atoms to explain the coherence of matter (Gleick, 2003). Using mathematics Newton proved the existence of one of the mysterious forces of nature, that of gravity, and theorized about the existence of a second to explain the coherence of atoms. He wrote "I had rather infer from their Cohesion, that their Particles attract one another by some Force, which in immediate Contact is exceeding strong," (Newton, 1704, cited in Gleick, 2003 p.187). It is likely that Newton's mental flexibility in hypothesizing these forces was influenced by his alchemical studies. Newton himself had believed in the vegetable force to organize particles of matter into the wide array of forms found in nature, so it was not such a leap for him to believe in a force that acted at a distance, especially when it had been proved mathematically, as in the case of gravity.

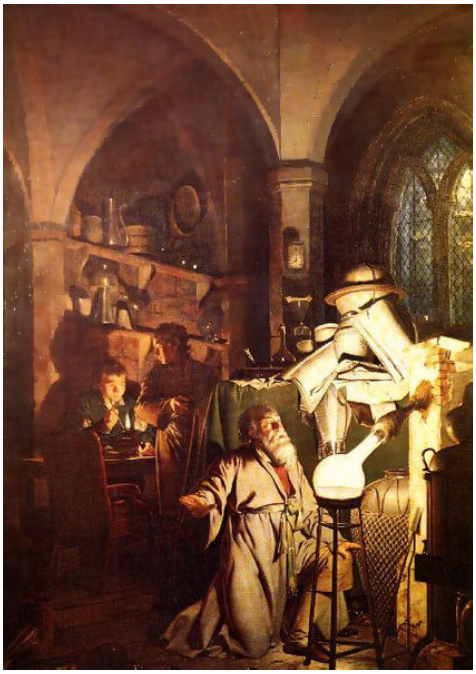


Figure 2.25 *The Alchymist in Search of the Philosopher's Stone by Joseph Wright, 1771 (right). Despite their enormous influence on modern science, both Newton and Boyle believed in the alchemist's dream of discovering the Philosopher's Stone, and searched for it themselves in numerous experiments.*

Like Boyle, Newton also believed in the transmutation of base metals into gold, writing "all things are corruptible. All things are generable," (Newton, unpublished, cited in Gleick, 2003 p.103) in the belief that matter could be rearranged by a knowledgeable alchemist to produce another substance. What set Boyle and Newton apart was their method of experiments. Both men practiced a disciplined approach to experiments, accurately measuring weight and time and recording the results thoroughly (Gleick, 2003; Hunter 1994). This would become an essential part of all later scientific analysis.

Impact on Geology

The scientific legacy of Boyle and Newton is vast, and their work in alchemy played an important role in the development of chemistry and geology. Due to Boyle's rejection of the classical Greek elements, the chemical theory of elements was able to develop into a more rigorous, scientific definition. By the time Antoine Lavoisier (1743-1794) published *Elements of Chemistry* in 1789, thirty-three elements had been identified under the definition of a substance that cannot be broken down any further into its components (Rezende, 2006). This far more detailed understanding of the elements aided geological study as well. In the century following Boyle and Newton, new elements such as oxygen, hydrogen, nitrogen, yttrium, titanium, uranium, zirconium, strontium, tellurium, tungsten, molybdenum, chromium and beryllium, were discovered in field work and isolated through chemical reactions (Rezende, 2006). It was also shown by Smithson Tennant in 1796 that diamonds were made of pure elemental carbon. In addition, using Newton's law of gravitational forces, Henry Cavendish calculated the mass of the Earth to a value close to today's accepted one, and estimated its density in 1798 (Rezende, 2006). This work would provide a valuable tool for future geologists to investigate the composition of the interior of the Earth. Thus, the work of Boyle and Newton had a strong impact on geological science in the century that followed them, paving the way for accurate chemical analysis and classification and in determining the mass of the Earth.

Formation of the Earth

Geologists have sucessfully used chemical analysis and graviational calculations to determine the outer and inner structures of the Earth. This has allowed development of a deeper understanding of how the Earth formed, what it was like in its early history and how these structures continue to affect the planet.

Formation Process

The composition of the Earth has provided clues into how the Earth formed and has changed over time. Current understanding holds that the Earth was originally created out of dust and gas orbiting in a disk around the sun. The gas and dust began to accrete into rocks and metals which were gradually collected into larger bodies through gravitational attraction and collisions (Plummer, et al. 2007). Eventually this accretion led to the formation of planets, including the Earth. The processes of accretion and gravitational attraction caused compression, and together with radioactive isotopic decay, this generated enough heat to cause the Earth to melt and become molten (Plummer, et al. 2007). In this state, the Earth's components began to differentiate, with the abundant and heaviest elements – nickel and iron – settling towards the centre and the lighter silicates moving to the crust. This separation of elements formed the basic layers of the Earth's structure that exist today (Plummer, et al. 2007).

Modern Impact

The earliest rock formations known today are 4 billion years old (Plummer, et al. 2007). These rocks formed the basis of the modern continental crusts upon which younger rocks exist. This has allowed for the relative dating of sediments and geological events. The ocean floor is much younger, however, indicating much more recent geological activity at the Mid Ocean Ridges, which continually regenerate the sea floor (Plummer, et al. 2007). In addition, the molten nature of the Earth's interior, generated by the early processes that formed it, has an important impact on continental movement. The increased temperature and pressure in the asthenosphere causes it to be more plastic than the crust and act as a lubricating layer over which the plates of the crust can move (Plummer, et al. 2007). These plate tectonics result in most of the geological activities that shape the planet's shell, including the occurrence of earthquakes, formation of mountains and volcanoes and change in sea floor topography (Plummer, et al. 2007).

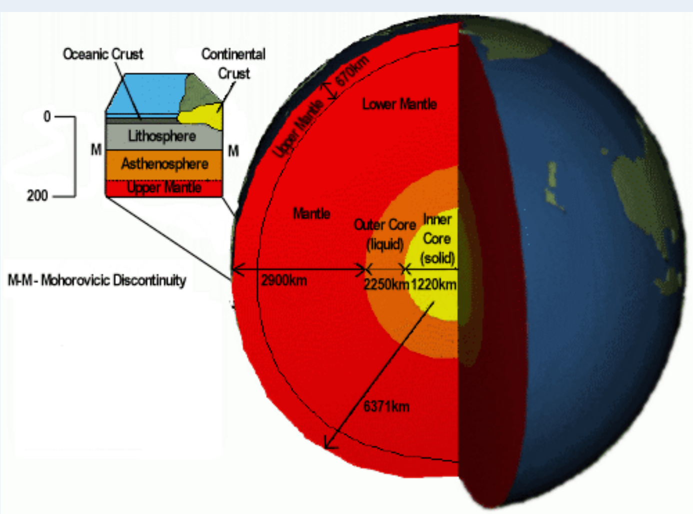


Figure 2.26 *Interior Structure of the Earth (left).Note the solid inner core, liquid outer core and asthenosphere below the lithosphere.*

James Hutton and Uniformitarianism

James Hutton (1726–1797), founder of modern geology, was born and raised in Edinburg, Scotland (Bailey, 1966). It was here that Hutton first developed an interest in chemistry which would continue to influence him throughout his lifetime. In particular, this interest led him from law, to medicine and finally farming (Bailey, 1966). Hutton's work, which required extensive travelling, allowed him to develop an interest in geology and the composition of the earth. He would spend 30 years of his life collecting specimens and studying the formations of the earth (Baxter, 2004).

Figure 2.27 *Portrait of James Hutton, the founder of modern geology, created by Sir Henry Raeburn in 1776. Raeburn included geological specimens in the background to represent Hutton's contributions to this field.*

James Hutton is known today for his detailed observations of the Earth's geological formations, which he later compiled into his great work, Theory of the Earth. In this work he presented original hypotheses on the age of the earth, and the uniformity of geological processes (Eyles, 1970). Hutton originally presented these controversial theories without concrete evidence, attracting significant criticism when first published. However, his hypotheses have since been proven correct and now form the basis of modern geological thought (Baxter, 2004).

18th Century Thought

Religion played a significant role in scientific thinking during Hutton's lifetime. In fact, about a century before the publication of Hutton's Theory of the Earth, James Ussher (1581-1656), an Irish Bishop, proposed that the Earth was only 6,000 years old. Relying solely on biblical passages, Ussher calculated that God had created the earth on the 22 of October 4004, BCE (Baxter, 2004). This date became widely accepted as the beginning of earth and was published in new editions of the Bible after Ussher's death. However, less than 100 years before Hutton's geologic work, scientists had already begun to question Ussher's thinking (Baxter, 2004).

Additionally, in Hutton's time it was thought that the formation of geologic structures was largely dependent on significant Biblical events. Many believed that all visible features of the earth had precipitated out of a universal ocean originally caused by Noah's Flood or the Creation itself (Repcheck, 2008).

Due to their prominence in society, it was inevitable that these religious principles would influence James Hutton and his work. In keeping with the deistic movement and his mentors, Newton (1643-1727) and Maclaurin (1698-1746), Hutton believed that nature was governed by physical and chemical laws but that they all displayed the design of the Creator (Baxter, 2004). However, unlike other scientists who were blinded by their beliefs, Hutton's belief in divine design allowed him to interpret his observations and develop his innovative theories (Baxter, 2004).

Theory of the Earth

After failed careers in both law and medicine between 1743 and 1749, Hutton pursued a livelihood in agriculture (Bailey, 1966). In order to learn and perfect agricultural techniques, he often travelled to various parts of England, such as Isle of Wight and Yorksire (Baxter, 2004). It was on these journeys that Hutton began to study geology seriously and make observations that allowed him to formulate his fundamental principles of nature (Baxter, 2004). Hutton is well known today for the description of three fundamental principles of the earth: sedimentation and igneous processes, the length of geologic time and the uniformity of geologic processes (Eyles, 1970). These principles originally stemmed from his observations that rocks are composed of recycled materials, such as decomposed minerals and animals, and will all eventually decay and flow into an ocean (Baxter, 2004).

Hutton published his ideas in several papers during his lifetime ranging from Considerations on the Nature, Quality and

Distinctions of Coal and Culm to Theory of Rain (Bailey, 1966). Today, however, it is Hutton's Theory of the Earth that remains most notable for its description of Hutton's fundamental principles. Originally published in 1788 in Transactions of the Royal Society of Edinburgh, Theory of the Earth was not republished alone until a decade later (Craig, Hull and Geological Society of London, 1999).

Formation of Rocks

"Strata formed at the bottom of the sea, are to be considered as having been consolidated, either by aqueous solution or by the effect of heat and fusion." (Hutton, 1960, p.225)

Hutton's Deistic views largely influenced his perception of the Earth and led him to believe that the Earth was a well designed machine composed of three observable parts: a solid component, surrounded by a body of sea and a body of air (Bailey, 1966). Being an object of divine design, Hutton proposed that the purpose of the Earth was to sustain all life inhabiting it. From this belief stemmed Hutton's idea of erosion and consolidation (Bailey, 1966).

Hutton initially argued that soil was a necessary element in sustaining life on Earth and he deduced that it was formed by the decay of solid rocks through water, winds and tides, a process termed erosion (Bailey, 1966). However, through fellow farmers Hutton learned that the erosion process was continuous, and the soil created by erosion was often also carried away. If erosion occurred repeatedly without replenishment, all the soil would eventually be removed from the Earth's surface and the Earth would cease to support life (Baxter, 2004). This did not fit with Hutton's belief in Earth's purpose, and his intuition told him that there must be a process to repair this damage caused by erosion (Bailey, 1966).

Through his observations of rocks, Hutton realized that the gravel and sand produced by erosion greatly resembled the components presently existing (Baxter, 2004). He inferred from this observation that the particles produced from erosion were then compressed into new rock under the sea, with the addition of heat. This theory was supported by evidence of fragmented marine organisms found over 2,000 metres above sea level, as described by geologist Horace-Bénédict de Saussure (1740-1790) (Bailey, 1966). However, Hutton was left questioning how the new rock formations were raised above the sea level.

Originally, because he believed that the consolidation of rock particles required the addition of heat, Hutton proposed that there was an upheaval process controlled by heat that was responsible for raising the earth above sea level (Bailey, 1966). He supported this theory by discussing the fact that there are fragmented and bent rocks found on earth in every possible attitude and direction, indicating an uplifting movement (Bailey, 1966). James Hutton summarizes his findings, 'the land on which we dwell [has been elevated] by extreme heat and expanded with amazing force for the purpose of the living world' (Bailey, 1966, p.42)

Through his interpretation of geologic evidence, Hutton was able to create his hypothesis on the formation of rocks and despite the Deistic influence on his thinking, many of his conjectures would later prove to be correct and would be reiterated in the years to come (Baxter, 2004).

Uniformity of Geologic Processes

"In examining things present, we have data from which to reason with regard to what has been." (Hutton, 1960, p. 217)

One of Hutton's greatest principles was that the geologic processes have not changed over time, which is today termed uniformitarianism. He assumed that the geological processes he was witnessing were the same processes that occurred in the past (Baxter, 2004) He also suggested that these would be the same processes acting in the future. Unlike others at the time, Hutton believed that there was no need to invoke catastrophes to explain past geological process that had created these geologic structures (Repcheck, 2008). Hutton further elaborated on this thinking by explaining that the geology of the Earth cannot be fully understood without analyzing many different processes through the succession of time (Bailey, 1966).

This theory remains only a conjecture, as there is no way to prove that these geological processes have not changed over time (Baxter, 2004). Despite this, Hutton's uniformity theory allows for the reconstruction of past events and even the ability to predict future ones. It is regarded as an essential theory to the current thinking of geology (Baxter, 2004)

Geologic Time

"The result, therefore of our present enquiry is, that we find no vestige of a beginning – no prospect of an end." (Hutton, 1960, p.304)

Through his previous geological work in Scotland, Hutton hypothesized that the earth went through cycles of erosion, deposition, consolidation and uplift, but he was unable to discern precisely how many cycles the earth had occurred in the past (Baxter, 2004). Hutton was especially interested in the study of the greywackes at Siccar Point on the Berwickshire coast. Here he found a distinct rock structure with a flat layer of Old Red Sandstone overlying sharply tilted beds of Silurian greywacke (see Figure 2.82) (Craig, Hull and Geological Society of London, 1999). This structure not only reconfirmed his previous principle of the cyclic nature of geological processes, but also provided insight to the age of the earth itself. Hutton reasoned that all sediments had to be deposited horizontally, but that another process was involved in tilting the bottom rock layers (Baxter, 2004). Again Hutton suggested that heat played a prominent role in this process, as in the formation of different types of rocks (Baxter, 2004). In the case of Siccar Point, he proposed that the lower tilted beds of rocks were originally deposited as horizontal beds but had become slanted due to extreme heating as it was raised above sea level. In order for the flat sandstone to be deposited on top of this layer, Hutton suggested that the land had to be submerged in water once again to allow for deposition and consolidation (Repcheck, 2008).

Hutton recognized that this process could not have occurred in less than 6, 000 years, the estimated age of that the Earth at the time (Repcheck, 2008). Knowing that sediments themselves were only deposited at a rate of about an inch a year, it would have taken hundreds of thousands of years for enough sediment to condense into the rock forms seen at this point (Repcheck, 2008). Hutton thus concluded that the earth had to be at least that old to allow for these formations.

Controversies

Although Hutton was regarded as one of the great scholars of Edinburgh, his ideas were not readily accepted among society. The common belief that the Earth was only 6,000 years old based on the Biblical perspective was still held and not many were willing to believe otherwise (Repcheck, 2008). However, some scientists before Hutton's time, had suggested that the world was more than 6,000 years old, but the oldest estimation had been a mere 75,000 (Repcheck, 2008). Due to his observations at Siccar Point, Hutton had proposed that the

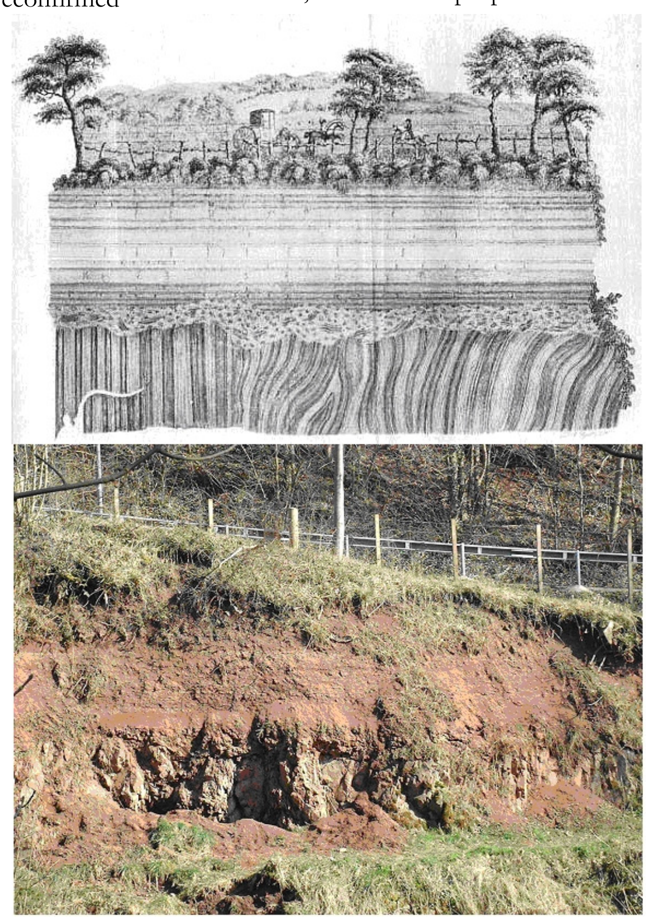


Figure 2.28 *Siccar Point in Jedburg, Scotland (right).Top: Cross section of Siccar Point illustrated by John Clerk in 1787, showing distinct changes in the rock strata. Bottom: Modern view of the unconformity at Siccar Point.*

earth was at least a couple hundred thousand years old, but he had no way of determining exactly how old. Hutton's ideas did not fit with the religious beliefs of the time, making people hesitant to believe his theories that today embody modern geology (Repcheck, 2008).

Unconformities

Despite being first sketched by Nicolaus Steno (1638-1686) in the 17th century, the true significance of unconformities was not realized until Hutton's observations of Siccar Point in the 18th century. Hutton described this formation as a 'conjunction of vertical and horizontal strata' in order to symbolize the flat-lying rock layer overlying a sharply tilted rock beds (Tomkeieff, 1962). It was not until 1805 that Robert Jameson (1774-1854) named this geological feature an unconformity, to represent the fact that the overlaying rock does not conform to the bottom layers (Tomkeieff, 1962).

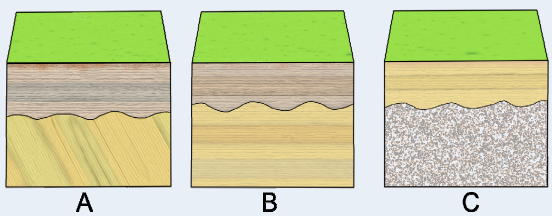


Figure 2.29 *Different types of erosional unconformities (left). (A) represents an angular unconformity, (B) a disconformity and (C) a nonconformity.*

Today, unconformities are still defined as surfaces where the rock units above the surface are significantly younger than the rocks below it. Unconformities represent an ancient erosion surface that shows a gap in the geological record. Presently unconformities are classified into three different groups: disconformities, angular unconformities and nonconformities, with each type representing a different geologic process in history (see Figure 2.83) (Plummer et al., 2007).

Angular Unconformities

Angular unconformities occur when a younger layer of rocks overlies an erosion surface that has occurred on a tilted layer of rock (Plummer et al., 2007). This was the first type of unconformity to be described by Hutton. He proposed that the bottom layer had been deposited earlier, tilted, with the help of pressure and heat, and then flattened through erosion. Afterwards, the younger layer of rocks was deposited on top (Repcheck, 2008).

As Hutton suggested, an angular unconformity occurred following the deposition and lithification of sedimentary rock, or solidification of lava flows, which were then uplifted and folded (Plummer et al., 2007). This process would have been followed by successive erosional periods and then another period of deposition. What Hutton failed to realize was that only the formation of metamorphic rocks, and not sedimentary rocks, required the presence of heat (Repcheck, 2008).

Nonconformities

A nonconformity occurs when a younger sedimentary rock overlays a much older plutonic or metamorphic rock (Plummer et al., 2007). It is now known that metamorphic and plutonic rocks form at considerable depths in the Earth's crust, indicating that the formation of this type of unconformity requires erosion over a prolonged period of time before it is covered by younger rocks (Plummer et al., 2007).

Disconformities

Disconformities are the last type of unconformity, which exist where the layers of rocks above and below the unconformity are parallel to each other (Plummer et al., 2007). These are the hardest type of unconformity to identify. Usually they are recognized by comparing the fossil content of rock layers (Plummer et al., 2007). Once identified, it can be inferred that the older rocks were eroded parallel to their bedding planes (Plummer et al., 2007). It is important to note that the determination of apparent ages of fossils can be misinterpreted if unconformities go unnoticed (Rogers, 1994).

Even though the presence of unconformities is illustrative of gaps in the geological time record, they are important in understanding the past environments and geological processes that were occurring during the history of the Earth.

Figure 3.1 *The 19th century laid the foundations of modern science through discoveries and exploration. Extensive mapping was one major component of these expeditions.*

Chapter 3: The 19th Century Foundations of Modern Science

During the nineteenth century, scientific thought evolved significantly in many disciplines. Most of this development occurred in the Western world with the publishing of pivotal scientific works that are still available and valuable today. The advent of many technological advances also allowed for more efficient communication between members of the scientific community and made information more accessible to the public.

At the beginning of the nineteenth century, science was largely influenced by religious thought. As the century progressed, scientists realized the limitations of this way of thinking and began to develop their own theories on natural phenomena. This era saw the emergence of theories on the age of the earth, impact craters and natural selection. Significant steps towards reconstructing Earth's history and explaining geological concepts were taken. This was accomplished through expeditions dedicated to earth science research and the understanding of geological processes such as glaciers and earthquakes.

Nineteenth century scientists made significant progress and laid the foundations for the rapid development of earth science in the 20th century. It marked an important evolution of the scientific method, which increased the potential for scientific discovery and opened up possibilities for growth across many disciplines.

Lord Kelvin and the Age of the Earth

William Thomson, better known as Lord Kelvin, was born on June 26, 1824 in Belfast, Ireland. From an early age Thomson demonstrated an aptitude for mathematics. He entered the University of Glasgow at the age of ten and became interested in the work of Joseph Fourier and his mathematical descriptions of the physics of heat (Dalrymple, 1991). Thomson went on to study at Cambridge University from 1841-1845 and graduated with high honours.

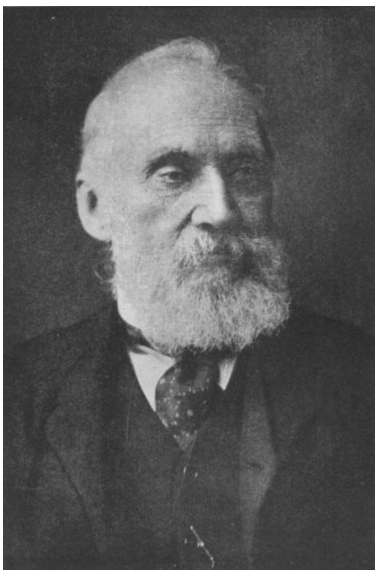


Figure 3.2 *William Thomson, 1st Baron Kelvin (1824-1907). A prolific scientist, he published 600 works on a variety of scientific matters.*

Thomson was an extremely productive scientist who held roughly 70 patents and published over 600 works on subjects ranging from electricity to geodesy (Dalrymple, 1991). However, Thomson's most important work dealt with thermodynamics. In 1852, he published *On the Dynamical Theory of Heat* which described the fact that in every transfer of energy, some is converted to heat and lost to the surroundings (Dalrymple, 1991). This discovery eventually became known as the second law of thermodynamics. Thomson also created the absolute temperature scale, designated the Kelvin scale in his honour. For his many achievements, Thomson was eventually made Baron Kelvin of Largs, Ayrshire in 1882. It is for this reason that Thomson is better known as Lord Kelvin.

The Age of the Sun

With the knowledge that all useful energy is ultimately lost, Thomson realized that the Sun could not supply heat and light for all time. It was previously accepted that the Sun's energy was the result of an ongoing chemical reaction, but simple calculations showed that a chemical process could not account for the energy expenditure of the Sun for more than three thousand years (Thomson, 1891). Thus, Thomson adopted a theory in 1854 that solar energy came from meteors crashing into the Sun and assumed that the rotation of the Sun on its axis would be caused by the impact of these meteors. He estimated that it would take "not many times more or less than 32,000 years" for meteors to generate the Sun's current rotation based on it initially having no spin (Thomson, 1854 cited in Burchfield, 1975, p. 24). This argument received little attention and Thomson turned his focus to other matters until 1860 when research demonstrated that a mass of meteors large enough to supply the Sun's heat would cause significant anomalies in Mercury's orbit (Burchfield, 1975).

Abandoning his previous assumptions, Thomson published a new hypothesis in 1862. Instead of assuming that the Sun was a solid surface, he proposed that the Sun was an incandescent liquid formed from the release of gravitational energy generated by the coalition of many smaller objects (Thomson, 1891). He calculated that the heat released by the accumulation of these bodies would be about 20 million times greater than what was currently radiated from the Sun. However, half of this energy could have been lost immediately during the formation of the Sun, so Thomson set the lower limit of the Sun's age at around 10 million years. He knew that the density of the Sun would increase towards its center, which would allow for much more energy to have been released during its formation. Assuming that the Sun could easily be up to 10 times more massive than would be predicted assuming uniform density, Thomson finally stated:

It seems, therefore, on the whole most probable that the sun has not illuminated the earth for 100,000,000 years, and almost certain that he has not done so for 500,000,000 years (Thomson, 1891, p. 375).

He went on to say that since the Sun was already losing heat, "the inhabitants of earth cannot continue to enjoy the light and heat essential to their life, for many million years longer"(Thomson, 1891, p. 375). By limiting the age of the Sun, Thomson also limited the age of the earth to a similar time scale. In 1862 he published another article, *On the Secular Cooling of the Earth,* which presented his theory for the age of the earth.

The Age of the Earth

Thomson calculated the age of the earth with the same basic principles he used to calculate the age of the Sun, namely that the energy for creating the earth was gravitational in origin, and that the energy was being dissipated according to the second law of thermodynamics (Burchfield, 1975). His first assumption was that the earth had formed as a hot molten ball and gradually cooled to its present state. His model also assumed that as the upper part of the earth cooled, it sank towards the center of the earth, generating convection currents that assured that the earth was isothermal when it solidified. He rejected the idea of a liquid or ductile core because this did not agree with the current notion of the earth being more rigid than iron (Thomson, 1890). Therefore, the only heat loss from the earth would be from its crust due to conduction.

The loss of heat via conduction from an isothermal body is very readily modelled by Fourier's differential equations that Thomson studied at Glasgow. Using the best values for geothermal gradient at the earth's surface and an estimation of the earth's initial temperature based upon the melting points of various rocks, Thomson calculated that the earth solidified from a molten state 98 million years ago (Thomson, 1890). Thomson realized that there could be significant error in this value due to ignorance on the effect of high temperatures on the thermal conductivities, specific heats and latent heat of fusion of rocks (Allegre et al., 1995). Thus he put the range on the earth's age to be between 20 and 400 million years old.

With time Thomson's estimates on the age of the earth became increasingly narrow (Burchfield, 1975). In 1868 he published a paper in which he calculated the frictional effect of the tides on slowing the rotation of the earth. Based on these calculations, the earth could be no more than 100 million years old. By 1876 Thomson accepted an upper limit on the earth's age to be 50 million years based on new data and a greater belief in the validity of his initial calculations (Burchfield, 1975). In 1881, he put the range to be between 20 and 50 million years. In his last major address on the topic in 1897, Kelvin stated that the actual age of the earth would be between 20 and 40 million years old, and would lie significantly closer to 20 million years. Despite his changing values for the age of the earth, Kelvin never changed his basic assumptions in his calculations, namely that the earth had finite energy which was constantly being dissipated.

Reception

The geological school of thought before Thomson's calculations revolved around the idea of uniformitarianism. Charles Lyell (1797-1875) published his *Principles of Geology* in 1830 and presented the idea of uniformitarianism, which argues that the earth is in a state of dynamic equilibrium. He assumed the forces acting on the earth to be constant in type and intensity for the vast, indeterminate expanse of time. The uniformitarian need for indefinite or infinite time repulsed Thomson, who considered such a view to go against the laws of physics (Thomson, 1890). Indeed, Thomson admitted that his 1862 paper on the age of the Earth was written to demonstrate that geologists had neglected thermodynamics in their theories (Burchfield, 1975). He was particularly bothered by Lyell's suggestion that a cyclic exchange of chemical, heat and electrolytic energy could account for the earth's heat (Thomson, 1890). Such a suggestion was in clear violation of the second law of thermodynamics.

Despite his 1862 papers, uniformitarianism still dominated British geology for a large part of the 1860's (Burchfield, 1975). This led Thomson to make several addresses directly attacking uniformitarianism. Ultimately, his persistence forced geologists to reconsider their previous theories. However, there were several prominent scientists who refused to accept Thomson's calculations on the age of the earth. Amongst them were Lyell himself, Charles Darwin (1809-1882) and Thomas Huxley.

Darwin's theory of natural selection required vast amounts of time for the evolution of life. Indeed, Darwin was profoundly influenced by the work of Lyell and based much of his book, *On the Origin of Species*, on the assumption of essentially limitless time. In his book, Darwin calculated that it took approximately 300 million years for the erosion of the Weald, an area in South East England (Darwin, 1859). This was based on the generally unfounded assumption that the Weald had eroded at a rate of one inch per century (Thomson, 1891). This did not agree with the time scale proposed by Thomson, and he used this estimate as an example of how uniformitarianism made grand statements based on very little fact (Burchfield, 1975). Many supporters of Thomson also attacked Darwin's position and used his calculation for the denudation of the Weald as a striking example of the fallacies that could arise from uniformitarian theory.

Thomas Huxley (1825-1895) was a supporter of both Lyell's and Darwin's theories. As President of the Geological Society of London, Huxley took it upon himself to refute Thomson's assertion that "a great reform in geological speculation seems now to have become necessary (Thomson, 1984, p. 10)." Huxley attacked Thomson's position based upon the large amount of uncertainty that was present in his age of the earth calculations. Huxley also criticized the number of assumptions made in Thomson's calculations. However, the majority of Huxley's argument picked at the minutiae of Thomson's calculations and failed to refute the fundamental basis of Thomson's position (Burchfield, 1975). Thus, Thomson was able to deliver a rebuttal that wholly discredited Huxley's argument. Although the exchange between Huxley and Thomson did not present any new arguments, it did help to bring Thomson's ideas to the general public, and further forced geologists to consider the reality of a finite timescale for the earth.

As Thomson's popularity grew, many geologists accepted that the age of the earth was likely around 100 million years and began to adjust their theories to accommodate this fact. However, as Thomson's estimates on the age of the earth grew increasingly narrow, geologists again began to distrust his calculations (Burchfield, 1975). Most geologists accepted the age of the earth to be around 100 million years old, but they could not accept that the earth was only 20-40 million years old. However, the fact that they accepted a limited timescale at all demonstrates Thomson's success in overturning the once popular belief in an essentially infinitely old earth. It would not be until 1895 that Thomson's calculations could be reasonably refuted. Ironically, the denunciation of Thomson's arguments would come from one of his former students, John Perry (1850-1920) (Allegre et al., 1995).

Faulty Assumptions

One of the greatest flaws in Thomson's argument was the assumption of an entirely solid earth of uniform composition. With this assumption, the heat loss at the earth's surface would be caused entirely by the cooling of a thin outer layer. However, John Perry argued that an increase of thermal conductivity in the core of the earth would transfer more heat to the surface, providing a much larger store of energy to account for the heat flux at the surface of the earth (Burchfield, 1975). Thus the heat flow from the earth could have been supported for much more than Thomson's estimates of 100-500 million years.

Perry assumed an increased conductivity in the center of the earth because increased density at its center suggested the presence of iron and nickel, which would conduct heat much better than a silica rich crust (Allegre et al., 1995). However, Perry's most important argument was that the inside of the earth may be partially fluid, which would mean essentially infinite conductivity due to convection currents in the earth. With an assumption of a solid crust and a high conductivity in the planet's core due to convection, Perry placed the age of the earth at several billion years.

Many geologists attached themselves to Perry's theory because the timescale it allowed was significantly larger than Kelvin's estimates. Unfortunately, Kelvin refused to accept the possibility of a semi-fluid core on the earth and argued that the age of the sun would put the age of the earth in the millions, rather than billions (Burchfield, 1975). Work done by Kelvin's supporters made him ever more confident in his calculations. Despite growing discontent amongst many geologists, Kelvin was unwilling to reevaluate his arguments. Ultimately, Kelvin never abandoned his position that the earth was between 20 and 40 million years old.

Lasting Effects

Current knowledge demonstrates that Perry's assumption of a semi-fluid interior was justified. The discovery of radioactive decay in the early 20th century also introduced a previously unknown heat source. The inaccuracy in Kelvin's calculations can be partially blamed on his ignorance of this phenomenon. Nevertheless, Kelvin's work significantly changed the face of geology. His insistence on applying physical laws to the theories of earth science led to a rejection of the infinite timescales of uniformitarianism. Geologists began to think within the boundaries of finite time. More importantly, Kelvin's influence forced geologists to look for tools that could make better measurements regarding the earth, and they sought to raise geology from a descriptive science to an exact science, similar to physics or chemistry. Ultimately, Kelvin spurred a revolution in geological thinking more lasting than any of his calculations on the age of the earth.

Radiometric Dating and the Age of the Earth

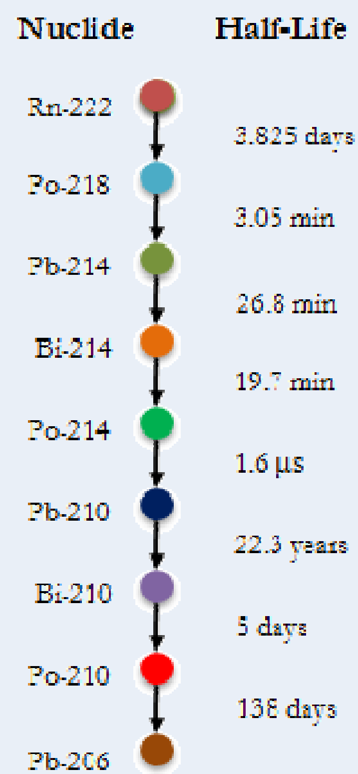
The discovery of radioactivity in the early 20th century revolutionized science in many ways. Radioactivity is caused when unstable atomic nuclei emit particles and energy in an attempt to transform into more stable nuclei. An important result of radioactivity is that it provides a fairly continuous heat supply which Kelvin's calculations did not account for (Burchfield, 1975). Not only does radioactive decay disprove Kelvin's calculations, it also provides the basis for the calculation of the true age of the earth.

The decay of atomic nuclei have well-determined half-lives. Half-life is simply the amount of time it takes for half of a sample to decay into its daughter products. One example is Uranium-238 which decays into Thorium-234 with a half-life of roughly 4.5 billion years (Argonne National Laboratory, 2005). Thorium-234 also decays, and after many intermediate daughter products, stable Lead-206 is ultimately formed.

Since Uranium-238 has such a long half life it is often used to calculate the age of meteorites and rocks (Allegre et al., 1995). The fact that Uranium-238 follows a defined decay route that ultimately leads to Lead-206, the age of a sample can be calculated by comparing the amount of Lead-206 to the amount of Uranium-238 in a sample. The oldest rocks on the earth's surface have been calculated to be approximately four billion years old based on the use of radiometric dating. However, we know that tectonic activity and erosion would have recycled the original rocks on the earth's surface (Plummer et al., 2004). Thus, the oldest terrestrial rocks will necessarily be younger than the actual age of the earth.

Instead of terrestrial rocks, meteorites are often used to determine the age of the earth (Allegre et al., 1995). Meteorites are considered to be fragments of solar system material that did not coalesce into a planet. Thus meteorites are assumed to be roughly the same age as the material that made up the earth. Radiometric dating has determined the age of most meteorites to be between 4.5 and 4.6 billion years old (Plummer et al., 2004).

The fact that a definitive age can finally be put on the earth has significant implications for geology and how we think about the history of the earth. It provides a working timeline that all geologic theories must align with. Furthermore, assuming that all of the bodies in the solar system formed at the same time, dating the earth to 4.6 billion years places the Sun at a similar age. With this knowledge and an understanding of a star's lifecycle, it can be estimated how much longer the earth has before it is destroyed by the Sun. Ultimately radioactive dating put an end to the age old debate on the true age of the earth.



3.3 *Decay scheme for Radon-222 to Lead-206. These are the last eight steps involved in the decay of Uranium-238 to Lead-206.*

19th Century Views of Impact Craters

Theories regarding the formation of impact craters have evolved over time. Initial theories of crater formation focused on the idea that volcanism was the process responsible (Nininger, 1956). Craters, such as Barringer Crater, Arizona, were thought to have been formed by steam forming under the sediment due to volcanic activity (Nininger, 1956). The eventual build up of pressure caused an explosion, forming the crater. These theories were believed to be true well into the 1890s (Nininger, 1956). The theory that impact craters were formed by volcanism was not limited to the earth; craters on the moon and other celestial bodies were also attributed to volcanism (Nininger, 1956). Only when scientists began to understand that the formations were created by impact events did the idea arise that meteorites could cause craters. This led to modern theories regarding impact craters; including the research done by Eugene Shoemaker and the implications that the comet Shoemaker-Levy 9 had on the development of impact theories (Kring, 2007). Physical characteristics and current mathematical models that illustrate the development of these craters will also be described (Plado and Pesonen, 2002; Eyles, 2002; Kring, 2007).

Figure 3.4 *Volcanic Crater (right) of the volcano Kelimutu, located in Moni, Indonesia. The crater has filled with water over time, creating a lake.*

Volcanic Craters

For most of the 19th century there was only one process that was known to create craters of any reasonable size: volcanic explosions (Nininger, 1956). It was thought that all craters were formed when a sufficient amount of gas built up under the surface of the earth. Once this gas was heated and under sufficient pressure the gas would overcome the containing rocks generating a large explosion. When the resulting debris settled, the remaining geologic formation would be a crater. Figure 3.21 is an example of a volcanic crater.

It was believed that meteorites were unable to create craters on large scales. Meteorites that had struck the earth and had been documented were found to be only a few hundred pounds or less (Nininger, 1956). The resulting "craters" made by these impacts were nothing more than holes a few feet deep. It seemed incredibly unlikely that a meteorite would be large enough to create craters similar in size to the craters formed by volcanoes.

G. K. Gilbert

Grove Karl Gilbert was an American geologist born in 1843 who participated in the U.S Geological Survey (Nininger, 1956). Gilbert was an important figure in the field of impact craters due to his theories concerning the development of craters on the moon (James, 1893).

Many scientists did not believe that the craters visible on the moon were caused by impacts reasoning that if there were meteorite impacts on the moon that caused such large craters then meteorites of equivalent size must have hit earth. However no proof had been found at the time (Nininger, 1956).

Gilbert was one of the first scientists to argue that most lunar craters were formed by meteorites and published a peer-reviewed scientific paper on the subject in 1893 titled *The Moon's Face* (James, 1893). This paper helped pave the way for modern theories concerning meteorite impacts.

In order to solidify his findings, Gilbert attempted to discover proof of an impact crater on earth. The crater that he chose to conduct his research on was Canyon Diablo Crater (Gilbert, 1896).

Canyon Diablo Crater

Canyon Diablo crater, now known as Barringer crater, was a crater found in the 1870s in Arizona (Figure 3.22). The crater is over 4,000 feet across and is approximately 120 to 200 feet above the surrounding plain. The crater was surrounded by thousands of chunks of iron ore, ranging from a few ounces to thousands of pounds in weight (Nininger, 1956). A. E. Foote was one of the first scientists to extensively survey the crater (Nininger, 1956). The collection of material around the edge of the crater was known to be pieces of meteorites. It was considered to be just a coincidence that such a large collection meteoritic material was surrounding a 'volcanic' crater. Foote's survey revealed that this crater was an odd geologic phenomenon as there was no evidence of igneous rocks, obsidian, or any other signs of volcanism other than the crater itself. Upon reading the existence of such an odd crater Gilbert hypothesised that this crater was in fact made by a meteorite impact. He travelled to the crater to test his hypothesis.

Gilbert investigated the crater with the following two major points as part of his meteorite hypothesis; if this crater was meteoritic in origin then the volume of the ejected matter on the rim would have a larger volume then the volume of the resulting crater; also, if smaller meteorites were composed of iron then larger meteorites should be no different (Gilbert, 1896). Gilbert believed that the large meteorite that created the Canyon Diablo Crater was composed of iron. This iron should be present, buried in the crater, and provide magnetic interference when a magnetic needle is used around the area of the crater (Gilbert, 1896).

Gilbert performed a two week survey of the crater and presented his findings in a paper entitled The Origin of Hypothesis, which was published in 1896. He had found that the rim of the crater was an unusual oval shape and that the majority of the iron fragments were found on the eastern side of the crater. This caused Gilbert to initially believe that a meteorite had struck the surface of the earth, rebounded, and then struck again, creating the crater. However as he continued to survey the land he found that the observed results did not match the first point of his hypothesis. The volume material ejected from the crater and the volume of the crater itself were equal.

To test the second point of his hypothesis, Gilbert took magnetic readings around the crater. Once again, his readings were against his hypothesis. The observed measurements for the magnetic field around the crater indicated a constant magnetic field in both direction and intensity. Gilbert assumed that unless the meteorite had managed to penetrate to an incredible depth then it would be impossible to have an iron meteorite buried in the crater.

Figure 3.5*Barrigner Crater (above) located in Arizona was one of the craters G. K. Gilbert attempted to use in order to find an analogue for the moon's meteoritic craters on earth.*

Although Dr Gilbert's paper was not published until 1896, the conclusion that Canyon Diablo Crater was not a meteoritic crater had taken hold of the scientific community as soon as the conclusion had been met (Nininger, 1956). Dr Gilbert was a respected geologist, and since he had come to such conclusive findings, the origins of the Canyon Diablo became a closed topic. For over 10 years, Dr Gilbert's conclusion was accepted as truth, and research into Canyon Diablo Crater's meteoritic origin ceased (Nininger, 1956).

It was not until 1905 that the topic of Canyon Diablo Crater's origin was reopened.

D. M. Barringer

In 1902, D. M. Barringer, a mining engineer, and S. J. Holsinger, a surveyor, were discussing how the locals around Canyon Diablo Crater believed that the crater's origin was from a meteoritic impact (Nininger, 1956). Interested by the subject, Barringer and his friend, B. C. Tilghmann, continued to look into the crater. Over the course of a few months Barringer believed that he had collected irrefutable proof that the crater was in fact created by a meteoritic impact (Nininger, 1956). Both he and Tilghmann published a paper on their theory in 1905. Based on samples taken by bore holes their conclusion was supported by nine points (Nininger, 1956):

"1. The large size of the crater implies a large, high velocity object impacting the land.

2. Evidence of volcanic activity is absent in the surrounding area and up to 1,400 feet underground.

3. Signs of a large projectile are present in and around the crater.

4. Large amounts of meteoritic material are present along the rim of the crater which are symmetrical with respect to the center of the crater.

5. The meteoritic material was deposited at the same time that the crater was formed.

6. The pulverized rock in this area cannot be accounted for by erosion.

7. No forms of erosion present in the area that could create and retain this feature.

8. Meteoritic material has been found up to 900 feet below the surface of the crater.

9. All the above points cannot be described by any phenomenon other than a large projectile."

Barringer was met with issues however. He still believed that the solid mass of the meteorite was buried under the crater. Numerous attempts to find the meteorite failed and his theory was subject to criticism (Nininger, 1956).

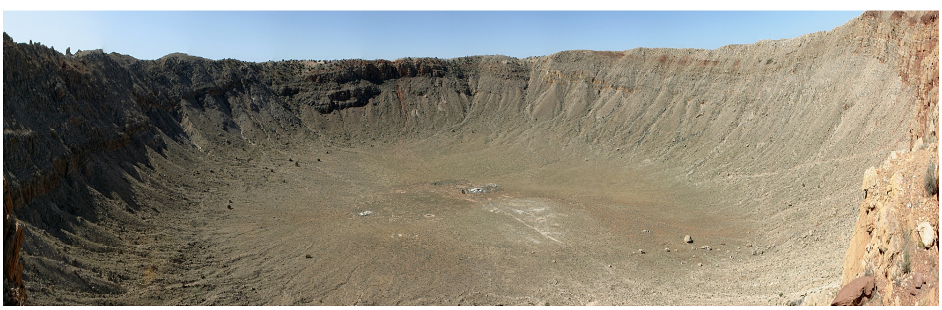
Although Barringer's theory was not completely correct it laid the ground work for modern theories of the origin of Canyon Diablo Crater, and impact craters in general

Eugene Shoemaker

Although some aspects of his theory were flawed, Barringer's work helped push forward research on impact craters. His work inspired numerous scientists to investigate Canyon Diablo Crater, including geologist Eugene Shoemaker. In 1959, for his thesis paper, Dr. Shoemaker investiaged Canyon Diablo Crater (Shoemaker, 1963) to compare it to craters formed at nuclear bomb test sites, which applied a great pressure to the earth, much like a meteorite impact would. The study resulted in one major feature being found at Canyon Diablo Crater that was present in nuclear craters, and not in volcanic craters. The major feature was the sixth point of Barringer's 1905 paper, pulverized rock (Kring, 2007). Shoemaker found two types of pulverized rock that led to the conclusion that Canyon Diablo crater was in fact a meteoritic crater. The first type, which was found buried under the crater, was breccia (Kring, 2007). A symmetrical breccia lens was found under the crater, yet breccia was not present in the surrounding area (Kring, 2007). The other rock that was found on the surface of the crater was composed of a variety of shocked rock types which were well sorted. The surface material contained fine grained sediments, progressively becoming coarser as the samples were taken deeper below the surface (Kring, 2007).

These two rock types, associated with nuclear craters, allowed Shoemaker's conclusion to be that the crater was formed by a meteoritic impact (Kring, 2007). The mechanism that Shoemaker proposed was quite simple. The meteoritic impact caused a downward pressure on the Earth's crust. This pressure continued downwards, shocking all rocks it passed through, losing energy as it progressed. Eventually the pressure disappated and the rocks rebounded, causing the rocks closer to the surface to be ejected from the crater (Kring, 2007). Once the fall-out rocks were sent upwards, the larger-grained rocks returned to the surface sooner than small grained rocks, causing the sorting which had been observed (Figure 3.23) (Kring, 2007). This proof of Barrigner's theory settled the origin of Canyon Diablo Crater once and for all (Kring, 2007). Canyon Diablo is now known as a meteoritic impact crater, and has been renamed Barringer Crater recognizing the contributions Barringer made towards the understanding of meteoritic craters.

Figure 3.6 *Barringer Crater (below) A panoramic view of Barringer Crater, showing the deposition of the deposits that Shoemaker observed.*



Shoemaker-Levy 9

Modern Impact Events

A recent impact event allowed researchers to look into the mechanics behind impact events. In 1994 comet Shoemaker-Levy 9 descended into Jupiter's atmosphere (Figure 3.24) (Field, Tozzi and Stanga, 1995). This event proved to astronomers that it is possible to predict impact events based on the trajectory of comets and meteors. It also caused scientists to realize that it is a very real possibility for a large meteorite to collide with earth. In order to best prepare for these events, programs such as LINEAR (Lincoln Near-Earth Asteroid Research) and NEAT (Near Earth Asteroid Tracking) were formed to discover and predict trajectories of meteors near earth (NEAT, 2010; LINEAR, 2010).

Physical Characteristics

There are numerous physical characteristics that are now used to define craters as meteoritic. One of these features is shatter cones. Shatter cones are cone shaped rock formations that point towards the point of impact of a meteor or the origin of a nuclear explosion (Eyles, 2002). They are created by the extremely large pressures associated with these events (Eyles, 2002). The shocked breccias, or pseudotachylytes, and fall-out sediments described by Barringer and observed by Shoemaker are also well known formations associated with impact events (Eyles, 2002). Pseudotachylytes are pre-existing rocks which were crushed and partially melted by a high pressure event (Eyles, 2002). The fall-out materials that form sedimentary structures are known as suevites (Eyles, 2002). Shocked quartz, which is quartz which contain criss-cross fractures, can be found in pseudotachylytes and is also a by-product of meteoritic events (Eyles, 2002).

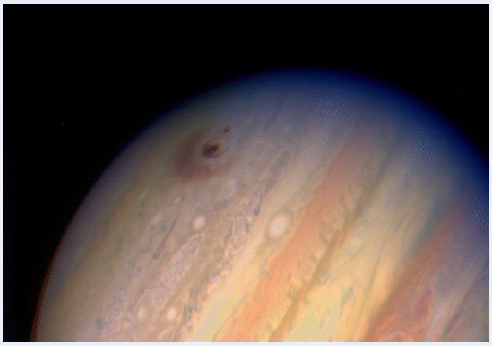


Figure 3.7 *Jupiter Impact (left) The zone of Shoemaker-Levy 9's impact with Jupiter. Distinct dark markings were present on Jupiter for months after the impact.*

It is possible to date impact craters by dating the metamorphic rocks created during the impact event. By dating these craters and establishing concurrent environmental conditions it is possible to determine if the impact caused a change in the evolution of the geologic or biologic environments in the surrounding area. An example of how an impact event changed the evolution of biologic organisms is the impact that created the Chicxulub Crater, Mexico. It is believed that this crater is the location of the meteoritic impact that caused the mass extinction of the dinosaurs at the end of the Cretaceous period (Koeberl et al, 2002).

The size of the crater has also been directly related to the size of the associated meteorite. A study of impact craters present on the Canadian Shield, completed by M. R. Dence, found the following relation (Plado and Pesonen, 2002):

$$P = 2512 * \left(\frac{R}{R_o}\right)^{-2}$$

Where P is the pressure caused by the impact, R is the size of the resulting crater and Ro is the size of the meteor. The pressure can be determined by surveying the area around the crater, observing structures formed, and the extrapolating an approximate pressure (Plado and Pesonen, 2002). This allows for a general approximation of the size of the meteorite that caused the crater (Plado and Pesonen, 2002). Knowing the size of these meteorites can help scientists understand the conditions of the solar system at that time.

Resources

Meteoritic craters have a major impact on the economy. Barringer Crater was initially surveyed due to its high level of iron ore. Most large meteoritic craters are associated with high levels of copper and nickel (Eyles, 2002). For this reason impact craters are not important solely for their geological information, but also for their abundant mineral wealth.

The *H.M.S. Challenger* Expedition

The idea for an expedition around the world's oceans dedicated entirely to research on marine conditions came from W. B. Carpenter (1813-1885), a biologist who specialized in marine zoology (Deacon, 1971). He first presented his idea to the British Association in 1871. The Association approved the expedition for collecting information on the physical and biological characteristics of the deep-sea in all the world's oceans and preparations began in 1872 (Deacon, 1971). Captain Nares (1831-1915) was put in command of the *H.M.S. Challenger*, the ship that would carry out the three and a half year voyage around the world (Deacon, 1971). The Royal Society selected several other scientists as research leaders on the expedition. These scientists were mostly naturalists including Wyville Thomson, Henry Nottidge Moseley, Rudolph von Willemose-Suhm, and John Murray (Deacon, 1978). John Young Buchanan was the appointed chemist who made many improvements to the experimental apparatus on board such as his invention of various piezometers as depicted in Figure 3.31 (Deacon 1978). The equipment used for seawater analyses included Miller-Casella thermometers, Hydra sounding machines, dredge devices, trawls, plankton nets and current meters (Idyll, 1969). The expedition was to perform various experiments to analyze oceans around the world, including deep sea temperature readings, seawater tests for specific gravity and gas composition, and marine life examinations (Pirie, 1973). With these experiments in mind, the Challenger Expedition set out to discover the answer to specific research questions including: is it possible for living organisms to survive at great ocean depths; is the sea floor covered of the protoplasmic substance Bathybius (thought to be a form of primordial and a source of life); and is it possible to measure the Atlantic ocean currents transporting ice water from the poles along the sea bed to the equator? (Pirie, 1973). *Challenger* left Portsmouth, England on 21 of December 1872 and began its voyage around the world (Idyll, 1969).

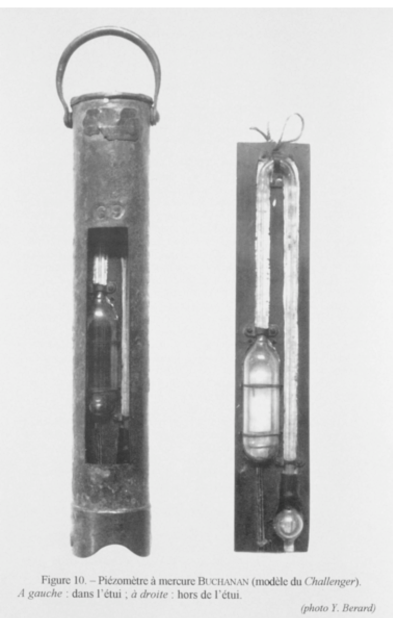


Figure 3.8 *Buchanan made many inventions on the* H.M.S. Challenger *such as this piezometer, an improved method of collecting and analyzing water samples. (above).*

Discovery of Life at Great Depths

Early on in the expedition, as *Challenger* left Teneriffe and made its way toward the West Indies, the scientists noticed a change in the sounding readings. As the water became deeper, the grey globigerina ooze that coated the ocean floor in local areas darkened in colour. Globigerina is a type of plankton from the group Foraminifera, a group of single cell organisms with fine strands of cytoplasm as seen in Figure 3.32 (Pirie, 1973). At a depth of 18900 feet, the sediment from the ocean floor consisted of smooth red clay containing organic matter. The red clay also appeared in the deep waters of the mid-Atlantic ocean where dredges brought up clay with marine worms (Pirie, 1973). The discovery of worms in the clay proved that it was possible for living organisms to survive at depths as great as 18000 feet (Pirie, 1973).

Murray was the scientist in charge of biological research on *Challenger*. He collected and examined biological samples from various ocean depths. He discovered that globigerina, the microorganism whose remnants coated sea floor, lived in the upper layers of the sea (Deacon, 1971). The scientists found populations of living globigerina all around the world with population size and organism size varying with latitude. The globigerina composition of the sea floor was found to correspond to the population of the living globigerina in the upper layers of the sea (Deacon, 1971). The only problem Murray found with this discovery was that the red clay found in deep sea areas did not contain any globigerina or foraminifera remains. Murray hypothesized that a chemical reaction was responsible for the removal of carbonate from the grey ooze and the red clay is the result of the reaction (Deacon, 1971). Buchanan confirmed this hypothesis by recreating the reaction in a lab.

He removed the carbonate from the globigerina grey ooze and examined the remaining material. Buchanan found silica, alumina and red oxide in the red coloured substance, which resembled the red clay (Deacon, 1971). Overall, the biological discoveries made by the Challenger Expedition were very successful.

Composition of the Sea Floor

Murray made some interesting observations of sea floor clay in the Pacific in 1875 during the Challenger Expedition. At depths of 12000 feet the sea floor was coated in materials such as clay, quartz, mica and pumice (Pirie, 1973). Murray suggested that the sea floor clay was made up of volcanic material instead of organic material. Manganese nodules were also present in the clay in the Pacific and many of the scientists on board *Challenger* proposed hypotheses for the presence of manganese in the sea floor (Pirie, 1973). Murray suggested that the manganese came from rocks from volcanoes. The weathering of rocks produced manganese carbonates, which were then oxidized by the sea water (Pirie, 1973). Buchanan hypothesized that organic remains on the sea floor reacted with sulphates to produce sulphides. These sulphides then combined with iron and manganese and were oxidized by sea water (Pirie, 1973). The French geologist Dieulafait (1830-?) suggested that manganese precipitated from a reaction that occurred between the surface water and the air (Pirie, 1973). These scientists could not agree on one hypothesis to explain the presence of manganese and no one could explain the formation of nodules.

One of the Challenger's goals was to find samples of the substance *Bathybius haekelii* on the sea floor. *Bathybius* is a protoplasmic substance that the scientist T.H. Huxley (1825-1895) discovered when he examined preserved samples of the sea floor obtained from *H.M.S. Cyclops* in 1857 (Deacon, 1971). The substance had a gelatinous structure with organic properties and was thought to be the original protoplasm of life. The sample of *Bathybius* supported the theory of abiogenesis, which states that life arises from non-living matter (Deacon, 1971). However, the scientists on the Challenger Expedition did not find any *Bathybius* in their sea floor samples. Someone on board *Challenger* noticed that the gelatinous substance only occurred in the preserved samples and not the samples contained in sea water. Buchanan realized the substance was a result of a precipitation reaction of calcium sulphate in sea water by the alcohol in which the sample was preserved (Deacon, 1971). The Challenger Expedition allowed Buchanan to disprove Huxley's evidence for abiogenesis.

Theories of Ocean Circulation

Many theories about ocean currents were developed from the discoveries made on the Challenger Expedition. The scientists on board Challenger made routine temperature and current measurements throughout the entire expedition that supported the development of these theories. Early in the expedition, as Challenger travelled from Bermuda to Halifax, the temperature readings confirmed known information about the Gulf Stream. The shallow warm waters created a current with the cold water below (Pirie, 1973). The team of scientists also made interesting observations at high latitudes. There existed a layer of thick warm water underneath the cold surface water in the Arctic seas (Pirie, 1973). This layer of warm water was also present in the southern hemisphere. The temperature reading at the surface of the waters was 29.5°F while the temperature reading at a depth of 3000 feet was 32.8°F (Pirie, 1973). The team of scientists developed two explanations for the cool surface water. They determined that in

Figure 3.9 *Records from the Challenger Expedition (1873-1876) illustrating Foraminifera, the type of organism (globigerina) whose remains were found on the sea floor. (left).*

the winter, cold air cools the surface water. In the summer, winter ice melts and sits on top of the warm water since it is less dense than the saline sea water (Pirie, 1973).

Figure 3.10 *A contour map of the Atlantic (above) was made from the sounding and temperature readings from the Challenger Expedition in 1877.*

The discoveries made on Challenger also initiated arguments between scientists about the mechanism behind ocean currents. While Challenger was in Australia in 1874, the debate on ocean circulation began between Carpenter and the scientist James Croll (1821-1890) (Deacon, 1971). The Challenger measurements showed that water from the poles was present below the surface of the equator indicating an undercurrent ran from the poles to the equator. Carpenter stated that this current was caused by the difference in water temperature. He believed if sources of heat are applied to the surface of the sea at different locations the equilibrium is disturbed and a current is formed (Deacon, 1971). Croll disagreed as he believed wind caused the movement of the water from the poles to the equator. He stated that when faced with a physical boundary or wind movement, the current takes the path of least resistance by dipping below the surface and creating the undercurrent (Deacon, 1971). The Challenger Expedition also recorded cold waters closer to the surface in the South Atlantic waters than in the North Atlantic waters. Croll believed that this evidence supported his theory, as winds in the North Atlantic transported water from south to north and brought cold water up to the surface in the process. He also stated that cold currents in the North Atlantic would cool the layer of warm water under the cold surface water. This meant that Carpenter's theory did not correspond with the Expedition's findings of a warm water layer under the surface (Deacon, 1971). Carpenter responded with the fact that there were very weak winds flowing from the South Atlantic to the equator in addition to there being no land barrier to drive the current under the surface. For these reasons, Carpenter thought Croll's theory was also improbable (Deacon, 1971). In 1875 Thomson suggested the movement of cold Antarctic water from the south to the north occurred to compensate for the evaporation of water in the northern hemisphere and the precipitation in the southern hemisphere (Deacon, 1971). The three scientists could not reach a consensus by the end of the Challenger Expedition.

Return of *H.M.S. Challenger*

The Challenger Expedition ended in 1876 in Spithead, Sheerness in England (Deacon, 1971). It was thought to be the "most extensive sea water analysis performed" (Sears et al., 1980). The Challenger Expedition was able to successfully address the scientific questions it set out to answer in 1872. The Expedition assembled information about ocean currents, marine organisms and sea floor geology. The information gathered on the Expedition established every major branch of modern oceanography (Idyll, 1969). Despite the primitive nature of the equipment, scientists were able to produce fifty folio volumes of observations, descriptions of new marine species and accurate charts of temperature readings, surface and subsurface ocean currents. The beginning of oceanography as an independent field within earth science began with the research conducted on the Challenger expedition.

Ocean Currents in Earth History

Ocean currents depend on many factors including continental position, sea level and salinity (Burroughs, 2007). Throughout the history of the Earth, ocean currents have fluctuated greatly due to the changes in these factors over time. Since ocean currents have the ability to cool or warm different regions they also have a significant influence on climate. Today, the thermohaline circulation (THC) or the "Great Ocean Conveyor" (Figure 3.34) is responsible for different climates around the world. The direction of the THC is a result of dense, cool, saline water sinking down below the surface and warm water rising to the surface (Burroughs, 2007).

Fluctuations in ocean currents can account for changes in climate throughout the history of the Earth. In the Mesozoic era the continents of the Earth were joined together in one supercontinent called Pangaea (Huggett, 1991). One large land mass allowed for a highly efficient ocean current that transported warm water towards the poles and cold water to the equator. The climate at this time was quite warm due to the evaporation of water around the equator where the middle portion of Pangaea was located (Huggett, 1991). The break up of Pangaea created the oceans that are still present today.

The development of the modern oceans caused many changes in the oceanic circulation patterns and resulted in various climate changes. For example, the formation of part of the thermohaline circulation current system occurred when the North Atlantic opened up due to sea floor spreading. The flow of warm equatorial waters to the North Atlantic regions caused evaporation at higher latitudes and precipitation at lower latitudes (Huggett, 1991). Also, in the Cenozoic era, the opening of the northeast Atlantic and the separation of Australia and Antarctica caused divergent surface currents and upwelling of water (Huggett, 1991). A current travelling west along the Pacific equator penetrated into the opening between Australia and Antarctica. The warm Pacific Ocean currents resulted in evaporation in the Pacific Ocean and heavy precipitation on Antarctica. The cooling of the precipitation on Antarctica led to the glacial conditions observed on the continent today (Huggett, 1991).

The presence, strength and direction of ocean currents have varied greatly throughout the history of the Earth because currents depend on so many factors. The fluctuations in ocean behaviour in the past have produced a variety of climatic regions observed today.

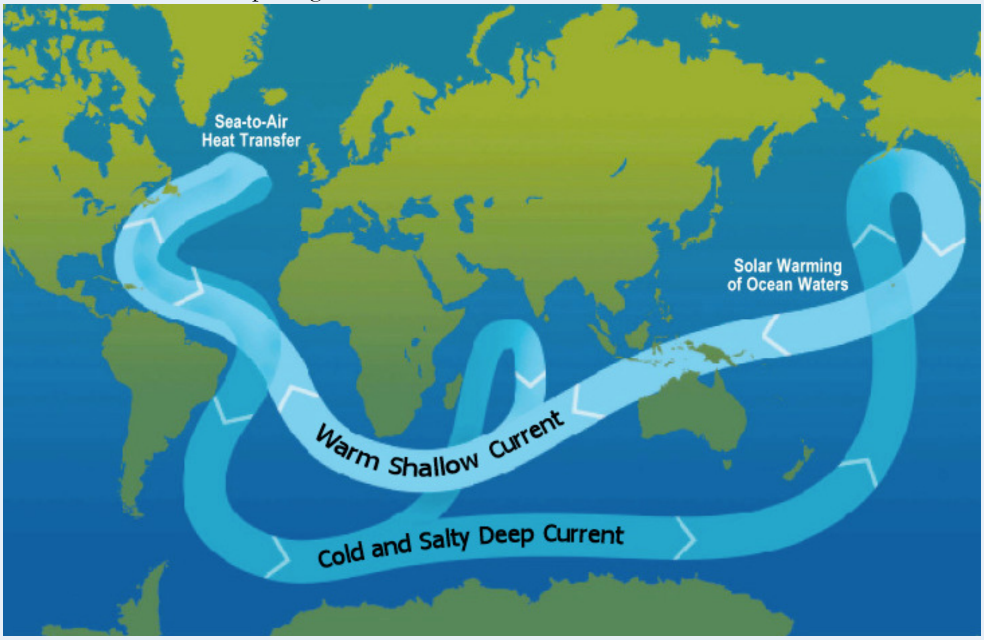


Figure 3.11 *The thermohaline circulation system as observed today (above). Cold, saline water sinks down and is carried to the warm regions by the ocean currents.*

The Arctic Expeditions of Sir John Franklin

By the 19th century, most of the Earth had been explored, but there still remained unvisited areas such as the Amazon Jungle, the African Interior, and the Arctic (Markham, 1873). Explorers from Britain and other countries were drawn to these places, and undertook extremely dangerous journeys to travel through them, logging their discoveries and observations and meticulously mapping their surroundings. Some returned with valuable information and encouraged others to follow in their footsteps and further their work; some did not return at all, and others followed them in the hopes of rescuing the lost explorers or at least determining the cause of their demise (Markham, 1873).

Figure 3.12 *Portrait of Sir John Franklin (1786-1847), a British explorer who led expeditions to Northern Canada and the Arctic (above).*

A significant number of expeditions in Northern Canada, Greenland and the Arctic were led by British adventurers and were sponsored by British government or the Royal Geographical Society of London. Explorers would study the geography, geology and ethnology of these regions and produce detailed maps of what they observed (Markham, 1873). These expeditions were particularly fuelled by the desire to discover a passageway to the Pacific Ocean that would be less time consuming than going around the southernmost tip of Africa. The benefits this would bring to trade were enormous and consequently the British government was particularly interested in sponsoring arctic expeditions (Markham, 1873).

Sir John Franklin (1786-1847) was one of these British explorers and participated in Arctic expeditions for 30 years, contributing greatly to the information being accumulated about this inhospitable territory (Traill, 1896). He and his crew perished on a journey through northern Canada in 1847. Sir John Franklin was an important contributor not only to 19th century exploration and the search for a passage to the Pacific Ocean, but also to the understanding of the geography, geology, and environment of Arctic regions (Traill, 1896).

First Expedition (1816-1818)

In the early 19th century, British explorers and government had their hearts set on being the first to reach the North Pole. Monetary awards were used as incentives for expeditions, with greater sums offered for higher latitudes reached (Traill, 1896). The exact reason for this enthusiasm for arctic exploration can only be guessed, but it may have been influenced by the secretary of the admiralty, Sir John Barrow, who had a particular interest in the Arctic. His actions led to the implementation of monetary rewards for reaching the northernmost latitudes, and eventually the admiralty dispatched four ships for this purpose (Traill, 1896).

Two of these ships, the *Dorothea* and the *Trent*, were under the command of Captain David Buchan (1780-1838), with John Franklin chosen as his lieutenant. This was Franklin's first arctic expedition, but his background in the Royal Navy allowed him to be made lieutenant and put in command of the *Trent*, the smaller of the two vessels (Traill, 1896). Their mission was to reach the North Pole and spend several days documenting what they found. If that failed, they were to attempt to find the Behring Strait and thus find a passage from the Atlantic ocean to the Pacific (Traill, 1896).

The mission was plagued by bad luck, especially concerning the state of the ships. Through the challenges they faced every day, the explorers managed to keep detailed logs from the voyage containing observations of the many features of polar regions such as icebergs and avalanches (Traill, 1896). Unfortunately, they were not successful, and were delayed for days at a time until they finally returned to London, having reached just over 80° of latitude (Traill, 1896).

Second Expedition (1819-1822)

Franklin's second expedition was to explore the coast of Northern Canada. He was the commander in this endeavour, and was accompanied by two midshipmen and a doctor (Franklin, 1859). Their journey began by traveling across land by rivers and portages in order to reach the Great Slave Lake and the Coppermine River. This river is located on the border of what are now Nunavut and the North West Territories (Franklin, 1859).

Instead of attempting to reach the North Pole, this journey's goal was to observe, draw and record everything they saw. Formal orders included measuring air temperature three times per day, as well as wind speed and weather conditions (Franklin, 1824). Franklin was to monitor the needle of his compass, and note any changes in direction or intensity of the magnetic field. Additionally, he was asked to determine if the Aurora Borealis had any impact on his compass, and pass on any other useful information related to this phenomenon. Drawings were an important part of the expedition, and along with two of his men, Franklin had to sketch the Inuit people and the natural surroundings frequently. Mineralogical investigations into the source of the copper in the Coppermine River were also made (Franklin, 1824).

The main purpose of the mission, however, was to map every aspect of the northern coast they sailed along meticulously. The northern coastline of Canada is characterized by rocky shores, vast amounts of ice, and numerous bays, points and inlets. Each of these was explored, named and painstakingly documented by Franklin and his crew (Franklin, 1859).

Franklin's expedition enabled him to conclude that a passage through the Arctic Sea to the Pacific Ocean was quite likely to exist, and that it was reasonable that British explorers would be able to locate it (Traill, 1896). His expedition was important for other reasons, however. None of this area had previously been mapped with the detail and attention paid by Franklin and his crew (Traill, 1896). This made it possible for others to follow in his path and be able to see the geographical and geological features that he had observed. While the region remained inhospitable, increased knowledge of its geography was a benefit to further research endeavours in the area.

Third Expedition (1825-1827)

After his return, Franklin married and had a daughter. He left for another expedition to the Mackenzie River (Figure 3.42) and the Beaufort Sea from 1825 to 1827, and his wife died of tuberculosis during that time (Traill, 1896). This exploration was fruitful, and added a great deal to British knowledge of Northern Canadian geography. The types of observations made were similar to those made in his 1819 expedition. The crew was

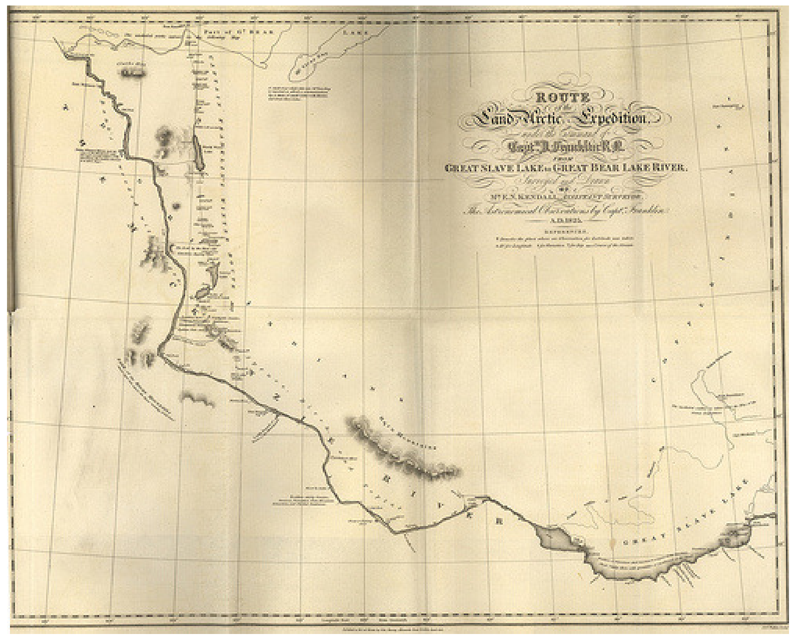


Figure 3.13 *Map from Franklin's McKenzie River Expedition: a land expedition, and Franklin's third journey to the Arctic (above).*

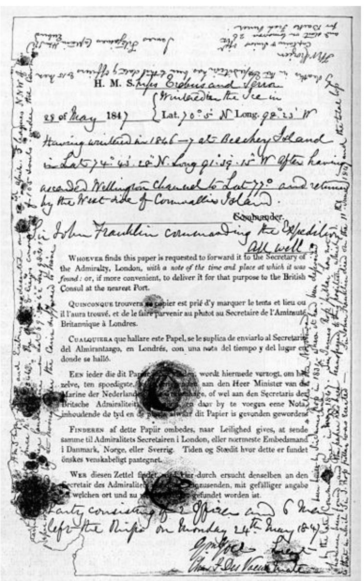
equipped with numerous tools that enabled them to make observations and take data (Franklin, 1828). For astronomical studies, sextants, artificial horizons, altitude instruments and small telescopes were used. For data on atmospheric conditions, Franklin used electrometers, hygrometers, photometers and thermometers. Compasses were also part of the list, with every crew member having their own, and some having specialized ones (Franklin, 1828).

Franklin and his crew mapped over 1200 miles of the coast that had not yet been mapped by any European explorer (Traill, 1896). Franklin had not yet found a northwest passage to the Pacific Ocean, but he had contributed to the accumulation of scientific knowledge. He was honoured by learned societies, and was knighted in 1829 (Traill, 1896).

The following decades of Franklin's life were not spent in Arctic expeditions, but in various appointments in the Mediterranean and in Tanzania. He never lost his love the Arctic though, and after being relieved of his colonial governor post in Tanzania, he returned to London and began preparation for what would be his last journey (Traill, 1896).

Final Expedition (1845)

Sir John Franklin had two ships commissioned for his expedition: the *Erebus* and the *Terror*, both top of line ships at the time. The party consisted of almost 140 men, and was equipped with the best gear, including steam engines for the ships and enough provisions for three years (Traill, 1896). The expedition departed England in May 1845. Early predictions for the length of their journey determined that they would reach the Pacific Ocean by the summer of 1846 (Traill, 1896). Everyone thought that their success was guaranteed. None could have predicted that Franklin's letter to Lady Franklin (1791-1875), the woman he married after his first wife had died, dated 7th of June, 1845, would be one his of last. It was sent from Disco Bay's Whalefish Island, just near Greenland. In his letter, he reassured her, "The navigation of the Arctic Sea is not near so full of danger as that of the Antarctic" (Traill, 1896).


H. M. Ships Erebus and Terror
Wintered in the Ice in
28 of May 1847 Lat. 70° 5' N Long. 98° 23' W
Having wintered in 1846—7 at Beechey Island in Lat 74° 43' 28" N. Long 91° 39' 15" W After having ascended Wellington Channel to Lat 77° and returned by the West side of Cornwallis Island.
Sir John Franklin commanding the Expedition.
All well

WHOEVER finds this paper is requested to forward it to the Secretary of the Admiralty, London, *with a note of the time and place at which it was found*: or, if more convenient, to deliver it for that purpose to the British Consul at the nearest Port.

QUINCONQUE trouvera ce papier est prié d'y marquer le tems et lieu ou il l'aura trouvé, et de le faire parvenir au plutot au Secretaire de l'Amirauté Britannique à Londres.

CUALQUIERA que hallare este Papel, se le suplica de enviarlo al Secretario del Almirantazgo, en Londrés, con una nota del tiempo y del lugar en donde se halló.

EEN ieder die dit Papier [illegible], wordt hiermede verzogt, om het zelve, ten spoedigste, [illegible] aan den Heer Minister van de Marine der Nederlanden [illegible], of wel aan den Secretaris der Britsche Admiraliteit, [illegible] daar by te voegen eene Nota, inhoudende de tyd en de [illegible] alwaar dit Papier is gevonden geworden.

FINDEREN af dette Papiir ombedes, naar Leilighed gives, at sende samme til Admiralitets Secretairen i London, eller noermeste Embedsmand i Danmark, Norge, eller Sverrig. Tiden og Stoedit hvor dette er fundet önskes venskabeligt paategnet.

WER diesen Zettel findet, wird hier-durch ersucht denselben an den Secretair des Admiralitets [illegible] einzusenden, mit gefälliger angabe an welchen ort und zu [illegible] gefundet worden ist.

Party consisting of 2 Officers and 6 Men left the Ships on Monday 24th May 1847.
Gm Gore Lieut.
Chas F Des Voeux Mate

Figure 3.14 *The letter found by Francis Leopold McClintock on King William Island. Written on it is the date of Sir John Franklin's death (above).*

The danger of his journey may be difficult to perceive considering the technologies for navigation at our disposal today. In 1845, there existed no accurate maps of Northern Canada up to the North Pole. Franklin did not know whether he was heading into open sea, solid land, or a vast archipelago. And while he was supplied with the toughest and best of his time, the obstacles of the vast unknown of the Arctic Sea proved too much for him and his crew (Traill, 1896).

The careful observations and logging of findings that made Franklin's other expeditions so fruitful continued. In his final letter, addressed to Lady Franklin, Franklin encloses twelve days worth of his diary, including drawings made by other members of his party (Traill, 1896). He describes their daily activities and plans, but also the natural surroundings and the magnetic properties of the area (Traill, 1896).

The last sighting of the *Erebus* and the *Terror* before their disappearance was about twelve days after Franklin's last letter, in Disco Bay, when they met with a British whaler. The captain of the whaler reported on the event, stating that the crew appeared to be in good condition both physically and mentally. This report, along with the crew's and Franklin's own assertions of confidence made their disappearance all the more shocking (Traill, 1896). After two years of no news, British authorities finally sent out expeditions to rescue the explorers, or at least locate their remains and determine the cause of their demise (Traill, 1896).

Rescue Missions

British authorities commissioned multiple vessels for rescue missions, and each mission was to begin searching from a different approach (Traill, 1896). One would take the same route Franklin's party had taken, another would start at the Behring Strait and work backwards, and another would go by land and work its way down the McKenzie River along the coast to the Coppermine River (Traill, 1896). It is possible that some of the maps from Franklin's expeditions through these rivers may have been used by the parties sent to search these places.

Led by John Rae (1813-1893), this land expedition was the most fruitful. From conversations with the Inuit, he gathered information about a party of men that had been seen moving along the ice, and that had later been found dead (Rae, 1855). The descriptions of the bodies indicated that the men had suffered considerably from illness, starvation and exposure to the elements before dying. Rae also managed to procure objects that the Inuit had scavenged from the dead men's tents and packs, including a silver plate engraved with Franklin's name (Rae, 1855).

More expeditions followed, aiming to locate the bodies and the ships. In 1859, Francis Leopold McClintock (1819-1907), who had been sent by Lady Franklin, found a note on King William Island that had been written by two men from Franklin's crew (Figure 3.43). The note included the date of Franklin's death, June 11, 1847 (Traill, 1896).

Over a century later, in 1981, a team from the University of Alberta excavated artefacts and human bones along the path Franklin's men had travelled. They determined specific causes of death, which included scurvy, lead poisoning and pneumonia (Geiger and Beattie, 2004).

The failure of Franklin's final expedition was by no means an indication of failure of his entire career. His work contributed greatly to the exploration of Northern Canada, even though he never found the Northwest Passage. Franklin and his crews gathered information pertaining to geology, geography, meteorology, geomagnetism, ecology, mineralogy, and more in a territory many would never have dreamed of entering themselves.

Polar Ice Caps

The North Pole has been at the centre of multiple events in human history. It has also played an interesting role in the history of the formation of the Earth as we see it today.

Formation of Polar Ice Caps

The Arctic and Antarctica have not always been iced over the way they are now. While the polar regions of the Earth receive less sunlight than the rest of the Earth, this is not sufficient to cause full glaciations (Cox and Moore, 2010). Ocean currents bring warmer waters up towards the poles, causing polar ice to melt (Cox and Moore, 2010). However, if these ocean currents are somehow blocked, glaciations will occur and polar ice caps will form (Cox and Moore, 2010).

This can happen in two ways. In the case of Antarctica, the land mass moved by plate tectonics and is now located over the South Pole (Cox and Moore, 2010). During the most recent ice age, it became covered in snow and ice. The warm waters brought by ocean currents can only melt the ice in the water around the land mass, but the continent itself stays frozen. Antarctica has hosted an ice cap for around 42 million years (Cox and Moore, 2010).

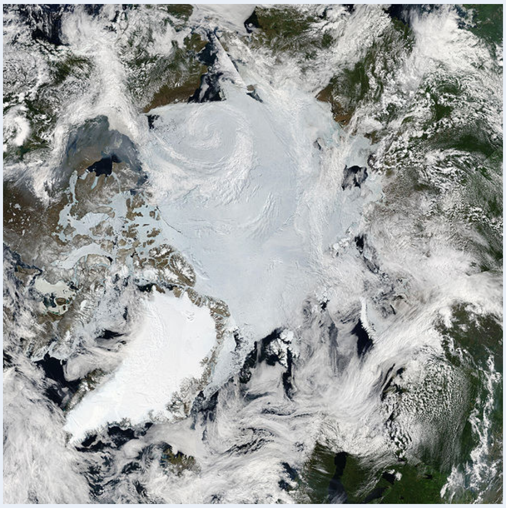
The other way a polar ice cap can form is when sea ice freezes. This can occur if ocean currents are blocked from accessing polar waters (Cox and Moore, 2010). This is the case of the Arctic Ice Cap (Figure 3.44), whose formation also occurred primarily due to plate tectonics. The configuration of continental masses around the Arctic Basin blocked the passage of warmer water to the polar sea, and thus the Arctic polar ice cap was formed approximately 3 to 5 million years ago (Cox and Moore, 2010).

While their barren, white landscapes may suggest otherwise, the polar ice caps are regions full of opportunity for research about both modern day phenomena and the history of the Earth.

Value of Polar Ice Caps

The composition of the atmosphere of the Earth changes over time in terms of concentrations of different gases. In modern studies of global warming, CO_2 levels are of particular interest. As ice crystals are compacted into dense layers, air bubbles become trapped. These air bubbles have a similar composition to the atmosphere at the time they became trapped (Bender, Sowers and Brook, 1997). Taking ice cores and analyzing trapped gasses from different layers in the ice can be used to trace levels of CO_2 in Earth's atmosphere for up to hundreds of thousands of years in the past (Bender, Sowers and Brook, 1997).

Figure 3.15 *Satellite image of the Arctic, showing the ice cap, Greenland and the surrounding continents. (below).*



Antarctica is the coldest place on Earth, and yet it supports many life forms. Organisms native to Antarctica are of particular interest to biologists and ecologists (Cox and Moore, 2010). Understanding how life persists in the extremely cold temperatures is valuable for several reasons. One in particular is the use of Antarctican organisms as analogs for possible development of life on other, colder planets such as Mars.

These unique environments have played important roles in our history on both a geological scale and a human history scale, and continue to be subjects of much exploration and research.

Development of Glacial Theory

The development of the Glacial Theory can be traced back to many natural scientists of the 19th century, all of whom encountered powerful opposition from their most esteemed colleagues (Rudwick, 1969). A chain of creative thinkers ultimately lead to its most forceful spokesperson Louis Agassiz (1807-1873), a Swiss naturalist who roused strong debates that could no longer allow the Glacial Theory to be ignored. The Glacial Theory ultimately played a critical role in the conceptual development of the earth sciences as it forced geologists to throw away both long-held scientific principles and religious convictions. Though the scientific dispute over a recent ice age continued for over 25 years it is now a universally accepted theory (Imbrie and Imbrie, 1979).

Figure 3.16 *Alestch Glacier, located in the Swiss Alps. In the early 19th century, the powerful erosional nature of glaciers was not recognized and it was not accepted that they had once covered much more extensive areas (above).*

The Glacial Theory is essentially the idea that a moving sea of ice had at one time covered much larger areas of the globe than at present. This theory has long been believed by Swiss peasants who had daily contact with the evidence of past glaciations, though it was repeatedly rejected by the most renowned scientists of the day (Rudwick, 1969; Imbrie and Imbrie, 1979). Phenomena that are now attributed to past glaciations were already explained by other theories that were too deeply entrenched in the minds of scientists, in an age where there was a general resistance to new ideas (Rudwick, 1969; Imbrie and Imbrie, 1979).

The Diluvial Theory

The diluvial theory was a prevalent belief in the 18th and 19th century. Diluvial deposits result from floods, and were often used to explain the geological history of a region in terms of the Great Flood, as described in Genesis. Erratic boulders are an example of glacial features that were previously interpreted as diluvial deposits. Erratic boulders sometimes weigh upwards of 20 000 tonnes and can be found spread throughout the slopes of the Jura Mountains in Switzerland. Far removed from their areas of origin, their paths can be traced many tens of kilometres back to the Swiss Alps. The position of these boulders certainly cannot be explained as the result of modern processes, so naturalists of the day were not wrong in their interpretation of a past catastrophic episode that was responsible for their movement (Rudwick, 1969).

There were many problems with the diluvial theory, but it was still strongly defended when the Glacial Theory was in its infancy. For example, a rise in sea level of over 1500 metres would be required to explain some of the erratic deposits in mountainous regions. The question of where this water came from or subsequently disappeared to had imaginative, but unconvincing explanations. By 1833, the diluvial theory was slightly modified and replaced by the 'drift theory'. The drift theory was proposed by English geologist Charles Lyell (1797-1875), who argued that the agents responsible for the deposition of erratics were boulder-laden icebergs that drifted about in the great flood (Imbrie and Imbrie, 1979; Hansen, 1970). This single modification in the theory better accounted for the movement of erratics and other debris without discounting the notion that a flood had occurred. The geologists of the day became engrossed in the drift theory, causing a further delay in the acceptance of Agassiz' glacial theory (Hansen, 1970).

Origins of the Glacial Theory

Louis Agassiz was not the first person to construct the idea of a period with much more extensive glaciation. However, as the young president of the Swiss Society of Natural Sciences, he brought it out of scientific obscurity by shocking his associates with his paper arguing that erratic boulders and other phenomena are evidence of an ancient ice age. This presentation in 1837 was highly controversial and became known as "The Discourse of Neuchatel" (Imbrie and Imbrie, 1979).

Many noted scientists who were early pioneers in this field independently developed ideas of past glacial episodes. The chain of innovative thinkers that ultimately lead to Agassiz' glacial theory can be traced back to Jean-Pierre Perraudin (1767-1858), a mountaineer from the Southern Swiss Alps. As early as 1815, he concluded that glaciers had once filled the entirety of the Val de Bagnes, although at the time they only existed in the southern portion. Perraudin stated that "Having long ago observed marks or scars occurring on hard rocks which do not weather, I finally decided...that they had been made by the pressure or weight of these masses" (Imbrie and Imbrie, 1979, p. 22).

Jean de Charpentier (1786-1855), a Swiss geologist who would later become an important advocate of the Glacial Theory, was impressed but overall unconvinced of Perraudin's conclusions (Imbrie and Imbrie, 1979).

Charpentier's reaction was typical of many geologists of the day. In the early 19th century, glaciers were merely regarded as peculiar features that were common in high altitudes and high latitudes. No one considered that they might have any importance in geological processes (Hansen, 1970). In regards to Perraudin's proposal of a period of more extensive glaciations in the past, Charpentier thought: "although I agreed with him on the impossibility of transporting erratic boulders by water, I nevertheless found his hypothesis so extraordinary and even so extravagant that I considered it as not worth examining or even considering" (Imbrie and Imbrie, 1979, p. 22).

In the following three years, a Swiss naturalist named Ignace Venetz (1788-1859) took notice of Perraudin's ideas. Venetz spent a substantial amount of time in the Val de Bagnes area between 1815 and 1818. Though he was very slow to adopt Perraudin's theory, he ended up expanding upon it and developing ideas of his own. In 1829 at the annual meeting of the Swiss Society of Natural Sciences, Venetz proposed that immense glaciers had once spread from the Alps to cover the entire Swiss plain, Jura, and other parts of Europe. This was the first true statement of the Glacial Theory in that it had more than local implications (Rudwick, 1969). His evidence for his hypothesis was the distribution of erratic boulders (Figure 3.62) and moraines in these regions. Furthermore, he made comparisons of these deposits to ones which had been formed by contemporary glaciers (Imbrie and Imbrie, 1979).

Figure 3.17 *An example of an erratic boulder found in Lake Superior Provincial Park, Canada. In the early 19th century, these were thought to have been moved by great flood waters to locations that can include very high altitudes (above).*

Although his evidence was sound, Venetz' theory was for the most part rejected or outright ignored. In the audience at the Society's meeting, however, was Jean de Charpentier. Finally seeing truth in the theory, he was inspired to study the glacial problem in more detail. In the following few years, Charpentier helped establish the theory by organizing and classifying supporting evidence. By 1834, he was ready to present a paper to the Society at an annual meeting in Lucerne, Switzerland. Charpentier argued that ancient erratic boulders, scratched bedrock and moraines were much too similar to the features formed by contemporary glaciers. There was no logic in attempting to attribute these features to other mechanisms such as those described by the diluvial or drift theory (Imbrie and Imbrie, 1979). Unfortunately, the idea of a past glacial period was once again unanimously rejected by the members of the Society.

Louis Agassiz: The Leading Advocate of Glacial Theory

Louis Agassiz, who had now established himself as a distinguished man of science in Europe, was among those who rejected Charpentier's ideas (Imbrie and Imbrie, 1979). Agassiz always had great admiration for Charpentier while in school. In 1836 he accepted an invitation from Charpentier to spend a summer in Bex. Charpentier often invited him here to his home since the area was rich with fossils and geological features of great interest to Agassiz. Although he was primarily concerned with his research on fossil fishes, Agassiz was not opposed to being shown the supposed evidence that favoured the glacial theory (Rudwick, 1969; Imbrie and Imbrie, 1979).

Figure 3.18 *Lyell's drift theory replaced the diluvial theory in the 19th century. For a time before the Glacial Theory was finally firmly established, a flexible combination of the drift and Glacial Theory was used to explain glacial features and phenomena (above).*

As a supporter of the drift theory, Agassiz expected to point out flaws in Charpentier's evidence and subsequent interpretation. However, Agassiz found himself rapidly becoming convinced by the Alpine phenomena that he observed (Rudwick, 1969; Imbrie and Imbrie, 1979). Learning quickly from the work of Venetz and Charpentier, Agassiz extended their ideas and formulated a new, more radical theory. In 1837 at the Society's annual meeting in Neuchatel, the young president startled his colleagues with his new conclusions. He described his personal observations and those of Venetz and Charpentier, rejecting any agent other than masses of glacial ice to explain the polishing of rocks, transport of erratic boulders, and moraines (Hansen, 1970). Agassiz also postulated that the glacial ice was once part of a widespread polar ice sheet covering Europe to as far south as the Mediterranean, as well as large parts of North America. He continued by saying that the ice sheet originated before the Alps were formed and subsequently slid down towards Jura during a later uplift of the region (Rudwick, 1969; Imbrie and Imbrie, 1979).

Agassiz was very confident in his evidence, thinking that no one could possibly find fault in his comprehensive glacial theory. Unexpectedly, geologists of the day still clung to the drift theory and maintained a strong opposition to the idea of any sort of ice age. The difference between Agassiz and his mentors in the Glacial Theory, however, was that he assumed the position of a forceful and persuasive spokesperson. In comparison, Charpentier did not see it as his duty to push for his theory's publication or acceptance. He was quite content with presenting his evidence and letting it prove itself over time (Imbrie and Imbrie, 1979). It was largely due to Agassiz and his "Discourse" that for the first time the glacial theory could no longer be ignored.

Slow Triumph of the Glacial Theory

The first important person to convert to Agassiz' new glacial theory was Reverend William Buckland of England (1784-1856). Buckland was one of the most influential and widely respected geologists of the day, known for subscribing to the traditional diluvial theory that accorded so well with the biblical record. Buckland visited Agassiz in 1838, travelling through the mountains around Neuchatel to see the glacial phenomena himself. He initially remained quite skeptical, but upon seeing the glaciers themselves in the Alps, Buckland became the first major British supporter of the theory (Imbrie and Imbrie, 1979; Hansen, 1970).

Buckland was able to use his influence to help gain additional support for the Glacial Theory. Within a short time, he had managed to convince Charles Lyell, the man behind the widely accepted drift theory of the validity of the concept of a past period of more extensive glaciation. In 1840, he wrote to Agassiz of this particular triumph:

"Lyell has accepted your theory in toto!!! On my showing him of a beautiful cluster of moraines within two miles of his father's house, he instantly accepted it as solving a host of difficulties which have all his life embarrassed him" (Boylan, 1998, p. 148).

Now, a trio of internationally famous Now a Now a trio of internationally famous geologists were in favour of the ice-age theory. The general reaction to the theory was still quite negative, and many heated debates were still to come. In the early 1840s, acceptance shifted to an expanded form of the drift-theory that invoked both land and floating ice to explain various phenomena. The flexibility of this theory made it quite convenient to account for a wide variety of glacial features. It took another 20 years until the ideas of Louis Agassiz re-emerged and won prominence over this modified drift theory. By the late 1860s, Agassiz' glacial theory was finally firmly established on both sides of the Atlantic.

Subglacial Processes

Since the 19th century, a much more detailed understanding has been gained about the science behind glaciers, particularly of subglacial processes. Hidden from view, subglacial processes act in the region of the glacier extending only a few meters above and below the contact point between glacial ice and the geological substrate (Clarke, 2005).

It was not until the early 1980s that glacial geologists recognized that the beds of glaciers are not always passive and rigid. In reality, some glacial beds are a component of an ice-bed system in which the deformation of unlithified subglacial materials is a response to glacial stress. Subglacial processes ultimately depend on the properties of water, ice, bedrock and sediment at the region of ice-bed contact (Clarke, 2005). It is now recognized that there is a spatial and temporal variation in subglacial processes, which indicates that a till sequence may contain a signature of the past transportation and deposition at the ice-bed interface. The main processes involved in the production of subglacial tills are subglacial sliding and lodgement, deformation and ploughing, melt-out, and deposition of meltwater deposits (Evans et al., 2006).

Tills are defined as poorly sorted and unstratified deposits formed from rock debris that is carried and subsequently deposited by a glacier (Plummer et al., 2007). There are various kinds of tills that are now recognized based on a process-specific classification.

Glacitectonite is a rock or sediment deformed by subglacial shearing, but which retains the parent material's structural characteristics. Subglacial traction till is sediment deposited from a glacier base by frictional drag on sediment within the basal ice and by pressure melting of sediment-rich basal ice. A third class of till is melt-out till, which is sediment released by the melting of stagnant or slowly moving, debris-rich glacier ice. Since conditions beneath glaciers vary both temporally and spatially, it is expected that subglacial tills in the geologic record result from a range of processes acting in the subglacial traction zone (Evans et al., 2006).

Figure 3.19 *A till deposit forming as a glacier retreats. Till is the unsorted sediment transported and deposited by a glacier, and is classified on the basis of a process-specific system (below).*

Charles Darwin

Charles Darwin (1809-1882) was born in Shrewsbury, England into a fairly educated family. His father was a doctor and the son of Erasmus Darwin (1731-1802), a respected doctor who speculated about biological evolution in his book *Zoonomia* (1794) (Browne, 1996). His maternal grandfather, Josiah Wedgewood (1730-1795), was creditted with the industrialization of pottery. Darwin's mother died when he was only eight years old, and he was raised by his aunts (Howard, 2001).

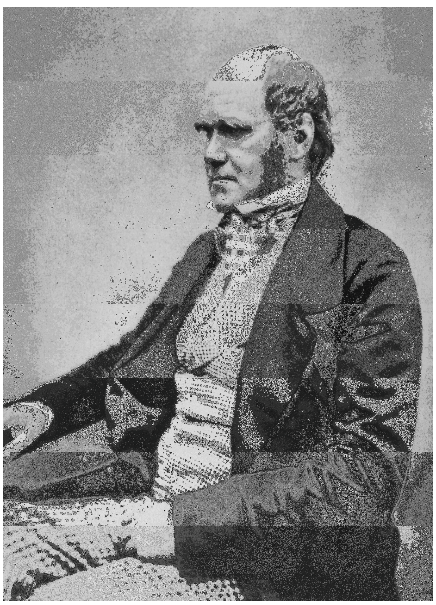


Figure 3.20 *Charles Darwin in 1854 at age 45*

After high school, Darwin enrolled in medical school at Edinburgh University, following his father's footsteps. Darwin soon realized he was unable to deal with the stress of tending to patients everyday. Thus he decided to move to Cambridge to become a priest (Howard, 2001). However, it was at Cambridge that Darwin first became seriously interested in science under the tutelage of the well-known Cambridge botanist John Stevens Henslow (1796-1861). It was Henslow`s recommendation that gave him the opportunity to become the naturalist on the *H.M.S Beagle* for its five-year global trip (Howard, 2001).

On The H.M.S. Beagle

The *Beagle's* circumnavigation of the globe spanned from December 27th, 1831 to October 2nd, 1836 and only represented five years of Darwin's life even though he considered this experience to be "by far the most important event in my life and has determined my whole career" (Darwin F., 1887, p. 61). On the *Beagle*, Darwin studied Charles Lyell's (1797-1875) book "Principles of Geology", which increased Darwin's understanding of geology greatly and expanded his observational skills. He applied these skills to understand the geological record and stratigraphy of various structures during his voyage (Howard, 2001). Darwin had so much respect for Lyell that he once said that "half of his books seem to come half out of Lyell's brain" (Darwin, C., 1903, p. 177). However, Lyell's book fundamentally disagreed with Darwin on the possibility of biological evolution (Howard, 2001).

Darwin made use of his knowledge in both geology and biology on the *Beagle* to understand "the geological relations of the present and past inhabitants of the continent" (Darwin, C., 1876, p. 1). To examine the past, Darwin observed the fossil record present in most of South America. He understood the many imperfections in the geological record and did not expect to find every transitional form in the fossil record (Darwin, C., 1876). Understanding this limitation was extremely important for Darwin in asserting his theory. Specifically, Darwin noticed a clear relationship between the fossilized pieces of armour found and the current living armoured armadillos present in South America. Darwin inferred that these fossilized remains of a species represented the progenitor of current species living in the same area (Darwin, C., 1876).

Darwin also made a major geological contribution in understanding the formation of coral reefs. His theory described the formation of fringing reefs by coral just below tide level, and how the growth of these reefs will follow the rise and fall of the coastline (Darwin, C., 1874). Any coral that becomes exposed will die off and leave a distinct strip of limestone in the geological record. From this theory, Darwin predicted that the coastline was sinking in the islands of the South Pacific, which accounts for the lack of barrier reefs (Darwin, C., 1874).

The Basis of Speciation

As Darwin toured the Galapagos archipelago, he noticed the relatively large number of endemic species present in comparison to the continent. This larger proportion can be explained by the confinement of a species to an island surrounding which forces a species to be selected for based on the island's environment (Darwin, C., 1876). This observation could have been the basis of Darwin's theory behind natural selection and the idea that led to

Perhaps the most famous group of species that Darwin studied was the selection of finches on the Galapagos. Like any naturalist, Darwin began by classifying each finch based on its type of beak t (Browne, 1996). Contrary to popular belief, there was no sudden realization by Darwin that the beaks represented evolutionary radiation of these birds exploiting different food sources. In fact, Darwin was not an expert on the various birds present on the island and even misclassified certain species (Browne, 1996). He did not realize the significance of the different beaks even after a shipmate remarked to him about the different shells of tortoises from different islands. He only formulated his theory when he returned from the Beagle trip, and consulted ornithologist John Gould (1804-1881) to identify the different birds (Browne, 1996).

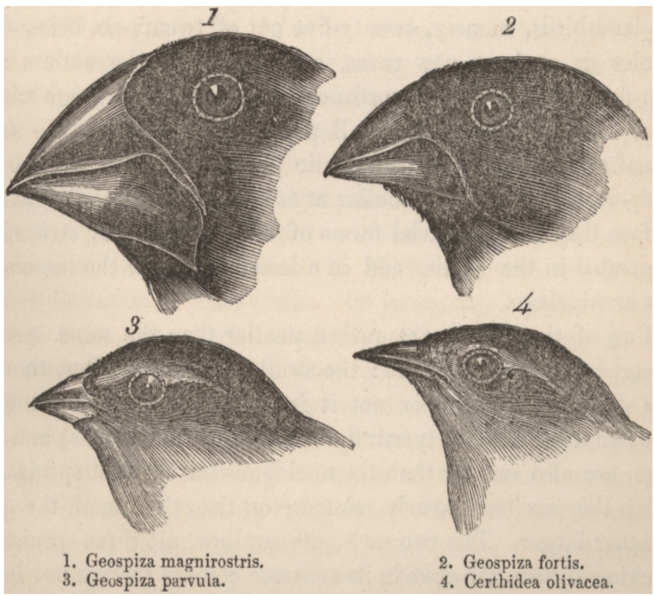


Figure 3.21 *An illustration done by John Gould of four birds that Darwin observed that helped him formulate his theory on natural selection. Note that the third bird is now classified as Camarhynchus parvulus.*

According to Gould's classification, Darwin had observed 26 land birds with 23 being endemic and 11 marine birds with only 2 endemic birds. Also, no endemic birds were observed on the mainland of Ecuador (Darwin, C., 1876). The greater number of endemic land birds can be accounted for by the fact that marine birds can migrate away from the islands. This allowed Darwin to understand the role of a secluded environment on the process of natural selection or speciation (Darwin, C., 1876). Unfortunately, Darwin's notes on the finches were incomplete and provided inconclusive evidence since he did not realize the significance of these various birds at the time (Browne, 1996).

Post Beagle days

After returning from his five-year trip, Darwin began to compile his ideas regarding descent with modification from 1837-1839 into nine hundred pages of personal notes. However, he did not publish any of his ideas on evolution at the time. Instead, he completed *The Journal of Researches*, a fairly popular travel book, which only provided the public with a description of the various areas he visited on the *Beagle* (Howard, 2001).

During this time his personal life changed dramatically as he married Emma Wedgewood (1808-1896) in 1839, and had his first of ten children in 1841. Shortly after, Darwin's good health was interrupted by an unknown illness; he was unable to sleep, had intestinal pains, and was very easily exhausted (Howard, 2001). This greatly limited Darwin's productivity. As a result, Darwin took precautions in preserving his legacy by producing a 230 page essay of his ideas in 1844 for publication in the case of an early death (Howard, 2001). At its completion he only shared this essay with Lyell and Sir Joseph Dalton Hooker (1817-1911), Darwin's closest scientific friends and colleagues (Howard, 2001).

Clearly in no rush to publish his theory, Darwin proceeded to switch his focus to conducting a thorough study on understanding the classification of barnacles; although not directly related to his evolutionary research, Darwin noticed the problems with classifying organisms without an understanding of natural selection (Howard, 2001). This project took Darwin eight years to complete, and culminated in the publication of *A monograph of the sub-class Cirripedia* in two volumes in 1851 and 1854. These books quickly became a fundamental text for understanding the classification and structure of barnacles (Howard, 2001).

In 1854, Darwin finally felt ready to publish his theory of natural selection. As urged by his friends and colleagues, Darwin began to compile all of his work over the last seventeen years into one huge book for publication (Howard, 2001). After four years, Darwin received a letter from a colleague, Alfred Russel Wallace (1823-1913), which outlined Darwin's theory of natural selection that Wallace had developed independently (Howard, 2001). Obviously shocked by this letter, Darwin proceeded to ask Lyell and Hooker for advice. Eventually, Darwin decided to send a part of his essay from 1844 and another letter to the Linnaean Society to be read with Wallace's essay. With a renewed urgency to publish, Darwin decided to scrap the idea of a large book and began to write a summary of his ideas. He published this piece on Nov. 24th, 1859 as *The Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life* (Howard, 2001).

Darwin continued to publish other works regarding his theory until his death in 1882. One notable piece, and perhaps Darwin's second most influential and controversial piece of literature was *The Descent of Man*, which outlines his views on the natural selection of the human race. He presented the idea that men could be treated in a similar way as any other animal species regarding natural selection (Howard, 2001). He also explained that the existence of races were only due to the geographical isolation of humans across the earth. Thus Darwin provided a biological argument against the idea that different races of men were represented by a hierarchical system of separate species and that humans were above other animals (Howard, 2001).

Reception to Darwin's Ideas

Darwin's publication sparked a divide in the scientific community and the public. Darwin, ill at the time, remained at home and did not make many public appearances to defend his ideas (Howard, 2001). Instead, Thomas Henry Huxley (1825-1895), a young anatomist was at the forefront of fighting for Darwin's views. Most famously, he adamantly stood his ground at a meeting in Oxford for the British Association for the Advancement of Science in 1860, by directly opposing Samuel Wilberforce (1805-1873), the Bishop of Oxford (Howard, 2001). Darwin promptly thanked Huxley for supporting his views at such an important meeting and lauded him for standing up to the Bishop of Oxford (Howard, 2001).

At the time of publication, Darwin was fortunate to see two major advances in communication technology: the laying of the first telegraphic cables across the Atlantic Ocean, and considerable advances in printing. Without these technological advances, Darwin's ideas would not have spread across the globe so quickly (Elshakry, 2009)

Darwin's ideas were not well accepted by the Church. At the time, the church even said that believing in Darwin's ideas would jeopardize one's soul (Elshakry, 2009). However, Darwin's theories were actually embraced by many other cultures and ideologies (Elshakry, 2009). Scholars from such major religions or schools of thought as Hinduism, Confucianism, Judaism, and Islam sought to integrate natural selection into their religion instead of rejecting it as nonsense (Elshakry, 2009).

Darwin's Legacy

Even after more than 150 years, Darwin's theory on natural selection still provides the best biological explanation of the diversity of life. In the field of life sciences, natural selection has not only been applied to explain the diversity of life as Darwin observed it, but also the formation of complex organs, the relatively rapid evolution of microscopic life, and descent with modification at the genetic level (Pagel, 2009). Although natural selection may seem to be a strictly life sciences topic, many scholarly articles referring to natural selection on sociology, economics, statistics, and many other fields have appeared. The integration of natural selection into such a vast diversity of disciplines illustrates the widespread impact that Darwin's theory had and is still having on the world (Pagel, 2009).

The acceptance of natural selection by the church has also come a long way since the publication of *The Origin of Species* in 1859. The Pope acknowledges that evolution can occur between members of a single population, but is not responsible for the creation of new species (Pagel, 2009). Instead of growing old in modern times like many theories developed in the 19th century, Darwin's theory of natural selection has strengthened and provided an explanation to phenomena across numerous subjects beyond the diversity of life (Pagel, 2009)

Explaining the Cambrian Explosion

Darwin provided the basis of understanding descent with modification, but he could not provide an adequate explanation for the fossil record of the Cambrian explosion 543 million years ago (Morris, 2006). This is often referred to as Darwin's dilemma and Darwin even wrote that: "The case (fossil record of the Cambrian explosion) at present must remain inexplicable; and may be truly urged as a valid argument against the views here entertained" (Darwin, C., 1876, 287). This event is also known as the Cambrian radiation since most of the diversity observed in animal body plans are first seen during this period. An example is shown in Figure 3.73 which is a fossil of one of the earliest chordates from the Cambrian explosion, and possibly the progenitor of all modern chordates (Gee, 2001). The two major aspects of the Cambrian explosion that need to be accounted for are the dramatic increase in both species diversity and disparity within an appropriate time-scale.

There are three primary mechanisms proposed to account for the Cambrian explosion: abiotic environmental changes, changes in the ability of animals to evolve, and biotic environmental changes (Marshall, 2006). An explanation considering all three of these mechanisms is necessary to fully account for all the changes observed during the Cambrian explosion. Some abiotic environmental changes that may have triggered the Cambrian explosion include the accumulation of sufficient oxygen to support more complex animal life, a mass extinction that eliminated previous fauna and opened up niche space, and a widespread glaciation event that affected global climates and environments. Taking a more biological perspective, researchers have also determined that the evolution of the bilateral system, and a variable gene expression based on epigenetics may play a significant role in the evolution of the unique species that first appear in the Cambrian explosion (Marshall, 2006). The Cambrian radiation must have also been influenced by evolutionary and ecological processes like predation, and coevolution (Marshall, 2006).

Although there is supporting evidence for each of these mechanisms, not one theory seems to prevail over the others. Each mechanism alone cannot account for the extent of the species diversity and disparity within the time period for the Cambrian explosion indicated by the geological record (Marshall, 2006).

Thus a combined explanation to this "fulcrum point" of life seems to be the only truly viable explanation since most of these theories are not mutually exclusive. Even though an absolute explanation has not been reached regarding the Cambrian explosion, a plethora of plausible theories have arisen since Darwin's time. If presented with these new ideas, Darwin may not have conceded that the Cambrian explosion was a plausible counter-argument to his theory on natural selection (Marshall, 2006).

Figure 3.22 *A fossil of the early chordate Haikouella lanceolata that first appeared during the Cambrian explosion (Gee, 2001)*

Japan after the Nōbi Earthquake

Japan has been suffering from earthquakes for hundreds of years because it is located on the meeting point of three tectonic plates (Mogg, 2001). The continuous collision between the Eurasian continental plate and two ocean plates known as Philippine Sea Plate and Pacific Plate has caused numerous earthquakes and volcanoes in Japan (Matuzawa, 1964).

Despite their long unavoidable relationship, Japanese were not obsessed with overcoming earthquakes until the Meiji Restoration. The Meiji Restoration was a revolution that modernized Japan's economy and politics. It started in 1868 when Emperor Meiji (1852-1912) overpowered the former ruler, the Tokugawa government. One of the biggest changes that Emperor Meiji made was opening Japan to the western world (Clancey, 2006).

Japan was forced to sign unfair treaties with western countries, which slipped Japanese behind and created gaps between Japan and western countries. Thus, the main goal of Emperor Meiji was to close down the gaps so that they could be independent from the treaties. One of the areas he focused on was architecture. Foreign experts were hired to take charge of rebuilding Tokyo after its destruction by fire in 1872 (Clancey, 2006). The buildings in the city were changed from traditional wooden buildings to new western brick and stone style buildings.

The ambitious Meiji government sent many students to western countries, such as Britain and the United States, to learn western architecture. Furthermore, many British teachers and experts were hired and brought into Japan to teach Japanese students (Clancey, 2006). Until 1891, the Japanese mistook the "strength" of western buildings.

The Great Nōbi Earthquake

On the morning of October 28, 1891, the most powerful inland earthquake in recorded history struck the Nōbi plain. The magnitude of the earthquake was 8.4 in Ritcher scale (approximated by the yet-to-be-invented Ritcher scale). The Nōbi Plain is in a rural area, where many highways, railroads, telegraph lines, and other infrastructure linked Tokyo to more southern cities, such as Nagoya and Gifu. The earthquake caused most damage to the areas that were near the epicenter, which were the provincial capital of Gifu and the castle town of Ogaki. A less powerful, but still vigorous earthquake shook Osaka and Nagoya (Bolt, 2003). Since the disastrous earthquake was more concentrated on the rural areas, there was a small number of casualties compared to its strength (210 people were killed in Osaka and Nagoya) (Clancey, 2006).

Since the Nōbi Earthquake was not an urban disaster, it did not appear on headline news at first. Slowly, the damage to rural areas was reported and people started to realize the severity of the earthquake. Although there were not many casualties, the damage to buildings and lands was relentless. More than 142,000 houses were destroyed and many more were damaged (Bolt, 2003). In addition, more than 10,000 landslides occurred in the area. The catastrophe of European-style building collapse was most vividly depicted on the drawings of woodblock prints (see Figure 3.81) (Clancey, 2006).

Despite the fact that thousands of Japanese buildings collapsed and burned, what caught people's attention was the collapse of European style buildings. They had failed dramatically. Two large brick textile mills, Tōkaido Railroad built in brick, and many other brick buildings were destroyed. Moreover, the brick buildings

Figure 3.23 Gifu shigai daijishin no zu. *This woodblock print depicts Nagoya's post office sheds bricks in foreground, while at top, a train plunges into a ravine and telegraph wires snap (right).*

caused more casualties and injuries than the traditional wooden buildings (Clancey, 2006).

People started to question the western architecture. Some people even started to blame the government for letting foreigners take charge of constructing buildings without any controls. They compared the damage to their own traditional buildings and newly built "western" buildings.

On October 31, the *Japan Weekly Mail* reported that nearly all Japanese houses survived the strong earthquake in Osaka. In comparison, many reports revealed that western style buildings failed to survive. The most shockingly destroyed buildings were the Post and Telegraph Offices. They symbolized the Imperial government, so they were built with the newest technology. People noticed that falling wood only caused minor injuries or broken bone, but falling brick caused fatal damage (Clancey, 2006).

Another report in the *Japan Weekly Mail* said, "Nothing seemed to prevent the complete collapse of some houses but the fact that they were built of wood, and so stood the strain far better than brick would have done, as proved by the terrible disaster at the mills on [sic] Osaka." The mills that were referred to in the article were the Naniwa cotton textile mills. It is a three-story red brick building, which was built in an usual English factory style. The falling of "brick," which was an emblem for Japan's modernizing by importing western disciplines, opened the eyes of the Japanese to the study of seismology and caused them to look back at their traditional buildings (Clancey, 2006).

Study of Seismology

After the Nōbi Earthquake, seismology became a key study in Japan, supported by the government. The government helped to form the Imperial Earthquake Investigation Committee (IEIC) a year after the Nōbi Earthquake. IEIC discovered numerous important fundamentals about earthquakes and volcanoes. In addition, many well-funded research projects were dominant in Japan. Along with the good resources to study and a lot of funds, the study of seismology in Japan became far more advanced than that of European countries and the United States (Clancey, 2006).

One of the scientists who raised the understanding of seismology up to a new level was Omōri Fusakichi (1868-1923). When the Meiji government hired European experts, John Milne (1849-1913), a famous British geologist, was one of them. Milne became a professor at the Imperial College of Tokyo. He taught mining and geology there and Omōri was lucky to have him as his instructor. He was Omōri's mentor and Omōri was greatly influenced by him (Clancey, 2006).

Omōri was one of the first seismologists in the world. His first significant work was published in 1896. It was about the relationship between aftershock frequencies of earthquake and the time after the earthquake. He argued that the aftershock frequency decreased when the duration after the shock got longer, which is now called Omōri's law (Bolt, 2003).

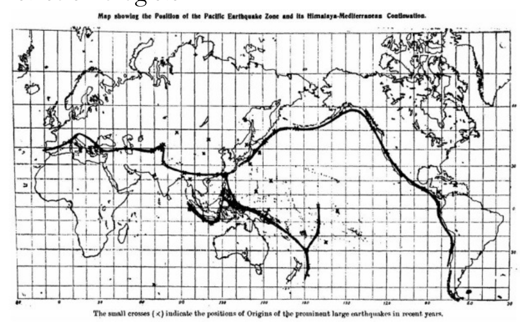


Figure 3.24 *Fault lines as a globe-spanning system. This map was recognized only later as the boundaries between tectonic plates (above).*

In 1901, Omōri introduced an instrument, a horizontal tremor recorder, which is called an Omōri seismometer. It is a mechanically recording horizontal pendulum that he used to record the vibrations of brick buildings, lofty chimneys, bridges, and railway trains (Clancey, 2006).

In 1896, Omōri became the secretary of the IEIC and the leader of volcano and earthquake research in Japan.

Omōri's world scale work was done in the early 20th century. He mapped fault lines as a globe-spanning system (see Figure 3.82). He was the first person to do this job and he even created historical earthquake maps for specific locations (see Figure 3.83) (Clancey, 2006).

Figure 3.25 *Historical earthquake map for southern Italy. Omōri mapped this to predict the locations of future disasters (below).*

Along with the seismology, other scientific disciplines, such as, physics, meteorology, and oceanography grew rapidly. The most notable advancement was physics. Physicists studied magnetism and seismicity and mapped isomagnetics lines of the entire Japan (Bolt, 2003).

The Nōbi Earthquake was a great source for scientists to research earthquakes from because it left uncommon traces.

One example is extensive surface breaks that were 80 kilometers long. Maximum horizontal offset was 8 meters long and many 2 to 3 meters vertical offsets were observed (Clancey, 2006).

Kotō Bunjiro (1856-1935), a professor at the Imperial University, took advantage of these resources to argue a revolutionary idea. After tracing fault lines bisecting the Nōbi plain, he argued that the seismic waves were caused by sudden fault slip. Back then, it was believed that earthquakes occurred due to underground explosions or magma movements (Bolt, 2003).

The studies done by Japanese scientists after the Nōbi Earthquake challenged many theories proposed by European scientists. For example, when Kotō finished his logical survey of Japanese volcanoes, he disagreed with the theory about the link between volcanism and seismicity concluded by German geologists. Kotō criticized that, "born in a volcanic and earth-shaking country, I cannot from my own convictions and daily experience, agree with him (an European scientist) on many points" (Clancey, 2006).

Architecture after the Nōbi Earthquake

One of the reasons why seismology and other scientific studies related to it became popular was that Japanese realized the need to prepare for the earthquake. They have already experienced the failure by expecting the western countries to do the job for them. Thus, they began to develop their own studies to prepare for it. Researching earthquakes was not the only way of preparation. Architecture was also another field in which Japanese put a lot of effort following the Nōbi Earthquake (Clancey, 2006).

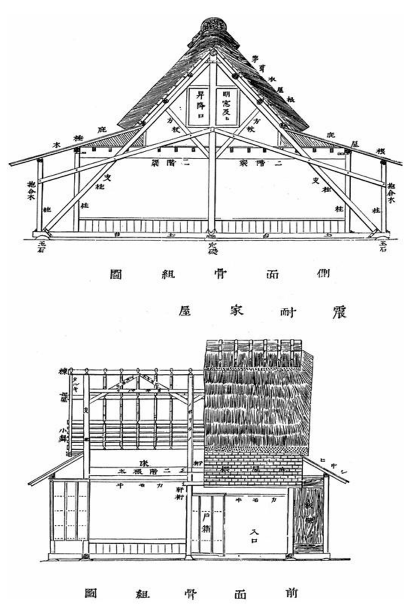


Figure 3.26 *Ito Tamekichi's "Safe from Three Damages House." The "damages" refers to earthquakes, floods, and typhoons (right).*

Destruction of western style buildings after the Nōbi Earthquake was certainly shocking. The first reaction to the failure was to try again with bricks and stones. They tried to modify the bricks so that they could be locked together and become a stronger foundation for houses. Unfortunately, their new trials collapsed after the strike of earthquake with small magnitudes. The continuous failure of constructing earthquake-proof buildings with western style finally made Japanese look back at their traditional materials, which stood up better against earthquakes (Clancey, 2006).

Itō Chuta (1868-1954), who had been studying western architecture until his graduate studies in Imperial University, began to analyze the architecture of temples and old shrines after his graduate studies. Studying both western and Japanese architecture, Itō tried to combine both Japanese traditional and western styles. He used the basic infrastructure of Japanese traditional buildings, wood, but built in western architecture style, called the "western carpentry" (Clancey, 2006).

Another expert who also worked on earthquake-proof building is Itō Tamekichi (1864-1943). Itō Tamekichi specifically studied the problems of the Japanese house. His solution was a house with its frame in a series of large trusses, designed to be assembled on the ground as "bents" and then raised into place in the manner of traditional Anglo-American houses and barns. Each bent was stiffened by long pieces of thin lumber to be fastened with nails. But unlike squarish American house frames, Itō's was triangular in cross section, similar to the frame of typical American roof. His another name for the house was in fact, *sankaku nagaya*, or Triangular House (See Figure 3.84) (Clancey, 2006).

Despite their hard work, architects failed to build earthquake-proof buildings. However, their work had improved stability and decreased the number of casualties when earthquakes occurred (Clancey, 2006).

Although significant improvement still has not occurred from the point of view of architecture to protect Japan from earthquakes, it is clearly shown that the Nōbi Earthquake at least woke Japan up. Japan finally started to think and prepare for earthquakes both academically and physically.

Applications of Seismic Waves

In 1906, a British geologist Richard Oldham (1858-1936) started to use seismic P and S waves as "x-rays" that could penetrate through the body of the earth (Claerbout, 1985).

The major difference between P and S waves is that P wave can pass through fluid, while S wave cannot. By using this difference, scientists established the structure of the Earth 's crust, mantle, and liquid/solid core by 1936 (Claerbout, 1985).

The study of seismic waves has not only been applied to find out the interior of the earth, but also to investigate earthquakes. The first application of seismograms was in 1887 when a German scientist, E. von Rebeur Paschwitz (1861-1895), observed horizontal pendulums, which measure the earth's tide, registered seismic waves. He noticed that these waves registered about half an hour after a large earthquake occurred in Tokyo. This suggested to him that seismic waves are related to earthquakes (Kearey, Klepeis and Vine, 2009).

The characteristic of P and S waves that scientists use in the study of earthquakes is their travel speed: P waves travel faster than S waves. Therefore, using the time difference by which each wave reaches its destination, the location of an earthquake epicenter can be found (Kearey, Klepeis and Vine, 2009).

In modern science, the use of seismographs has been extended to the interpretation of sound waves. Sound waves (sonar) are widely used to study seafloor topography.

The two basic techniques that use sound are seismic reflection and seismic refraction. A sound pulse is sent from an airgun and the time it takes for the sound to return is measured by hydrophones (see Figure 3.85). The seismic data provide information about sediment type, thickness and structure and may be used to reconstruct the depositional history og the region. For example, these data may be used to determine sea level changes over time (Bangs et al., 2004).

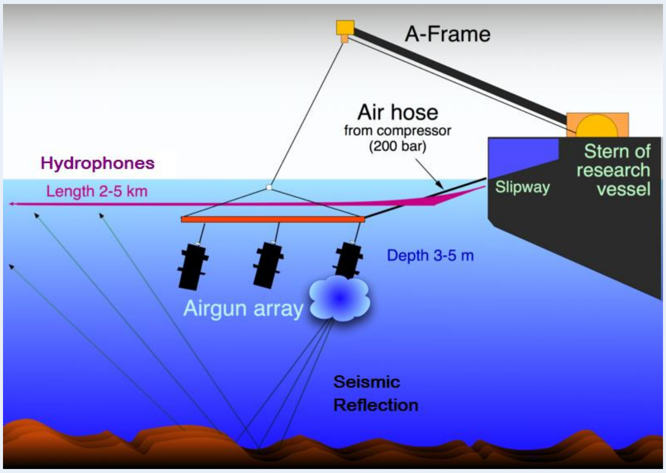
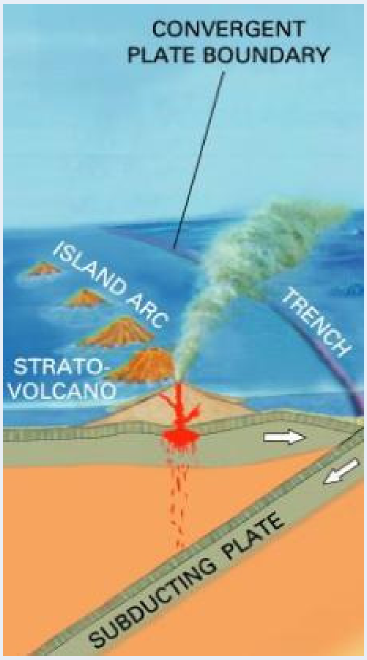


Figure 3.27 *Seismic reflection. Seismic reflection can be used deeper environments than the figure (left).*

Another application of seismic waves is to predict when and where undersea earthquakes will occur. In 2004, a huge tsunami created by massive earthquake along the Sumtra subduction zone killed more than 185,000 people in Asia. If the margins of two plates get locked, stress builds up and an earthquake occurs when the stress is released. By using seismic reflection and refraction, it is possible to map out plate boundaries located undersea. This will enable scientists to identify locked regions and establish the amount of plate movement that occurred in the past. This information will assist in the prediction of future earthquakes and tsunamis (Bangs, Gulick and Shipley, 2006).

Figure 3.28 *Cross-section of a subduction zone (below).*



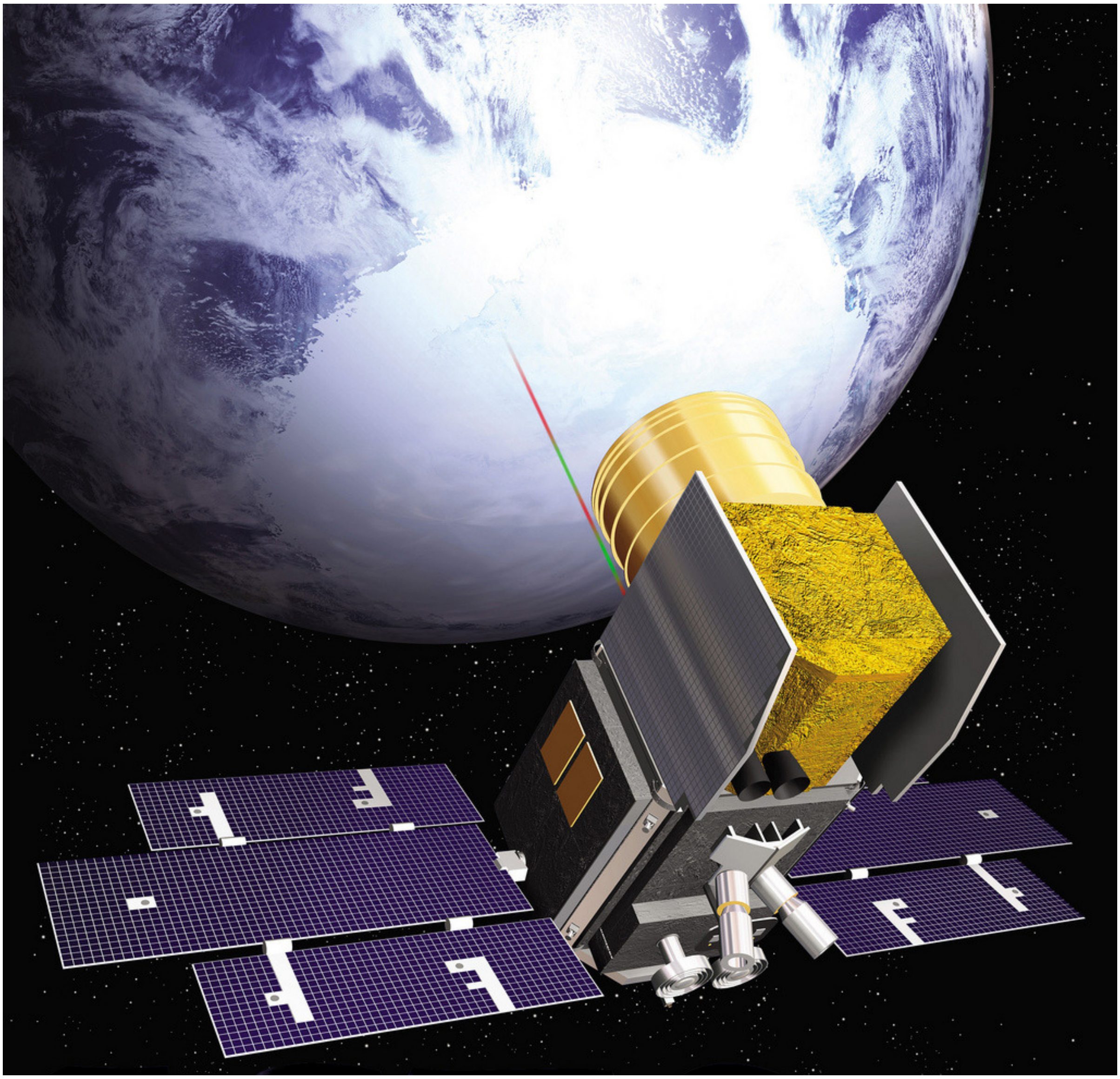


Figure 4.1 *A satellite taking pictures of the Earth. Technological advancement helped scientists in the 20th century refine their understanding of the Earth.*

Chapter 4: The 20th Century
Refining Theories and Integrating Sciences

The 20th century saw a significant change in methods of scientific discovery; scientists began to integrate and refine past theories to formulate new ideas about earth processes. This trend can be observed by examining the theories explaining continental movement, which are all built upon one another. The development of global climate mapping also depended on previous scientific thought.

A major change in the 20th century was the emergence of new technologies that allowed scientists to confirm their theories. Additionally, the way scientists viewed the environment also changed drastically in the 20th century. Previously, the purpose of most research was to further our understanding of the Earth and its processes. At the turn of the century, however, research began to focus on how humanity impacts the environment. Additionally, the rise of corporate business and consumer demand became a major motivation for new scientific discoveries.

In the 20th century, big questions about the history of the Earth remained unanswered, which continued to inspire new hypotheses. Nevertheless, the 20th century was still a time of rapid development in the study of Earth sciences.

Svante Arrhenius and the Greenhouse Effect

For a long time, people believed that the Earth had been cooling since its initial formation (Christianson, 1999). It was not until the late 19th century that mounting geological and fossil evidence prompted scientists across Europe to realize that the Earth's surface climate had undergone several drastic changes since its formation: Glaciers were observed to be able to transport sediments, and fossils of plants were found at places that could not accommodate plant growth today (Casper, 2010). However, it was not clear what factors could have such great impacts on the Earth's surface temperature. Joseph Fourier (1768-1830) and John Tyndall (1820-2893) were among the first to investigate this problem. However, Svante Arrhenius (1859-1927) was the first to define quantitatively the influence of greenhouse gases on the surface temperature of the Earth.

Figure 4.2 *Svante Arrhenius (1859-1927), taken in 1906. (Above)*

Theoretical Framework

Jean-Baptiste-Joseph Fourier, a French mathematician and physicist, was the first scientist to investigate the Earth's ability to retain heat from the sun, which directly dictates the surface temperature. He envisioned the atmosphere as a bell jar made of glass with black corks that could receive and conserve heat (Weart, 2003). Fourier attributed the heat receiving and conserving property to the water vapour in the atmosphere. His ideas were published in 1824, but this bell-jar hypothesis was thought to be too speculative and obscure at the time of publication (Weart, 2003).

Although Fourier's theory did not gain popularity in the scientific community, the investigation of the atmosphere's ability to affect Earth's surface temperature was not fully abandoned. John Tyndall, a British physicist, published a paper in 1861 demonstrating the high absorbency of water vapour, carbon dioxide and ozone. All three gases are present in the Earth's atmosphere; thus, he reasoned, a significant drop in the amount of carbon dioxide in the air would result in an ice age (Weart, 2003).

While Fourier and Tyndall's works set good theoretical background for the relationship between atmospheric composition and the Earth's climate, they lacked quantitative analysis that would allow for predictions on long-term climate changes. Svante Arrhenius, a Swedish physical chemist, was the first to complete this task.

Svante Arrhenius: Early Life

Svante August Arrhenius was born on February 19, 1859 in Vik, Sweden (Gribbin, 1990). His early works were focused on the electrolysis of chemicals in aqueous solutions, which eventually won him the Nobel Prize in Chemistry in 1903. Arrhenius did not turn his attention to geology and atmospheric chemistry until the late 19th century, but continued his work on this subject throughout the rest of his life (Christianson, 1999).

Arrhenius's interest in the Earth's climate was inspired by two other scientists: U.S. physicist Samuel Langley (1834-1906) and Swedish geologist Arvid Högbom (1857-1940). In 1881, Langley led an expedition upon Mount Whitney to collect data on the infrared radiation emitted by the moon. This data was later used by Arrhenius to calculate the effect of carbon dioxide on the Earth's climate. In 1893, Högbom delivered a lecture on variations in the atmospheric level of carbon dioxide during geological cycles (Christianson, 1999). This lecture greatly influenced Arrhenius, who quoted Högbom extensively in his work on climate changes (Arrhenius, 1896).

"On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground"

Basing his ideas on the works of Fourier and Tyndall and integrating results produced by Langley and Högbom, Arrhenius formulated his theory of the "greenhouse effect" in the late 1890s. His work was published in The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science in 1896 under the title *"On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground"*.

In the paper, Arrhenius presented detailed calculations of the increase in the Earth's surface temperature caused by changes in the atmospheric carbon dioxide and water vapour contents. Arrhenius used Langley's data regarding the infrared radiation from the Moon at different heights to calculate absorption coefficients of carbon dioxide and water vapour at different angles of incidence. Arrhenius was able to produce a table that expresses the heat-absorbing ability of the atmosphere as a function of water and carbon dioxide content. It was evident that the higher the concentration of either gas, the greater the absorptivity of the atmosphere. He concluded that "a geometric increase in carbon dioxide" would cause "an arithmetic increase in air temperature."(Arrhenius, 1896)

To expand on his work, Arrhenius applied his mathematical model to major geological changes. Arrhenius estimated that a decrease of 55-62% of the present carbon dioxide level would decrease the Earth's surface temperature by 4-5oC, which would throw the Earth back into another ice age. He also estimated that such a change would take more than 3000 years to complete (Arrhenius, 1896).

In the last section of his paper, Arrhenius explored the possibility of the Earth undergoing drastic variations in the carbon dioxide level within a short geological time period. He quoted extensively from Högbom's work on factors that could affect the carbon dioxide level in the atmosphere. Högbom explained that the main natural processes through which carbon dioxide is released into the atmosphere are volcanic eruptions, the combustion of carbonaceous meteorites as they enter the atmosphere and the formation of carbonates through weathering (Arrhenius, 1896). Both scientists recognized that the industrial use of coal could amount to a net increase in atmospheric carbon dioxide level. Nevertheless, this increase would be so small that it could be easily compensated by the formation of limestone through weathering (Arrhenius,1896).

TABLE III.—*The Transparency of a given Atmosphere for Heat from a body of 15° C.*

→ H_2O ↓ CO_2.	0·3.	0·5.	1·0.	1·5.	2·0.	3·0.	4·0.	6·0.	10·0.
1	*37·2*	*35·0*	*30·7*	*26·9*	*23·9*	*19·3*	*16·0*	*10·7*	*8·9*
1·2	*34·7*	32·7	28·6	*25·1*	22·2	17·8	14·7	9·7	8·0
1·5	*31·5*	29·6	25·9	*22·6*	19·9	*15·9*	13·0	8·4	6·9
2	*27·0*	*25·3*	*21·9*	*19·1*	16·7	13·1	10·5	6·6	*5·3*
2·5	*23·5*	22·0	19·0	16·6	14·4	*11·0*	8·7	5·3	4·2
3	*20·1*	18·8	16·3	*14·2*	12·3	9·3	*7·4*	4·2	*3·3*
4	*15·8*	14·7	12·7	10·8	9·3	*7·1*	5·6	3·1	2·0
6	*10·9*	10·2	*8·7*	*7·3*	6·3	4·8	3·7	*1·9*	*0·93*
10	*6·6*	6·1	5·2	4·3	3·5	*2·4*	1·8	1·0	*0·26*
20	*2·9*	2·5	2·2	*1·8*	1·5	*1·0*	0·75	0·39	*0·07*
40	*0·88*	0·81	0·67	*0·56*	0·46	*0·32*	0·24	*0·12*	*0·02*

Figure 4.3 *Table III in* "On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground" *by Svante Arrhenius. The entries are coefficients in Arrhenius's mathematical model that describes the atmosphere's ability to transmit infrared radiations. (Left)*

Reception

Arrhenius's model was not well received in the early 20th century. Among the many critics was Knut Ångström (1857-1910), a Swedish physicist, who demonstrated that passing infrared radiation through carbon dioxide could not change the amount of radiation (Weart, 2003). Additionally, Ångström found that water vapour and carbon dioxide absorb heat at the same wavelengths. Since water vapour is more abundant in the atmosphere, more carbon dioxide cannot block more radiation than water vapour already does (Weart, 2003). After Ångström published these results in 1900, many scientists accepted that Arrhenius's theory had been proven wrong. It was not until many years later that scientists realized that Ångström's experiment was flawed.

Figure 4.4 *Industrial burning of fossil fuels contributes to the increase of atmospheric carbon dioxide content. (Right)*

One of the flaws in Ångström's results was that instruments back in the early 20th century were not as advanced as they are today. Instruments could not measure the change in the absorption of infrared radiation accurately. A later result showed a 1% decrease in infrared absorption when the pressure of carbon dioxide was halved, which contradicts Ångström's result of a 0.4% decrease (Weart, 2003). Additionally, the absorption bands of carbon dioxide and water vapour are in fact not the same, though they are close (Weart, 2003). Lastly, Ångström argued that the lower atmosphere could be saturated easily, thus reducing the greenhouse effect. However, Earth's temperature is regulated by the thin upper layers where radiation can escape into the space. The balance between carbon dioxide contents of the lower and upper atmosphere is delicate and even a small increase could lead to drastic changes (Weart, 2003).

World in the Making

Although the evidence supporting Arrhenius's theory did not appear until the 1950s, he was not deterred by criticism from the scientific community. In 1906, he published a book titled "Världarnas utveckling" (Worlds in the Making), in which he expressed his view of how the greenhouse effect could affect the human race.

Arrhenius explained that the storing up of carbon dioxide comes chiefly from the formation of sedimentary strata, the weathering of rocks and photosynthesis of plants (Arrhenius, 1906). It was estimated at that time that it would take 10,000 years for carbon dioxide in the air to be consumed by these processes. He estimated that the carbon dioxide produced by the burning of coal would cover the loss of carbon dioxide by weathering by at least seven times (Arrhenius, 1906). Arrhenius believed this to be beneficial to the human race. He reasoned that increasing atmospheric carbon dioxide content would increase the intensity of vegetation. He envisioned the future Earth to be a place of enormous plant-growth, which would help to feed a growing human population (Arrhenius, 1906). This view is contradictory to the modern view on global warming because Arrhenius did not consider the negative implications associated with global warming, such as rising sea level. Nevertheless, his work set the fundamentals for future investigations in climate changes.

Legacy

Arrhenius can be considered a scientist ahead of his time. Being knowledgeable in both physics and chemistry, he was the first to quantify the effect of carbon dioxide on global climate and the first to make predictions of climate changes on the geological time scale. Additionally, he was one of the few scientists in the early 20th century to recognize that human activities could potentially affect global environment. Although his theoretical model received little attention at the time of publication, it opened up a field that would later have prominent socio-economical effects on the human race.

Ice Ages and Carbon Dioxide

The cause of ice ages remains poorly understood even today (Casper, 2010). The Milanković cycles are widely accepted as a model for calculating glacial and interglacial cycles. This model speculates that variations in solar radiation reaching the Earth caused by astronomical variables are the major cause of surface temperature fluctuations (Casper, 2010). However, while the timing of glacial and interglacial cycles appears to correlate with temperature changes predicted by the Milanković model, astronomical variables alone cannot generate the amount of temperature change required for these cycles. This suggests that there are other important factors contributing to changing temperature conditions on the Earth. One of these factors is the concentration of atmospheric carbon dioxide.

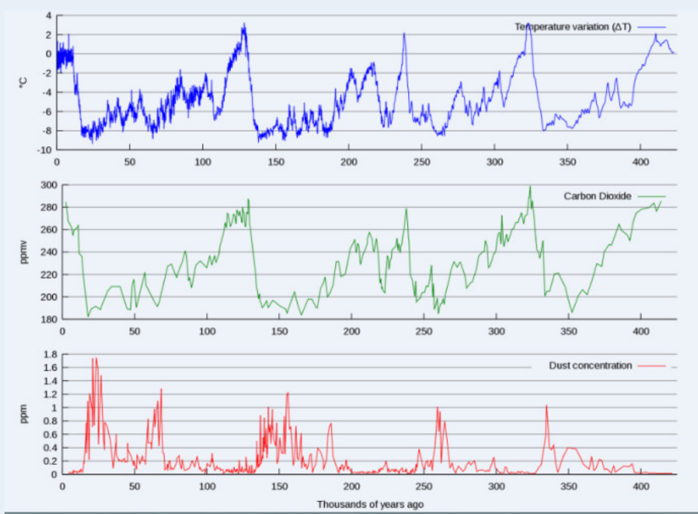


Figure 4.5 *Industrial burning of fossil fuels contribute to the increase of atmospheric carbon dioxide content. (Above)*

Scientists estimate the former carbon dioxide content of the atmosphere by studying the composition of air bubbles trapped in glacial ice (Weart, 2003). These data can be correlated to past glacial events to determine the relationship between carbon dioxide and surface temperature. It is evident that a reduction in atmospheric carbon dioxide content is correlative with geological periods of low temperature (Casper, 2010). However, it is not clear if a reduction of atmospheric carbon dioxide is a direct cause of a glacial episode. This is because the geological processes involved are intrinsically related: Low atmospheric carbon dioxide level can lead to cooling, but cooling also reduces the intensity of weathering processes, which in turn can lower atmospheric carbon dioxide levels (Casper, 2010). Studies of glacial air bubbles also show that there was a period of high atmospheric carbon dioxide content before the latest glacial episode, which began approximately 100,000 years ago (Weart, 2003).

One of the topics that modern scientists are most interested in is the effect of human activities on global warming. Human activities have led to a rapid increase in atmospheric carbon dioxide levels, which may contribute toward global climate change and may alter the timing of glacial and interglacial cycles (Weart, 2003). By studying and gaining a better knowledge of past glacial events in relation to atmospheric carbon dioxide, scientists will be able to better predict future geological events and make better decisions at critical times.

Wladimir Köppen and Climatology

Wladimir Köppen was a climatologist, paleoclimatologist, geologist, meteorologist and botanist during the late 19th to early 20th centuries. He was born on September 25, 1846 in Saint Petersburg, Russia to a family of German descent. After studying botany at the Universities of Saint Petersburg, Heidelberg and Leipzig, he worked for meteorological organizations in both Russia and Germany (Wegener-Köppen, 1955). After his meteorological work, Köppen focused on researching paleoclimatology and climatology. Throughout Köppen's life his major area of study was climatology and his most notable contribution to science was the Köppen climate classification system, which he worked on for over 50 years until his death on June 22, 1940 (Wegener-Köppen, 1955). He published over 500 papers and made significant contributions to several branches of science during the more than seventy years of his professional career (Hensen, 2002).

Figure 4.6 *Wladimir Köppen (above) in 1921. Photograph by Friedrich Becks.*

Education and Early Research

Wladimir Köppen's father was a geographer and historian appointed to the rank of Academician by Tsar Alexander II. His father's work inspired Köppen at a young age to apply his own intellect and interpretation to the varied environment of the Crimean Peninsula where he lived (Wegener-Köppen, 1955). While travelling from his family's home on the Crimean coast to secondary school in the inland city of Simferopol, Köppen observed the changes in flora throughout the Crimean Peninsula. Köppen later reflected that his travelling as a schoolboy awakened his interest in the relationship between climate, plant life and the geography of the land (Aguado and Bert, 2004).

Köppen studied botany at the University of Saint Petersburg from 1864 to 1867. During this time he had to travel from Saint Petersburg to the Crimean coast and Simferopol (Wegener-Köppen, 1955). During his frequent travels Köppen encountered the geographic transitions from coastal ranges, to extensive plains of the peninsular interior and mountain ranges along the Black Sea coast. The floral diversity along the route also showed the natural variation in the region with its suptropical shores and thick northern forests. The floral richness and climatic variety inspired Köppen to study the correlation between plant life and geological conditions.

Köppen transferred to the University of Heidelberg in 1867 and completed his doctoral dissertation there. His dissertation concerned the effects of temperature on plant growth. After defending his dissertation at the University of Leipzig Köppen received his degree in botany in 1870 (Wegener-Köppen, 1955).

Meteorological Work

After the Franco-Prussian War, Köppen was employed by the Russian meteorological service. He worked as an assistant at the Central Physical Observatory in Saint Petersburg from 1872 to 1875 (Wegener-Köppen, 1955). In 1875, he accepted a position at the German Naval Observatory (*Deutsche Seewarte*) based in Hamburg, Germany. He was appointed chief of the newly formed Division of Marine Meteorology, which specialised in weather telegraphy and forecasting, storm warning systems, and marine meteorology (Hensen, 2002). In 1879 Köppen was appointed meteorologist of the observatory (a new job title at the time) and given the task of establishing a weather forecasting service for north-western Germany and the adjacent seas (Allaby, 2002).

In 1884, Köppen produced a world map displaying temperature belts from the polar to tropical latitudes that divided areas by the number of months having temperatures above or below a particular mean value (Trewartha, 1968). This temperature map acted as a precursor to Köppen's more detailed climate classification map developed in his later life. He also co-authored the first cloud atlas in 1890 along with Hugo Hildebrandsson (1838-1925) and Georg von Neumayer (1826-1909) (Trewartha, 1968). Köppen retired from his position at the German Naval Observatory in 1919 and moved to Graz, Austria to work solely on fundamental research (Allaby, 2002).

Climatology and Paleoclimatology

While working at the German Naval Observatory Köppen formulated a mathematical system of climate classification. Published in 1900, Köppen's system assigned a mathematical value, formulated according to temperature and rainfall, for each of the five major climate types (Hensen, 2002). This development proved a major achievement in geographical climatology and many later systems introduced by other scientists have been based on Köppen's work. This forerunner to Köppen's climate classification map provided quantitative data for the division of climate types.

Köppen was also a pioneer in aerological research and experimented with early weather balloon technology in order to obtain data from the troposphere and stratosphere (the first two layers of the Earth's atmosphere) (Battan, 1985). He used data gathered regarding barometric pressure, temperature and humidity to associate plant growth with meteorological conditions in various regions.

In 1927, Köppen and Rudolph Geiger (a German climatologist) began writing a five-volume work, *Handbuch der Klimatologie* (*Handbook of Climatology*). The work was designed to include all information known at the time regarding climatology and became a very large undertaking for both men. The books were never completed but several parts were published by Geiger after Köppen's death (Allaby, 2002).

In addition to Köppen's studies of climate types, he worked extensively in the field of paleoclimatology. Köppen published a paper, along with his son-in-law Alfred Wegener, in 1924 called *Die Klimate der Geologischen* (*The Climates of the Geological Past*). The paper outlined past climate changes and provided support for the Milanković theory on ice ages. The ice age theory was not accepted until Köppen and Wegener presented evidence for the periodic changes in climate occurring during the history of the Earth (Allaby, 2002).

Köppen Climate Classification System

Early efforts to classify climates were determined using information on travel, regional knowledge and latitude. Ancient Greeks created the first recorded climate classification systems. Aristotle (384-322BC) classified Earth's climates using the categories of temperate, torrid, and frigid zones (Hensen, 2002).

Variation in plant life formed the basis for the first major advance in global climate classification after the Ancient Greeks. A number of scientists, many of whom were German, worked during the 1800s relating plants to weather and climate characteristics (Hensen, 2002). Alexander von Humboldt (1769-1859) is credited with devising one of the first modern classifications in 1817 based on isotherms. In 1842, Samuel Forry (1811-1844) and John Hind (1823-1895) were the first to combine multiple climatic characteristics into one classification system (Anderson and Strahler, 2008). Wladimir Köppen synthesized and expanded upon the work of the scientists before him to form his own mapping of global climate. It is one of the most highly regarded classification systems due to its broad scope and integration of climatic characteristics. The Köppen climate classification system was first published in 1918 and was modified several times in subsequent years by Köppen and others.

Figure 4.7 *Mountains on the coast of the Crimean Peninsula (above). Photograph by Kyrylo Kalugin.*

Köppen designed his system to capture the variability of vegetation around the globe. The spacing of observation stations used to obtain quantitative data was inadequate to delineate climate regions. To overcome this problem, he used the distribution of natural vegetation to indicate the boundaries between climatic regions (Battan, 1985). He defined the climates by mean annual precipitation and temperature, as well as precipitation during the driest months, using information gathered from weather stations throughout the world. Köppen combined the weather data with the vegetation boundaries he observed to draw a map of the global climatic regions (Anderson and Strahler, 2008). As a result, the classification system was devised using both descriptive and empirical information. Although the climatic types of the map were determined by temperature and precipitation, Köppen's system was inherently tied to natural vegetation.

Köppen's climate classification system used a multi-tiered system with the highest level of classification having five major climate types. These major climate types (designated by a capital letter) are: A, tropical; B, dry; C, mild mid-latitude (mesothermal); D, severe mid-latitude (microthermal); and E, polar (Aguado and Bert, 2004). These five categories demonstrate that climate is dependent on latitude, degree of continentality and location relative to major topographic features (Trewartha, 1968). The second tier of classification subdivides the five major climate types based upon the seasonal distribution of rainfall or the degree of cold or dryness. These smaller zones are represented by a second letter indicating: the season of least precipitation for A, C and D; the aridity of the zone for B; and the division of tundra and icecap for E (Aguado and Bert, 2004). Köppen designed the classification to include a third division indicating the severity of the seasons. Others after Köppen have added more tiers of classification to show more detail and divide similar climatic regions (Battan, 1985).

Köppen published the last version of his climate classification system in 1936, after he worked on it for more than half a century. Rudolf Geiger (with whom Köppen wrote *Handbook of Climatology*) continued to work on and make modifications to the classification system after Köppen's death in 1940 (Anderson and Strahler, 2008). Köppen himself admitted that he never thought his classification system was complete.

Köppen's Legacy

Although it still commonly appears in many textbooks, Köppen's classification system is not the only one, and many of the later systems take their cues from Köppen's. Two other notable scientists who created climate maps were Charles Thornthwaite (1899-1963) and Glenn Trewartha (1896-1984).

Köppen's system downplayed an important aspect of climate: the balance between precipitation and evapotranspiration.

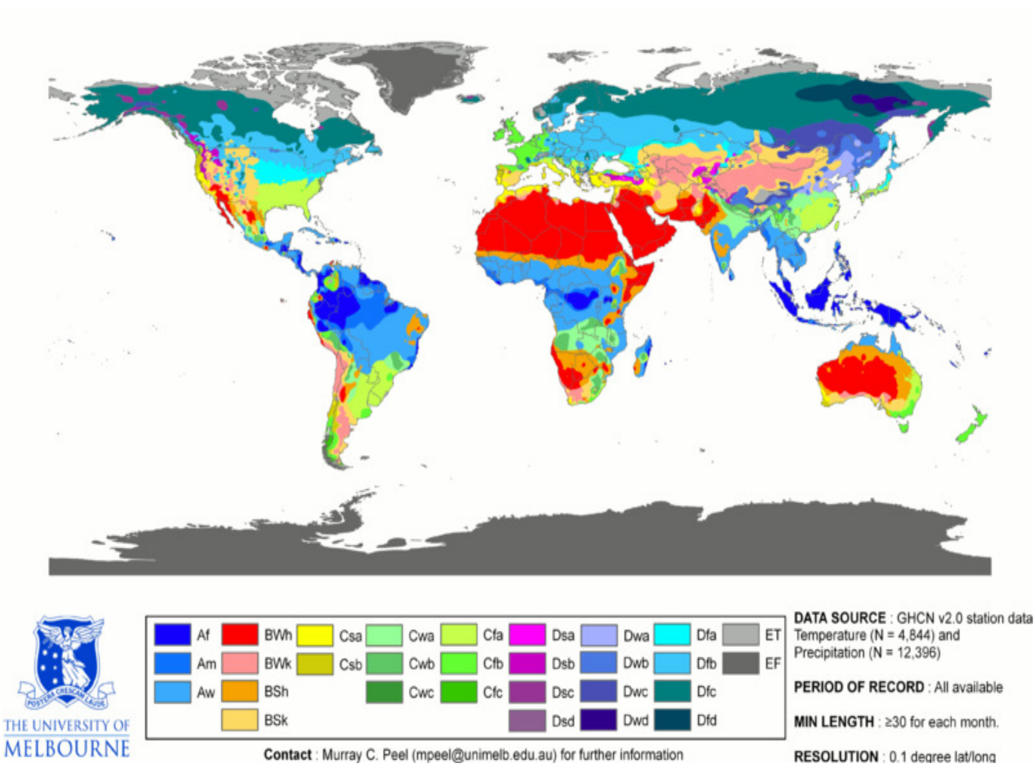


Figure 4.8 *Köppen-Geiger climate classification world map with letter code (right). Diagram by Peel, Finlayson and McMahon.*

Thornthwaite also used natural vegetation as an indicator of climate but divided climate zones according to the ratio of precipitation to evapotranspiration (Hensen, 2002). Nevertheless, a number of climatologists proposed that purely descriptive explainations were inadequate as they did not reference the underlying processes that differentiate climate zones. Trewartha and his colleagues created a climate classification system that had origins in Köppen's but substantially modified it on the basis of the dynamical aspects of the atmosphere. Trewartha also included such traits as solar radiation, wind and pressure systems, atmospheric moisture, air masses and fronts, and atmospheric disturbances (Trewartha, 1968).

Wladimir Köppen was a prolific scientist who worked on many of the founding principles of, what is now classified as, the atmospheric sciences. His broad range of knowledge and ongoing intellectual curiosity made him a valuable asset to the study of Earth processes.

Paleoclimatology

Paleoclimatology is the study of climate on the scale of the entirety of Earth history (Allaby, 2002). There are many different methods of determining the paleoclimates of an area. These methods measure proxy data (information used for indirect measurement of past climate characteristics) such as: sedimentary rock records, oceanic deposits, glacial ice cores, tree rings, coral reefs, remnant landforms, relic soils and past vegetation. Proxy data is sensitive to temperature and environmental changes, thus reflecting the state of past climates (Anderson and Strahler, 2008). Combining the different techniques, brought together by scientists of different disciplines, the information can paint a complete picture of changing paleoclimates.

Past Vegetation as an Indicator of Paleoclimates

Studying past vegetation can provide insight into climatic changes over short and long time scales. An example of using plant life to discern temperature changes over a short time scale (thousands of years) is measuring the thickness of annual tree rings. The growth of some species of trees in stressful environments is strongly affected by temperature. At high elevation, during warmer years trees grow more quickly and thus produce thicker growth rings, whereas in colder years trees grow more slowly and thus produce thinner growth rings. At lower elevations this relationship is switched (Anderson and Strahler, 2008). An equation can be written to correlate the changes in ring width with the temperate changes. Similarly, if trees grow in an area limited by the amount of annual rainfall the ring width can be used to calculate changes in rainfall (Aguado and Bert, 2004).

Figure 4.9 *Seed fern fossils from the Carboniferous found in North Carolina, USA (above). Photograph by Peter Schultz.*

Although climate is not the only important factor influencing the distribution of vegetation, it exerts a strong influence upon the distribution of vegetation communities. Reconstructing climates over a large time scale can be done by comparing the abundance of various vegetation types over time. This can be completed by counting the relative abundance of plant fossils in a specific area and sedimentary layer. Sedimentary layers represent time periods and depositional environments that, when combined with the biological record of the layers, provide insight into past climates (Allaby, 2002).

The invention of radiocarbon dating has also provided new ways of matching fossil remains with the time period they were from. For example, pollen and spores commonly preserved in lake beds and bogs can be extracted and radiocarbon dated (Aguado and Bert, 2004). Because many types of vegetation species are associated with particular climate types, deciphering the climatic history of an area can be completed by analyzing past vegetation.

Alfred Wegener and Harry Hess

When the 20th century began, geologists believed that the surface of the earth was isostatic; that is, able to move up and down vertically, but not sideways (Plummer et al., 2007). Although a good theory about the reason or mechanism for isostasy did not exist, it was a fundamentally accepted geological belief, and the thought that the continents move across the surface of the Earth was thought to be laughable (Bryson, 2003).

Frank Bursley Taylor (1860-1938), an American amateur geologist, did not accept the idea of isostasy, but instead realized the similarity in shape between the facing coastlines of South America and Africa (Bryson, 2003). In 1908, Taylor was the first to propose the idea that the continents had once moved around the surface of the earth, and that South America and Africa had once been joined together. He even presciently suggested that the crunching together of continents could have caused the formation of mountain chains (Bryson, 2003). Unfortunately, Taylor produced very little evidence, and made no attempt to explain how or why the continents moved, so his theory received little serious attention in North America. In Germany, the theory was further developed by Alfred Wegener (Bryson, 2003).

Alfred Wegener: Father of Continental Drift

Figure 4.11 *Alfred Wegener (1880-1930). Scientist, soldier, and adventurer. Picture (below) taken in Greenland on the 1913 Danish Greenland expedition.*

Born in 1880 in Berlin, Wegener studied the natural sciences with a focus in astronomy, receiving a Ph.D. in 1904 from the University of Berlin (Schwarzbach, 1986). He was adventurous, participating in five different expeditions over the course of his life, and leading two of them (Schwarzbach, 1986). Although Wegener was professionally a meteorologist at the University of Marburg in Germany, his research varied widely, and he published on many topics, including paleoclimates (with Wladmir Köppen, his father-in-law. See page 94) and thermodynamics (Schwarzbach, 1986). His most significant work was in geology, where he developed Taylor's idea into the theory known as continental drift.

Wegener's theory of continental drift expanded on Taylor's idea that the continents move in relation to each other across the Earth's surface. Wegener stated that the continents have gradually drifted apart over long periods of time, originally assembled together in a supercontinent known as Pangea (left). Over 225 million years ago, Pangea broke up and slowly drifted apart, forming new oceans as it separated (Plummer et al., 2007).

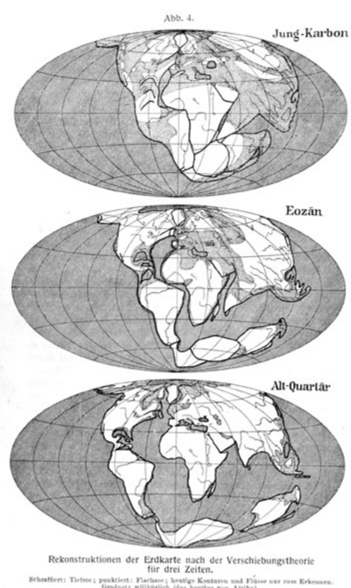


Figure 4.10 *Wegener's suggestion for Pangea and how the continents have moved (right), as it appeared in his book.*

Wegener's first clue for continental drift was the shape of the continents. Similar to pieces of a puzzle, the edges of the continents seemed to 'fit' together, not only in Africa and South America, where Taylor observed, but the entire east coast of North America 'fit' with the west coast of Europe. By bringing the continents back together, it was not difficult to reconstruct the general shape of Pangea (Plummer et al., 2007).

The fossil record also provided strong evidence for continental drift. Identical animal fossils could be found on continents that were separated by thousands of kilometres of ocean, far too wide to swim. Finding similar marsupial fossils in South America and Australia, identical gastropod fossils in Scandinavia and New England, and identical trilobite fossils in Europe and Newfoundland, it was impossible for Wegener to accept the principle of isostasy.

If continental drift was assumed to be true, and the continents were reassembled into Pangea, the regions where these similar fossils are found in proximity to each other (right), which very simply explained this curious distribution of fossils. In the same way identical rock formations were found on continents on both sides of vast oceans, in regions that match up in Pangea (Plummer et al., 2007).

Paleoclimatic evidence provided the final evidence for continental drift. Glacial deposits were found in South America, Africa, India, and Australia: areas that are now much too warm for glaciation to take place. Incidentally, the distribution of these glacial deposits matched up with the positions of the continents in Pangea, and suggests that those continents had drifted through an area of much colder climate (Plummer et al., 2007). Conversely, coal and other tropical fossil evidence was found in areas such as Spitsbergen, an island in the Arctic Ocean four hundred miles north of Norway, where no such life could exist today (Bryson, 2003). This strongly promoted both the idea that the continents moved, and that they had once been grouped together.

The existence of Pangea explained all of these phenomena in the geologic record in a much more natural and feasible way than the traditional isostatic understanding of the earth. Life, both plants and animals, had been able to be distributed across this large, single landmass, and did not have to be transported across vast oceans. After separating, the continents drifted, passing through different climactic zones, allowing for the unexpected paleoclimate deposits (Bryson, 2003).

Wegener assembled all of this theory in a book called *Die Entstehung der Kontinente und Ozeane* (The Origin of Continents and Oceans), which was published in 1912 (Bryson, 2003; Schwarzbach, 1986). Despite the onset of World War I, in which Wegener served as an officer and was wounded twice while fighting for Germany on the Western Front, the book was published in English in 1915, under the title *The Origin of Continents and Oceans*. Because of the war, Wegener's book received little notice until 1920, when he published a second revised and expanded edition (Bryson, 2003; Schwarzbach, 1986).

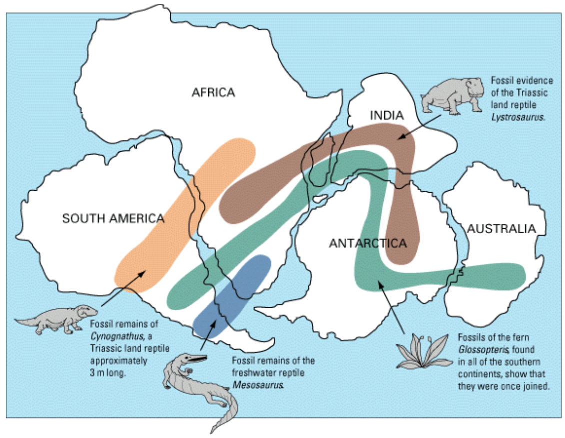


Figure 4.12 *The correlation of some plant and animal fossils in Pangea (left).*

When continental drift theory received attention, it was not well received by the scientific community. Geologists were displeased that a meteorologist with no geologic background could suggest a theory that undermined their fundamental understanding of the structure of the Earth, so tried desperately to disprove continental drift (Bryson, 2003). Unfortunately for Wegener, he could not explain the mechanism of how or why continental drift occurred. He guessed that continents simply ploughed through the denser oceanic crust, but this was quickly proved to be impossible. Geologists dismissed continental drift for its lack of mechanism (Plummer et al., 2007).

In 1930, Wegener died while leading an expedition in Greenland, long before any of his ideas on continental drift were accepted. Because of his poor explanation of the mechanism, continental drift took nearly 50 years before it was properly understood, and even then met with strong resistance from many geologists (Schwarzbach, 1986).

Arthur Holmes (1890-1965), a British geologist who was famous for his pioneering estimates of the age of the earth, was a strong supporter of continental drift. In 1944, he published an influential textbook, *Principles of Physical Geology*, which presented Wegener's theory of continental drift with his own mechanism added. Holmes proposed that radioactive heat from the core of the earth produced convection currents within the Earth, and it was these convection currents that moved the continents around. Although his mechanism is accepted as true today, it was initially widely criticized by the geologic community. Without visible evidence of convection on the surface of the Earth, geologists continued to refuse continental drift for years (Bryson, 2003).

Figure 4.13 *Harry Hammond Hess (1906-1969). Picture (above) taken aboard his ship, the USS* Cape Johnson*, during World War II.*

Harry Hess

Marine science developed swiftly and dramatically during the 1950s. Previously, technological limitations had prevented any thorough analysis of ocean systems. During World War II, advances in naval warfare led to post-war scientific advances. Particularly, the use and development of sonar and of submersibles allowed for detailed mapping and cataloguing of deep marine environments (Bryson, 2003).

Sonar is the general term for imaging techniques that use sound waves to detect the size and proximity of other objects. First developed in World War II, sonar works by emitting a sound wave and measuring the sound that reflects back at the source. The longer time the sound takes to return to the source, the farther away the object is that the sound was reflected off of. In much the same way that bats use echolocation, warships used sonar to locate enemy vessels, especially submarines. Sonar was also used by a depth sounding tool called a fathometer. Fathometers were designed to measure the depth of shallow waters, and were particularly useful for manoeuvres near shore (Bryson, 2003).

Harry Hess was an American mineralogist at Princeton University. A Rear Admiral in World War II, Hess captained the USS *Cape Johnson*, an attack transport ship equipped with a brand new fathometer. Hess realized that the fathometer could be used not only for navigation in shallow waters, but also could be used to map the topography of the sea floor. Hess used his fathometer at all times, even while in battle, and was surprised by his observations (Bryson, 2003).

If the ocean floors were ancient, then they should have been covered by thick layers of fine-grained sediments, an accumulation of millennia of deposition. However, Hess found the sea floor to be heavily fractured with canyons and trenches, formations typical to active volcanism, which implied that the sea floor was in fact much younger than anticipated (Bryson, 2003).

After the war, oceanographers took systematic surveys of the ocean floor to create a topographic map, much like the one below. These surveys revealed an immense underwater network of branched mountain chains, 80, 000 kilometres long in total, spanning all the way from Iceland around the south coast of Africa to Alaska. These mountain chains soon became known as mid-ocean ridges (Bryson, 2003).

In 1962, Hess proposed that these mid-ocean ridges were actually the site of sea floor spreading. This meant that new ocean crust was being formed at the mid-ocean ridges, and then was being pushed away to either side of the ridge as new sea floor was formed and took its place. This theory was supported by core samples of the ocean floor that revealed that crust closer to the ridges was much younger than the crust farther away (Plummer et al., 2007). It also explained how the continents had moved: not ploughing through the sea floor, but rather moving with the sea floor. Even with this copious evidence, continental drift was still considered erroneous, and was ignored. It would take an addition of paleomagnetic evidence, plus a meeting of the Royal Society in 1964, before geologists could accept that the continents move, and would develop the theory of plate tectonics (Bryson, 2003).

Figure 4.14 *An elevation map of the sea floor (below). The mid-ocean ridges can be seen in light blue, extending down the middle of the Atlantic Ocean and around Africa to the Pacific Ocean.*

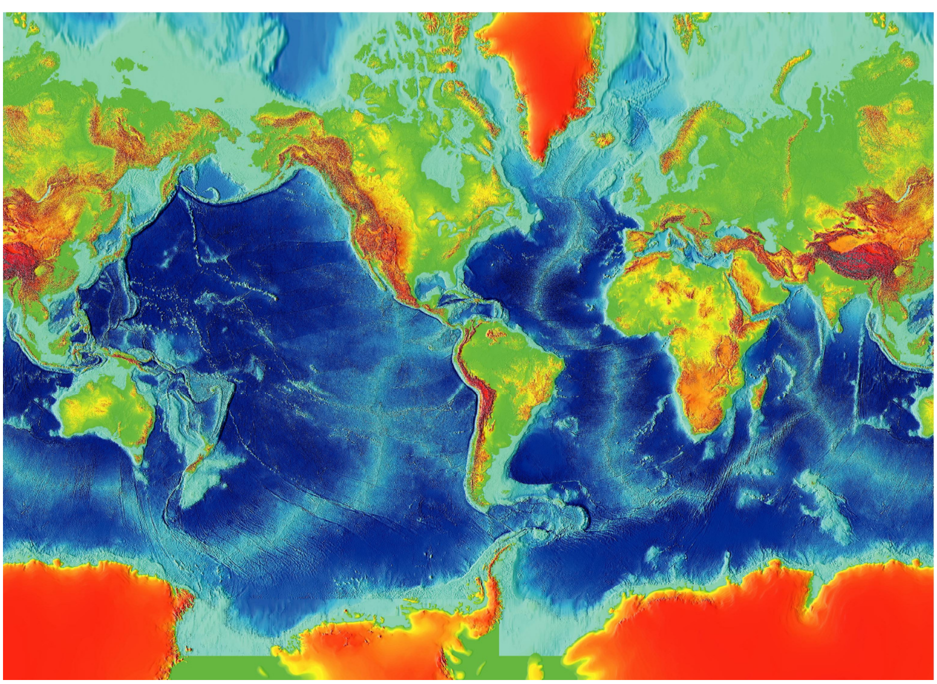


Plate Tectonics

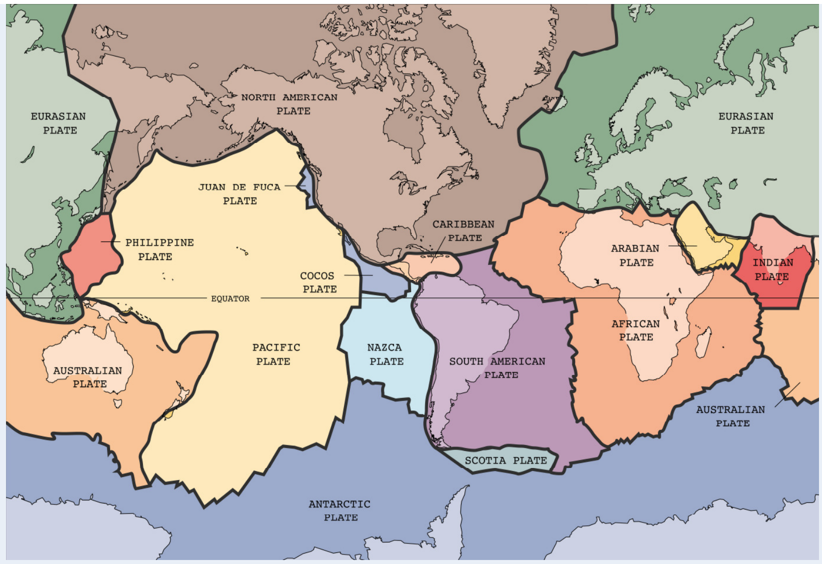


Figure 4.15 *A map of the tectonic plates and their plate boundaries (above).*

The Earth's lithosphere is broken up into regions of crust called plates: large, mobile slabs of rocks. These plate vary in size, and move relative to one another. Earth's lithosphere consists of seven major plates and 27 minor plates, which may be composed entirely of sea floor, or may be made up of both continental and oceanic crust (Plummer et al., 2007). Oceanic crust is heavier and thinner than the less dense, thicker continental crust. The plates move on top of an asthenosphere that is plastic and deformable, and are driven by convection currents in the mantle. The speed at which a plate moves can vary, but is in the range of 1 to 10 cm per year (Plummer et al., 2007). The movement is caused when new crust is formed at the mid-ocean ridges, pushing the older crust outward and forcing the plates to move. This motion causes interactions at the tectonic plate boundaries that are classified into one of three categories: divergent, convergent, and transform plate margins.

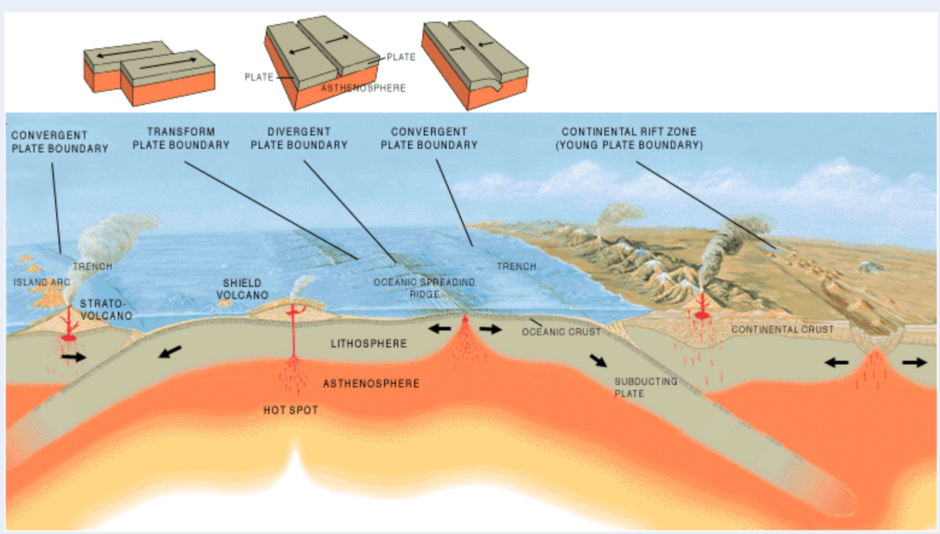
Divergent plate boundaries are regions where two plates are moving away from each other. The mid-ocean ridges are examples of divergent margins. New crust is being formed at divergent margins, pushing apart the plates. Divergent margins usually occur above the hot, rising parts of convection currents in the mantle, and produce basaltic ocean crust (Plummer et al., 2007).

Convergent plate boundaries are regions where two plates are moving towards each other. The characteristics of the plate boundary depend on the type of plates that converge. If two oceanic plates converge, the older, denser plate will subduct, creating a deep trench. If an oceanic and a continental plate converge, the dense oceanic plate subducts, creating an oceanic trench and an accretionaty wedge. If two continental plates converge, neither plate subducts, but both crumple and form mountain ranges. Convergent plate margins usually are associated with earthquakes and volcanic activity (Plummer et al., 2007).

Finally, transform plate margins are regions where two plates slide horizontally past each other. Often, transform faults occur as a series of parallel faults. Shallow-focus earthquakes are common along transform faults because friction between the plates causes sudden releases of energy (Plummer et al., 2007).

Plate tectonic theory comprehensively explains both continental drift and sea floor spreading, and is the universally accepted theory for the movement of the Earth's crust. Plate tectonics also provide us with insight into how the Earth has changed through time, a crucial consideration when studying the History of the Earth.

Figure 4.16 *Examples of convergent, divergent, and transform plate boundaries, and some common associated landforms (below).*



The Advancement of Science and Technology during World Wars I and II

During the Second World War a rich store of scientific wonders was opened to the world and, at this point in history, science became a vital influence on political and social relations. Atomic bombs, radar, supersonic aircraft, and ballistic missiles offer only a glimpse at the relationship between scientific advancements and military technology. These are some of the more obvious developments, but it is important to note that other modern innovations such as modern chemical pesticides, herbicides and antibiotics were all developed during times of war too (Zuckerman, 1966). So it seems that there is some truth in the conclusion that war stimulates and accelerates the growth of scientific knowledge.

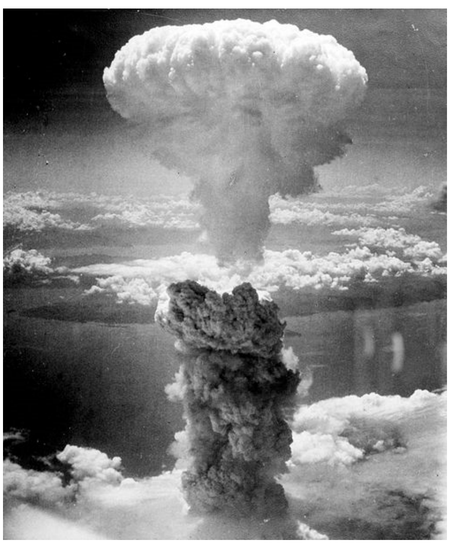


Figure 4.17 *Atomic bombing of Nagasaki on August 9, 1945. A lot of research was put into developing nuclear weapons during World War II, especially due to the Manhattan Project (above).*

Not only did more developments in science and technology occur during the First and Second World Wars, developments in the study of geology and the Earth also occurred. As time progressed, the military became more aware of how to use their surroundings to aid them in battle. An example of this is related to the atomic bomb. In 1939, during World War II, uranium-235 was not easy to extract. As a result, a huge industrial plant had to be constructed in Tennessee where effective extraction could be completed (Hughes, 2002). This required scientific knowledge of the environmental impacts of building such a plant. Also coming into existence during these wars was the idea of military geologists. As this idea became popular and the importance of their role became recognized, the significance of geology in war became more apparent (Zuckerman, 1966).

Ever since the inception of war, geology has shaped the art of warfare. Even early humans used caves as protection against the elements and other dangers (Terman, 1998). The Greeks and Trojans fought the Trojan War at a site where geology dictated the importance of a hilltop dominating a coastal plain (Terman, 1998). However geology itself did not become an independent science until the end of the 18th century and military geology did not fully develop until the First and Second World Wars (Guth, 1998). Specifically during World War I, an understanding of subsurface geology, including hydrogeology, was required because of the importance of locating and utilizing underground water supplies (Doyle & Bennett, 1997). During World War II, geologic principles were applied to construct massive underground installations and also became more important in the planning and field operations for the army, navy and air force. As a result of the increasing need for geologists in the military and the growing recognition for the subject, geology became more respected during the twentieth century as a science and more efforts were put into the development of geological knowledge (Guth, 1998).

World War I

The Western Front, which extended from the English Channel to the Swiss Border, was one of the most important geographical locations in terms of battles of the First World War during 1914 to 1918. Of this area, the Somme-Flanders lowland was of great strategic importance (Doyle & Bennett, 1997). The terrain played an important part in determining the nature and outcome of many of the battles that took place throughout the course of the war. The Somme region is a rolling chalk upland and the Flanders region is a clay-plain with occasional sand units. The occurrence of low hills and ridges provided the landscape for many of the most famous battles on the Western Front as each side tried to gain the advantage of high ground.

The military assessment of terrain has two aspects: strategic and tactical (Doyle & Bennett, 1997). Strategic assessment deals with the disposition of large-scale geographic features in the planning of military operations. Tactical assessment deals with detailed aspects of terrain and their influence on the outcome of battles. There were four different aspects to the tactical assessment that were important for this region of the Western Front. They were: the topography, specifically in providing positions for observation and concealment; ground suitability for engineering defensive works and mining operations; the availability of resources, especially water and aggregates for construction; and weather conditions and the impact they had on the landscape (Doyle & Bennett, 1997). It was of the utmost importance to control high ground during the war because the characteristics of the ground controlled the ability of troops to move and attack their opponents and high ground provided a better vantage point to do so.

Figure 4.18 *Seal of the United States Geological Survey. In 1942 the USGS created the Military Geological Unit, which studied terrain in order to aid the military during World War II (left).*

During World War I, the original use of geologists on the battlefield was to locate water supplies. This later changed to encompass many more duties, including studying the terrain, making predictions about stream and river heights, and locating sources of construction materials. Despite these growing responsibilities, by the end of the war most geologists felt that they had not contributed enough to the war effort and so it forced professional geologists to take a deeper interest in education and to ensure that others knew the importance of geology (Doyle & Bennett, 1997).

World War II

On June 24, 1942 the Military Geology Unit of the U.S. Geological Survey was formed after the U.S. Army Corps of Engineers requested them to prepare studies of the terrain (Kaye, 1957, Terman, 1998). The unit consisted of 114 professionals, including 88 geologists, 11 soil scientists, and 15 other specialists. The unit contributed much to war time efforts and produced a total of 313 studies. The principal effort of the unit was the preparation of the terrain portfolios, which were titled *Strategic Engineering Studies*. All the portfolios focused on providing information regarding terrain appreciation, construction materials, and water resources. In 1944 and 1945, consultants from the unit were sent overseas and each team of consultants produced terrain reports, mostly with the aid of aerial photography, and consulted with engineer units and tactical officers in the field. The unit played a vital role during the war in allowing the military to utilize their surroundings to their advantage (Terman, 1998).

Another example of how geologists were used during World War II is the participation of British geologists in “Operation Overlord” and the battle in Normandy, France in 1944. “Operation Overlord” was the Allied invasion of northwest France. The British geologists participated in the planning of the operation for more than a year (Rose & Pareyn, 1998). They prepared beachhead maps prior to the invasion with the aid of published topographic and geologic maps as well as aerial photographs. They identified characteristic properties of the beaches and cliffs, the distribution of surface sediments, and other factors likely to affect cross-beach mobility. These geologists were also responsible for assessing the impacts of aerial bombing, soil conditions affecting vehicular movement, ground conditions for river crossings, and the nature of the sea floor beneath the English Channel. Once again geology, and geologists themselves, were playing an important role in strategizing for the military (Rose & Pareyn, 1998).

Manhattan Project

One of the most impressive and consequential technological developments during a period of war was the development of nuclear weapons. During World War II it became the mission of British and American scientists to develop such a technology through a project known as the Manhattan Project (Hughes, 2002). From 1943 to 1945 the Manhattan Project brought together thousands of scientists, engineers, and technicians to work on the design and production of atomic bombs. The Manhattan Project was a turning point in 20th century science. Funding for military technical and scientific developments skyrocketed. Huge effort was put into being the first country to develop nuclear weaponry and combat the possible threat that Hitler had acquired nuclear weapons. Large amounts of attention were given to physicists, chemists, and metallurgists.

The chemists and metallurgists initially focused on uranium, devising procedures for: producing, purifying and handling; exploring its compound properties for possible weapon use; determining sample densities; and so on (Hughes, 2002). The properties of plutonium were also explored by these scientists. They developed new ways of purifying, handling, and characterizing plutonium.

On July 16, 1945 at 5:30 AM the first nuclear bomb was exploded and so the world entered the nuclear age (Hughes, 2002). Now that the results of the project had been seen, the project was no longer used to simply combat the threat of Nazi nuclear weapons; it would be used to bomb Japan. Bombs were dropped over Hiroshima and Nagasaki, effectively ending the war with Japan. After Hiroshima, a White House press release later that day described the bombing as "the greatest achievement of organized science in history" (Hughes, 2002).

The Manhattan Project undoubtedly left a huge impact on the world and also science. After the war was over, the connections created during the war amongst different scientists and military personal proved crucial to the development of science. Universities were given money by the military to study such topics as aeronautical and nuclear engineering, underwater acoustics, optics, space science, and electronics. Science rose to the forefront of society (Hughes, 2002).

Relation to Earth History

Much scientific advancement came about during the time period of 1914-1945 in areas surrounding Earth science. There were developments in remote sensing and aerial photography, which are used to obtain images of the Earth's surface. Another large development dealt with submarine usage during the wars. Submarines first made a significant impact during the First World War, particularly in the case of the German U-boats (Kaye, 1957). From there on submarine technology developed further and submarines were ultimately used in the mapping of mid-ocean ridges, which provided some of the first information about plate tectonics. The concept of plate tectonics was an important discovery in the

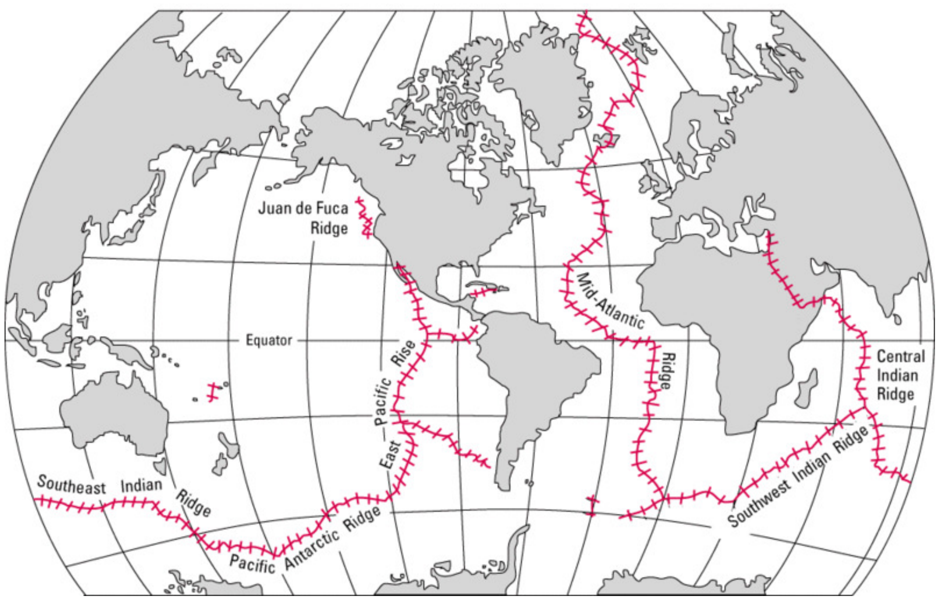


Figure 4.19 *Map of the world distribution of mid-ocean ridges. Developments in submarine technology made mapping the ridges possible (right).*

field of geology and resulted in a paradigm shift in geological thinking. Thus, not only were World War I and World War II affected by geology, but the wars brought about many new ideas and technologies surrounding Earth science and also new attitudes towards geologist and their importance in both war and the understanding of the Earth and how it formed.

Remote Sensing and Aerial Photography

Remote sensing involves observing and measuring objects on the Earth's surface from a large distance without coming into direct contact (Smith & Pain, 2009). The process involves taking observations using various forms of sensors mounted on platforms and recording the observations with a suitable medium (Ramachandran et al., 1998). Aerial photography is a type of remote sensing as it involves taking pictures of objects on the Earth's surface from the lower layers of the atmosphere (Rao, 2002). Increasingly, scientists are using different types of remote sensing to obtain information about the Earth's terrestrial surface, oceans and atmosphere. The data can be used to study how geographical features of the Earth have changed and evolved over time, as well as the geomorphology of the planet. Remote sensing is also now being used to gain information about other planets in the solar system, such as developing topographic maps of Venus (Smith & Pain, 2009).

Applications of Remote Sensing

Remote sensing can be used to study the ways in which the Earth's geology and structures have changed through time. In order to study geomorphology an understanding of how various processes lead to different land formations is essential. Remote sensing provides information pertaining to the ground materials, landforms, the ecology, and the resources contained in an area, as well as the impact of human activities on the landscape. To study how the landscape changes over time, repeated images of the desired area are taken at different times, which allow scientists to see what changes occur as time progresses (Rao, 2002).

One example of how remote sensing is being used today is a study being run by NASA's Jet Propulsion Laboratory. The study is examining ocean surface topography in order to develop an understanding of changes in ocean currents and heat storage over time (Jet Propulsion Laboratory, 2001). Continuous data from satellites over the past three decades have given scientists an insight into global climate change. Models for tides in open oceans have been built using this information and have lead to the discovery of the role tides play in deep ocean mixing, a process that is important in determining the patterns of large-scale ocean circulation (Jet Propulsion Laboratory, 2001). All of this information can be used as an analogue with which to reconstruct events that have occurred in the past. This provides scientists with a better understanding of the history of the Earth's oceans.

There are many different ways in which remote sensing can be used to collect data to help understand the history of the Earth and the processes involved in forming the landscape seen today. Remote sensing is an increasingly utilized tool and has a wide range of applications that help to give people a better understanding of the Earth and nearby planets.

Figure 4.20 *"Blue Marble" image of the Earth. This image was a result of a single remote sensing device – NASA's Moderate Resolution Imaging Spectroradiometer. This device is a tool used to observe terrestrial, oceanic, and atmospheric features of the Earth (left).*

Alfred Treibs and the Birth of Organic Geochemistry

Today, organic geochemistry focuses on the study of the origin, composition, and distribution of organic substances in rocks (Durand, 2003). This field is a unique blend of geology and organic chemistry that emerged recently in the beginning of the 20th century. The evolution of this field is a direct result of the expansion of petroleum exploration and research that occurred during the same time period (Figure 4.51). As the economic significance of petroleum steadily increased, so did research into the origins of petroleum and the mechanisms of its formation. Several scientists contributed extensively to this area of research, particularly Alfred E. Treibs, a German scientist who, in 1936, provided strong evidence for the theory that petroleum was organic in origin. Not only did Treibs' discovery elucidate the origins of petroleum, but it also provided the background necessary for future discoveries in this field.

Figure 4.21 *Organic geochemistry is a science born of economic desire, specifically the industrial expansion of petroleum exploration, in the early 20th century. This oil well (above) symbolizes the powerful influence of industry on scientific research during this time.*

The Inorganic Theories

Prior to the end of the 19th century, very little research had been done on the origins of petroleum. Since petroleum was not used extensively at this time, it lacked economic importance and was not the subject of any significant scientific research. As a result, the prominent belief of the day – that petroleum was inorganic in origin – remained well-established and accepted. This belief was rationalized by several eminent scientists, as they believed that no life could exist at the depths where petroleum was formed (Durand, 2003).

Although many scientists agreed that petroleum was inorganic in origin, there was disagreement on the mechanism by which it was formed. For example, some believed that petroleum was formed through the reaction of water with iron and aluminum carbides that were believed to be abundant in the Earth's crust (Durand, 2003). Others believed that petroleum was formed by bacterial action on organic deposits (Durand, 2003). The latter theory was one of the few theories at the time that considered the possibility of an organic link to petroleum formation.

In the early 20th century, many more scientists began hypothesizing that petroleum did indeed have an organic origin. At first, this idea was not well-received, owing to the strength and pervasiveness of the inorganic theories. However, as more evidence was collected, it became increasingly clear that petroleum originated from organic sources. The most significant piece of evidence supporting this theory was published in 1936 by Alfred E. Treibs, who is considered by many to be the father of organic geochemistry (Durand, 2003).

Oil Shales and Organics

Alfred E. Treibs (1899-1983) was born in Idar-Oberstein, Germany. He studied chemistry in Aachen and Munich and later received his PhD from Technical University in Munich. His graduate supervisor was Hans Fischer (1881-1945), an organic chemist who won a Nobel Prize in 1930 for his study of hemin and chlorophyll, two biological pigments whose structures contain porphyrin rings (Kvenvolden, 2006). Naturally, Treibs was involved with Fischer's research and eventually applied Fischer's findings to his own work.

Treibs was one of the first scientists of his time to apply the concepts of organic chemistry to the seemingly unrelated field of geology. He had knowledge of the advances made by German geologists in the 1930s, specifically the discoveries of organic materials in various sediment, coal, and fossil deposits (Treibs, 1936). For instance, Treibs was aware that green pigments similar to chlorophyll had been discovered in young clay sediments from the Black Sea; furthermore, he knew that the remains of green leaves and crocodile feces had been found in lignite coal deposits from the Geisel valley in Germany (Treibs, 1936).

In 1933, Treibs added to this list of discoveries by identifying an organic anthraquinone pigment known today as Graebite in blocks of shale from a fault zone at Olsnitz, Germany (Treibs, 1936; Mineralogical Society of America, 1934). Since shale is often a source rock for bituminous materials such as oil (Plummer et al., 2007), this discovery agrees with the theory that petroleum is organic in origin. This particular finding, along with his knowledge of similar discoveries, motivated Treibs to search for similar organic substances in oil shales.

Porphyrins and Petroleum

Treibs then expanded his search for organic materials by choosing to study a bituminous oil shale from the Carvendel Mountains of the upper Isar River, which flows through parts of Germany. This shale is part of the main dolomite formation of the upper Alpine Triassic strata (Treibs, 1936). Treibs studied this sample by a method known as extraction. In a geologic extraction, the desired components of the sample are removed by chemical treatment and studied individually (Treibs, 1936). In this case, Treibs' goal was to extract and identify any organic compounds that were present in the sample. He accomplished this by treating the sample with hot glacial acetic acid followed by bromoacetic acid to dissolve and isolate any organic compounds present. Treibs then attempted to identify the compounds present in the extract primarily through analysis of their absorption spectra and comparison to the spectra of known substances (Treibs, 1936).

Upon further analysis, Treibs determined that the extract consisted of two main components: a majority was composed of a basic etioporphyrin (a violet-coloured pigment), while a small amount was composed of an acidic porphyrin (Treibs, 1936). Treibs studied both substances using absorption spectroscopy. First, he determined that the basic etioporphyrin had a similar absorption spectra to a substance known at the time as deoxophylloerythrin. This was an extremely significant discovery, as deoxophylloerythrin is a derivative of chlorophyll, a photosynthetic pigment found in almost all plants and cyanobacteria. Second, he determined that the acidic porphyrin had very similar absorbance spectra to a group of compounds known at the time as mesoporphyrins. Mesoporphyrins are another name for a series of blood pigments that includes hemin, and hemin is a derivative of the main component of hemoglobin, an oxygen-carrying protein found in the red blood cells of almost all vertebrates (Treibs, 1936).

Treibs repeated these experiments for numerous other bituminous shales and other petroleum-containing materials from the Tertiary. He found that these chlorophyll and hemin derivatives were present in all of the samples he analyzed, although the concentrations varied between materials. For example, bituminous coal usually had lower concentrations of these substances than oil shales (Treibs, 1936). Nevertheless, Treibs undeniably linked petroleum, in the form of bituminous deposits, with organic molecules, especially chlorophyll and hemin. This is considered by many to be the first undeniable piece of evidence supporting the theory that petroleum is organic in origin (Durand, 2003).

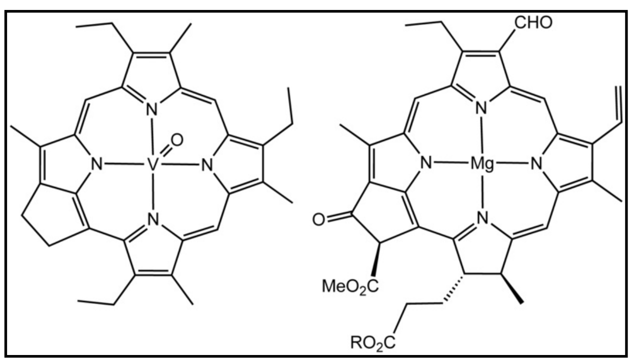


Figure 4.22 *Structure of the vanadyl chlorophyll derivative isolated by Treibs (far left); simplified structure of chlorophyll a (left). Note the close similarity.*

After further analysis involving spectroscopy and synthesis reactions, Treibs was able to identify the structure of the chlorophyll and hemin derivatives he discovered. The chlorophyll derivative was a vanadium complex – the magnesium ion normally found in chlorophyll had been replaced by a vanadyl ion (VO^{2+}) (Figure 4.52) – and the hemin derivative was a nickel complex – the iron ion normally found in hemin had been replaced by a nickel ion (Treibs, 1936). This finding was quite intriguing, as these molecules were both similar, yet distinctly different from chlorophyll and hemin.

Next, Treibs began researching the mechanism by which these transformations occurred. By comparing the initial and final molecules, he was able to devise a mechanism for the transformation reactions. He then attempted to recreate the transformations in the laboratory. For both chlorophyll and hemin, Treibs encountered steps that required strong reducing agents and very high temperatures, above 250°C. However, he knew that the samples he was analyzing were not exposed to such conditions in nature. He reasoned that some other factor, present in nature but absent in the laboratory, was involved in these transformations. Following this logic, Treibs eventually proposed that certain steps in the transformation process were biochemically-mediated by organisms present in the environment (Treibs, 1936). This theory was supported by the subsequent discovery of the chlorophyll intermediates to these steps in various deposits (Figure 4.53), including the Geisel valley coal deposits (Treibs, 1936).

Figure 4.23 *Treibs analysed numerous oil shale formations over the course of his research. The Ordovician kukersite oil shale in northern Estonia (right) is similar to the samples Treibs studied, although he focused mainly on samples from the Triassic for his 1936 article.*

Based on all of his findings, Treibs was able to draw two striking conclusions regarding the origin and formation of petroleum. First, based on the biological mechanism of chlorophyll degradation, it is possible that biological processes assist in the formation of petroleum. Second, since porphyrins are found in most samples containing petroleum, chlorophyll must have been present in the source rock from which this petroleum originated (Treibs, 1936). These revolutionary ideas confirmed that petroleum forms because of organic, biological processes and not inorganic mechanisms. His work on porphyrins and petroleum is now internationally recognized, and it marks the birth of organic geochemistry – the science that studies these organic components in rocks, sediments, and other geologic deposits.

Expansion and Improvement

In the 30 years after Treibs' influential work, the technology available for chemical analyses improved substantially. Advances in analytical instruments such as paper chromatography, mass spectrometry, and gas chromatography allowed molecules to be separated and identified much more easily and effectively (Durand, 2003). As a result, thousands of molecules in addition to the chlorophyll and hemin derivatives Treibs discovered have been identified in various sediments (Durand, 2003). With this mounting evidence, it became clear that petroleum and many other components of sediments are biological in origin.

The history of geochemistry was shaped primarily by the economic value of petroleum and the demand for petroleum exploration. As a result, industry and economy – not academia and the pursuit of knowledge for its own sake – controlled the petroleum research being formed (Durand, 2003). This aspect of science history subtly emphasizes the value of an integrated approach to scientific research. Although driven by economic demand, industry-led research is, by nature, problem-based and thus much more interdisciplinary than most specialist-based university research groups (Durand, 2003). As scientific thought continues to advance, it is essential to merge different disciplines to tackle new problems, in much the same way as Alfred Treibs and other early organic geochemists did. Even in the 20th century, there was evidence of integrated science, and this way of thinking is still highly relevant in science today.

Petroleum and Past Environments

The term petroleum is used to describe a broad variety of hydrocarbon-rich liquids and gases that originated from organic material and evolved over time through biological and thermal processes (Killops and Killops, 1993). Petroleum formation is dependent upon several environmental and spatial conditions, and the nature of these conditions influence the type and behaviour of petroleum that is formed. Thus, by analyzing a present-day petroleum reserve, we can infer what environments the deposit experienced in the past (Plummer et al., 2007).

The first requirement for petroleum formation is a relatively large source of organic material. This is often derived from primary producers such as terrestrial plants or aquatic phytoplankton (Killops and Killops, 1993). In addition, the environment must facilitate the deposition and preservation of this organic material. Thus, low-energy, marine depositional environments are generally necessary for petroleum to form (Killops and Killops, 1993).

As these organic materials are deposited, several processes can alter their composition. For example, microorganisms can degrade amino acids and carbohydrates present in the sediment and recycle them into the environment (Killops and Killops, 1993). However, as the sediments become increasingly compacted and lithified, these biological processes tend to subside and are replaced by thermally-mediated changes. Eventually, the sediments are converted into kerogen, the polymer precursor to petroleum (Killops and Killops, 1993).

During compaction and burial, exposure to different temperatures for different periods of time will convert kerogen into different petroleum products, such as crude oil and natural gas (Killops and Killops, 1993). Thus, the type of petroleum present in a deposit is related to the environmental conditions the sediment and source rock experienced during burial and compaction.

However, when correlating present-day deposits to past environments, migration of petroleum from its source must also be considered. Petroleum can form in a source rock in one location and then migrate through sufficiently porous and permeable rock to a new location. If the petroleum encounters a structural or stratigraphic feature, such as an anticline or a sand bar, that traps it in the rock, then a new petroleum reservoir will form (Plummer et al., 2007).

Figure 4.24 *An anticline (left) is an example of a structural feature that can trap oil to form a reservoir.*

By comparing the stratigraphy of an area – rock types, layers, and boundaries – and the type of petroleum deposited, it is possible to correlate a sedimentary unit containing petroleum deposits with the environmental conditions it experienced during its formation, deposition, and migration. Another very useful piece of information that can help with this correlation is the nature of the organic molecules present in the sediment. Organic molecules can act as biomarkers that can be used to relate different petroleum deposits to their source rocks. If two different deposits contain the same biomarkers, then it is likely that the deposits originated from the same source (Hunt, Philp and Kvenvolden, 2002). The biomarkers present in a sample can be analyzed and identified using techniques such as gas chromatography and mass spectrometry (Durand, 2003). Thus, biomarkers are a powerful tool in correlating present-day deposits to past environments.

As with all forms of history, learning about the past is essential to our situation in the present. Learning about past geologic environments has numerous applications, ranging from petroleum exploration to ecological preservation. An understanding of earth science, both present and past, is thus essential in society today.

The Earth Expansion Theory

The Earth Expansion Theory was developed in order to provide a reasonable account of events in the history of the Earth that could not be explained, such as the movement of continents after the break-up of Pangea. Earth expansion has been first suggested as early as 1927 (Carey, 1975). In the 1930s, an increasing number of geologists and geophysicists began to develop their own theories regarding Earth expansion, including Ott Christoph Hilgenberg (1896-1976) and Paul Dirac (1902-1984). However, the possibility of Earth's growth was not widely considered until the late 1950s (Carey, 1975). Geophysicists and geologists such as László Egyed (1914-1970) and Samuel Carey (1911-2002) were the most influential supporters of this theory. The interest in Earth expansion increased at this time largely because of the introduction of sea floor spreading as a mechanism for continental drift. However, at the same time, the plate tectonics explanation for continental movement arose. In order for Earth expansion to dominate these rivalling theories, geologists provided evidence such as a decreasing gravitational constant, sea floor spreading, and the shape of Pangea to reinforce the idea of a growing Earth.

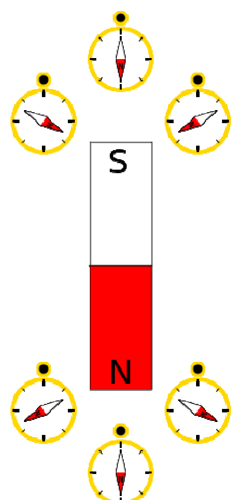


Figure 4.25 *At the poles of a magnet, the magnetic field points vertically (right). Towards the magnetic equator, the field becomes more horizontal.*

Hilgenberg and the Bud-Petal Analogy for Expansion

In 1933, Ott Hilgenberg proposed that the Earth expands in a manner similar to the opening of petals in a flower bud (Carey, 1975). This model for expansion, called the bud-petal analogy, suggested that when the Earth first started expanding, the sial layer which once completely covered the planet separated into pieces resembling petals. These "petals" stayed closely connected at one pole of the Earth, and separated at the other pole. This is a useful analog to the expansion of the Earth because it was thought that as the Earth increases, the continents separate further from each other near the south, modeled by the opening of the bud, and over time have migrated towards the north, where the "petals" stay closely connected (Carey, 1988). Carey provided evidence for this theory of expansion, which he called the Arctic paradox (Carey, 1976). Regions north of the equator, such as what is now called North America, were most likely much closer to the equator before the Earth began to increase in size. Fossil evidence supports this claim; found in these regions are traces and remains of organisms that would normally live in tropical areas, such as corals and brachiopods (Carey, 1988). It is possible, then, that the Earth is expanding in a way similar to the bud-petal analogy, since the continents were once much closer to the equator than they are today.

Paleomagnetic records can also be used to support this theory. When the magma released at mid-ocean ridges cools, the atoms in the magma record the direction of the Earth's magnetic field. After analyzing rocks found north of the equator, some had horizontal magnetic inclination, indicating that they were once at the equator. Rocks formed at a magnetic pole would have a vertical magnetic inclination (Jordan, 1971).

Hilgenberg was one of the first geologists to think about Earth expansion. At the time, it was believed that the sial layer formed the continents, and when the Earth expanded, the sima layer underneath was exposed, and formed the ocean floor (Carey, 1975). When new ideas began to develop about the composition and formation of continental and oceanic crust, the theories behind the mechanism for Earth expansion also changed. This can be seen in research from the 1950s and 60s, when sea floor spreading became widely accepted as the method of forming the ocean floor.

Dirac's Theory of the Gravitational Constant

In 1937, Paul Dirac, a theoretical physicist, introduced the idea that the Earth is increasing in size. This belief stemmed from his work with the gravitational constant, *G*, which is used to describe the attraction or repulsion force between two objects. Dirac's hypothesis was that the gravitational constant was not actually constant, and that it was decreasing over time (Jordan, 1971). Dirac found that the radius of the universe and the age of the universe are proportional to the inverse of the gravitational constant; that is, as the universe expands and as time goes on, the gravitational constant will become smaller (Runcorn, 1980). Using a series of relationships between the gravitational constant and the density of matter, Dirac determined that with a decrease in *G*, the pressure in the centre of the Earth would decrease, which would cause the volume of the Earth to increase while the mass of the Earth remains constant (Jordan, 1971).

Pangea and reconstructions of a past Earth

The need for the expansion theory originated with the problem of continental movement. In an attempt to figure out how the continents, as they are today, came from Pangea, geologists such as Carey used a model of the Earth to resolve this issue. He constructed a replica of the Earth as it was prior to the Mesozoic era. When the continents were rearranged to resemble Pangea on a globe scaled to the modern size of the Earth, the continents fit together roughly but there were still many gaps between the continents (Carey, 1988). Carey found that when the continents were rearranged on a sphere slightly smaller than the modern globe, the continents fitted perfectly to form Pangea. Carey estimated that an increase of 30% in the Earth's radius occurred after the late Paleozoic era (Rickard, 1969).

Figure 4.26 *This illustration shows the ancient supercontinent Pangea, with the outlines of the shapes of the modern continents (left).*

Egyed and the Expanding Oceans

László Egyed, a geophysicist who made large contributions to the Earth expansion theory, made observations about the increasing size of oceans. Egyed calculated that the amount of water on Earth has increased by 4% over time (Carey, 1975). However, when maps of the early continents are compared with modern maps, the continents are slightly less submerged than those in the Precambrian era (Carey, 1988). This conflicted with the bud-petal model of expansion, in which the amount of continental crust remains constant as the Earth gets larger. Egyed concluded that the ocean basins must be enlarging in order to accommodate the increase in water, resulting in a relatively lower sea level which exposes more of the continental crust (Carey, 1988).

Measuring the rate of expansion

When studying the expanding oceans, Egyed estimated an increase in the radius of the Earth by about 0.5 mm per year (Carey, 1988). He came to this conclusion by comparing the surface area of the continents as they are today and the current value of the surface area of the Earth over a four billion year period, as he believed that at the beginning of the Earth, it was covered in the sial layer that makes up today's continents (Jordan, 1971).

Shortly after this first approximation, scientists began to use paleomagnetic data to calculate the rate at which the Earth expands. As the sea floor spreads, the newly formed ocean crust cools, recording information about the Earth's magnetic field. Since this process occurs continuously, geologists found that these changes in the magnetic field over time can be used to discover how much the sea floor has spread and how long it took to do so (Jordan, 1971). However, this method of calculating the rate of expansion was discredited by sceptics of the Earth expansion theory, as many results were inconclusive about the occurrence of expansion (Jordan, 1971).

Rifts and Trenches – Eliminating the Plate Tectonic Theory

Further evidence supporting the expansion theory can be found by analyzing rifts and trenches. A rift is caused by the separation of two continental blocks. This phenomenon would occur if the Earth was enlarging (Jordan, 1971). Supporters of Earth expansion also pointed out that at mid-ocean ridges, rift valleys in the ocean, new sea floor is being created by the release of magma. This also suggests that the Earth is expanding, since more oceanic crust is continuously being formed, and the surface area of the Earth is increasing.

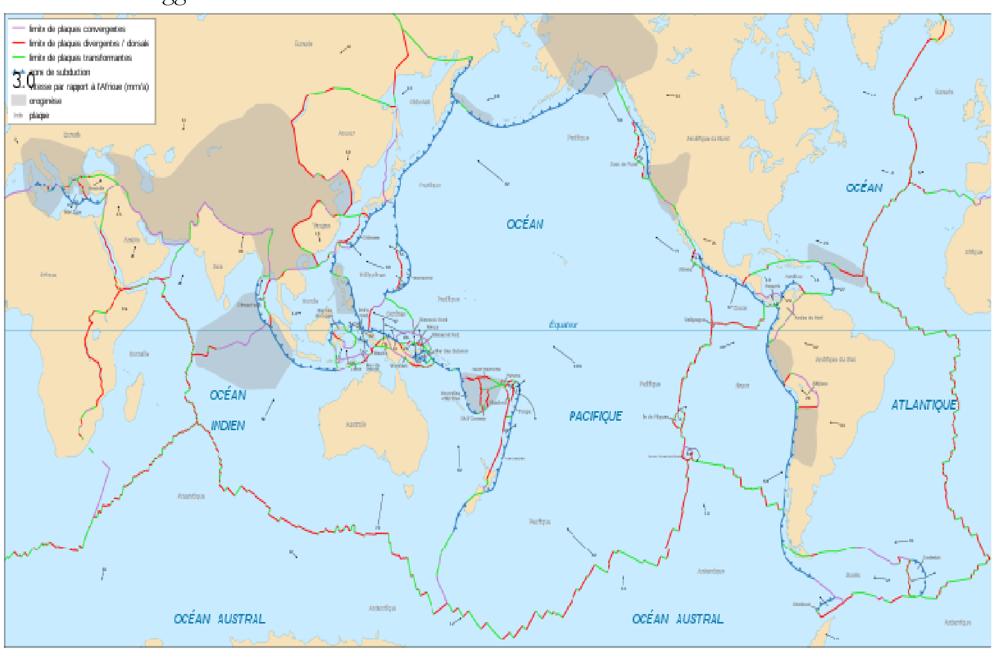


Figure 4.27 *In this map, purple lines represent convergent plate boundaries, red lines represent divergent boundaries, and blue lines represent subduction zones (right).*

Recall that at this time in scientific thought, the plate tectonics mechanism of continental movement was also being developed. This theory suggests that because oceanic crust is being created, it must also be destroyed by subduction in order to keep the size of the Earth constant (Carey, 1988). Supporters of the Earth expansion theory rejected the idea of subduction. They claimed that trenches are not positioned in the same way as mid-ocean ridges, oceanic crust would not be consumed effectively (Carey, 1976). Also, the small number of trenches suggests that the sea floor cannot be subducted at the same rate at which it is being produced (Carey, 1976). Therefore, the Earth must be expanding to accommodate the newly created oceanic crust.

An obstacle that expansion supporters had to overcome, however, is the age of the sea floor. The oldest sea floor is found to be 150 million years old, substantially younger than the age of the Earth (Carey, 1988). While the plate tectonic theory would argue that this occurs because of the subduction of old oceanic crust, expansion theorists ruled out the possibility of subduction. One possible explanation for this is the creation of the oceans after the initial expansion of the Earth, when the sial layer started to separate.

Legacy

Although the Earth expansion theory is no longer considered to be correct, the process by which the theory was created gives us much insight into how scientific thoughts are developed. Many scientists have independently hypothesized about the movement of continents in terms of Earth expansion. Each of their theories varies slightly, but all make a small contribution to the overall idea that the size of the Earth is increasing. Overall, the Earth expansion theory used ideas developed previously, such as sea floor spreading, and incorporated the evidence provided by several geologists and geophysicists to formulate a more complete theory. The progress of scientific discovery as it relates to continental movement made in the 20th century was astonishing, as the accepted theories changed from sea floor spreading and continental drift to Earth expansion, and finally reaching our current understanding of continental movement: plate tectonics and subduction.

Subduction

Supporters of the Earth expansion theory rejected the possibility of plate tectonics because they believed there is of a lack of subduction. However, their knowledge of this process was different from our modern perspective. We know now that continents do in fact move by plate tectonics, in which subduction plays a key role.

Mechanism of subduction

Subduction is the process of one plate moving underneath another plate, typically an oceanic plate subducting under a continental or another oceanic plate. This occurs at convergent boundaries, where two plates are moving towards each other (Plummer et al., 2007). If an oceanic plate meets a continental plate, the oceanic plate must subduct because it is more dense than the continental plate. Oceanic plates consist mostly of basalt, a substance more dense than the silica-rich crust of continents (Plummer et al., 2007). In the case of an ocean-ocean convergent boundary, the older plate will subduct. The older plate will have had more time to cool, and a cooler plate is more dense than a hot, newly formed plate (Plummer et al., 2007). At these subduction zones, a deep trench is created; this is called an oceanic trench.

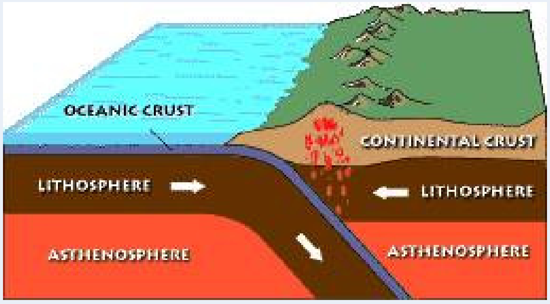


Figure 4.28 *An oceanic plate subducts under a continental plate, resulting in the melting of the asthenosphere and the rise of magma (left).*

Effect of subduction on Earth's topography

Many of Earth's processes are related to subduction. Subduction is the driving force behind plate tectonics and the movement of continents, because an old, dense oceanic plate descending into the core-mantle boundary results in the movement of ocean lithosphere (Stern, 2002).

This process is also responsible for the formation of continental crust. As subducting ocean plate reaches depths of approximately 100 km below the surface of the Earth, it begins to produce magma (Plummer et al., 2007). A large amount of water contained in the rock is released because the plate is being squeezed and stretched. The addition of this water allows the asthenospheric mantle to melt easily. The magma then rises to the crust (Stern, 2002). Typically these magmas are andesitic to basaltic in composition. The rise of andesitic magma forms island arcs parallel to the oceanic trench (Plummer et al., 2007). This magma could also be expelled from a volcano at the Earth's surface, and depending on the composition of the magma, could result in hazardous eruptions (Stern, 2002).

Subduction is also responsible for the occurrence of earthquakes. Although earthquakes pose a hazard to those living close to the convergent boundary where they occur, they can reveal important information about the process of subduction. The depth at which an earthquake occurs, along with its strength depends on the type of crust that is subducting, its age and the speed of subduction (Stern, 2002). Seismic information is often used to discover more about plate activities.

A complete understanding of subduction is necessary because of the major role this process plays on plate tectonics, one of the largest discoveries made in Earth sciences in the 20th century.

Abiogenesis

Abiogenesis is a fundamental question about life and is still unsolved. Rather than simply being a story of how chemistry became biology, abiogenesis is a deep problem that requires the amalgamation of several scientific disciplines to understand. It is also a demonstration of how science is a dynamic body of knowledge. The history of abiogenesis shows how hypotheses in science are rigorously tested with experiments and accepted only when repeatable results are obtained. But, the impeccable standards of scientific knowledge do not stop new scientific discoveries from inspiring brilliant minds to develop new hypotheses. This repeated pattern of developing and testing hypotheses is what progresses science to its goal of knowledge and understanding.

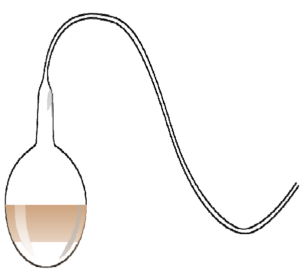


Figure 4.29: *Pasteur's apparatus for his 1860 experiment (above). He placed boiled broth in a sterilized flask with an S-shaped neck. The unique shape prevented airborne bacteria to reach the broth. As expected, the broth was clear for a long time. But when the flask was turned to let bacteria reached the broth, the broth turned cloudy. With this experiment, Pasteur had disproved spontaneous generation of bacteria (Joseph, 2010).*

The Power of Experiments versus Spontaneous Generation

For the larger part of scientific history, abiogenesis was not a major scientific problem because spontaneous generation was the accepted theory (Joseph, 2010). It was not until the Renaissance that spontaneous generation was heavily challenged. In the 16th century, Joan Baptista Van Helmont (1579-1644), an adherent to the scientific method, showed that the mass gained by a growing willow tree over five years is equal to the mass lost by the soil (Paweletz, 2001). In 1668, Francesco Redi (1626-1697), a pioneer of the 'controlled experiment', famously disproved the spontaneous generation conjecture that rotting meat produces maggots. He placed rotting meat in a variety of containers and showed that the sealed containers did not produce maggots (Ruestow, 1984). Classical Spontaneous Generation was mortally discredited in the 1860s by Louis Pasteur (1822-1895), the father of modern bacteriology. In a series of elegant experiments (one of them is shown in Figure 4.71), he showed that even bacteria, the simplest known forms of life, arise only from pre-existing bacteria (Joseph, 2010). If cells only come from pre-existing cells, how did the first cell arise? Once covered by the veil of spontaneous generation, the question of abiogenesis had resurfaced and now represented a significant gap in scientific understanding.

Recall from the introduction that experiments disprove incorrect hypothesis, such as spontaneous generation. However, it takes inspiring discoveries and brilliant minds to create new hypotheses. Ironically, Charles Darwin (1809-1882), the man who directed biology away from the weak conjectures of creationism, believed that it was possible for life to arise from inorganic matter (Joseph, 2010), despite the scientific understanding of his day.

Darwin's Notion and the Oparin-Haldane theory

In 1828, Friedrich Wöhler (1800-1882) synthesized urea, an organic molecule created by certain organisms, from ammonium cyanate, an inorganic molecule (Joseph, 2010). Darwin, inspired by this result and the Christian belief that life originated from earth, wrote to his friends about his idea of the 'organic soup'. He hypothesized that energetic events could excite inorganic molecules to form organic compounds. By random chance, these compounds would create proteins which, also by chance, would create a proto-cell. The proto-cell is then subject to the laws of evolution and will eventually form a true cell (Joseph, 2010).

Regardless of Darwin's idea, Pasteur's experiments were ironclad and dominated scientific thinking. To prove Darwin's idea, several experiments were done with countless recipes, including just mixing the organic molecules normally composing a cell (Joseph, 2010). But Pasteur's results still held: life cannot arise from non-life.

Rather than still searching for the origin of life, scientists began trying to answer how early life could have survived. They believed that answering this question might uncover clues to abiogenesis itself. Darwin's notion inspired Alexander Oparin (1894-1980), who further developed Darwin's idea into the Oparin-Haldane theory. Published in 1928, this theory stated that early life, unlike cells today, relied on external nutrients that did not require biosynthesis to be of use. Oparin believed that these external organic nutrients could be produced from energetic processes, such as sunlight, acting on the atmosphere (Fondi, Giovanni and Fani, 2010).

The Miller-Urey Experiment

In 1952, Stanley Miller (1930-2007) and Harold Urey (1893-1981) designed the most famous experiment in abiogenesis to test Oparin's hypothesis (Joseph, 2010). The Miller-Urey experiment demonstrated that it is possible for abiotic factors to create the organic nutrients and molecules required for life (Joseph, 2010).

The experimental apparatus (Figure 4.72) consisted of one flask half-filled with water connected with another flask containing electrodes. The apparatus was a closed loop with an internal atmosphere composed of hydrogen, methane and ammonia (Joseph, 2010), which Oparin believed were the primary components of early-earth atmosphere (Lal, 2008). The water was evaporated in one flask and the vapour diffused into the other flask. The electrodes in the second flask would create sparks, which are analogous to early-earth lightning. The atmosphere was then cooled, resulting in the water condensing back into the first glass so that the cycle could be repeated (Miller and Urey, 1959). With this simple experiment and a matter of weeks, Miller was able to convert nearly half the carbon stored in methane into several organic compounds necessary for life (Lal, 2008).

The Miller-Urey experiment, though revolutionary, contained several flaws and assumptions that were the target of scientific criticism. Firstly, Oparin, and subsequently Miller and Urey, made a critical assumption that the early-earth atmosphere was like that of the outer planets: rich in hydrogen, methane and ammonia but scarce in oxygen (Lal, 2008). This assumption was later discovered to be untrue. In actuality, the atmosphere was more likely composed mainly of nitrogen, carbon dioxide and water, all of which are more oxidized than methane (Copley, Smith and Morowitz, 2010). Secondly, the experiment only generated amino acids and nitrogenous bases but not their respective life-essential polymers – proteins and nucleic acids (Joseph, 2010). Both proteins and nucleic acids are essential to modern life; the former is required to catalyze several biological reactions which could otherwise take millions of years (Copley, Smith and Morowitz, 2010), while the latter is used to pass down genetic information during reproduction. Thirdly, sugars, an essential component of DNA and RNA, were never produced. Even after repeating the experiment with unreasonably ideal conditions, not a single DNA fragment was ever produced. Finally, some of the amino acids were incorrect optical isomers. The experiment could not explain why L-amino acids are more abundant in nature than D-amino acids (Joseph, 2010).

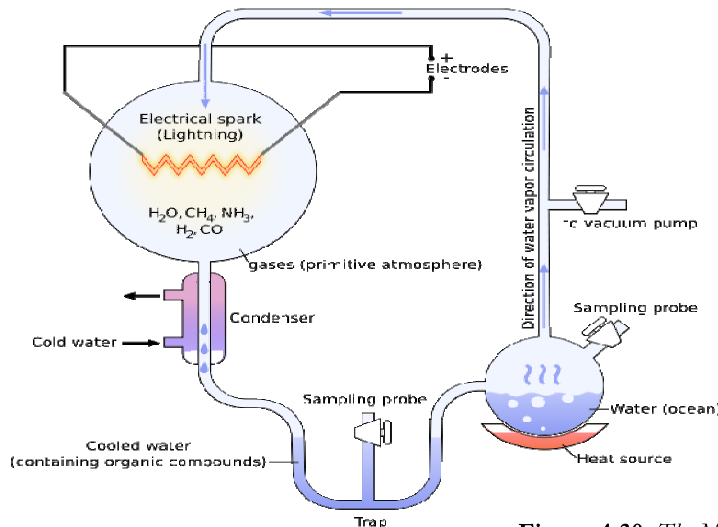


Figure 4.30: *The Miller-Urey experiment (above) was a breakthrough in abiogenesis research. Not only did it establish that it is possible to generate organic molecules in early earth conditions, but also inspired several other similar experiments, which greatly enriched abiogenesis research.*

The Miller-Urey experiment, regardless of its flaws, did show that it was possible to generate some of the organic monomers required for life. Early life could have used these simple organic molecules to survive (Fondi, Giovanni and Fani, 2010). The true legacy of the Miller-Urey experiment is that it provided a template for a flurry of similar experiments that made landmark contributions in their own right. Oró and Kimball (1961) generated Adenine, a monomer of DNA, using a modified version of the Miller-Urey experiment. Klussmann et al. (2006) showed that when using the correct atmospheric concentrations, there is a slight predominance of L-amino acids produced over D-amino acids. Cleaves et. al. (2008) proved that the organic products generated by the Miller-Urey experiment in the incorrect atmosphere are similar to the products generated in the correct atmosphere.

The Miller-Urey experiment, as well as subsequent experiments, showed how organic molecules can be synthesized in primitive earth. However, going from organic molecules to life is not straightforward. The biggest problem is that biological reactions are too slow without an enzyme catalyst (Copley, Smith and Morowitz, 2010). Even if there were an abundant supply of organic molecules, without catalytic activity, life cannot exist.

The breakthrough for the catalyst problem mentioned above did not come from physics or chemistry, but from earth science with the discovery of hydrothermal vents in 1979 (Corliss et al., 1979). The discovery of hydrothermal vents brought forth enormous scientific activity regarding abiogenesis. Within a few years, the catalyst problem, as well as several other issues, had testable solutions. This is yet another example of how discoveries stimulate scientific activity.

Hydrothermal Vents: New Discoveries, New Ideas

Hydrothermal vents (Figure 4.73) are undersea areas where geothermally-heated water bursts from fissures in the crust (Corliss et al., 1979). In addition to water, several mineral and chemicals are also spewed from the vents (Copley, Smith and Morowitz, 2010). The methane and ammonia produced at vents can undergo the same reactions described in the Miller-Urey experiment to generate organic molecules.

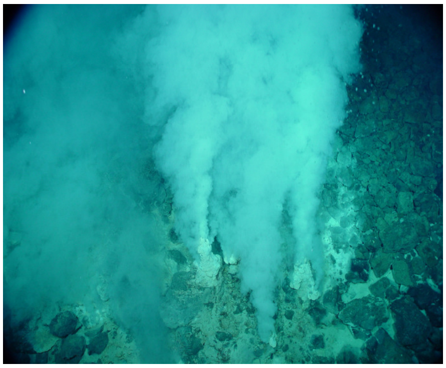


Figure 4.31: *Hydrothermal vents have very extreme conditions: high pressure, high temperature and lack of sunlight. Nonetheless, there is a lush and vibrant ecosystem of extremophiles around these vents (Dover, 2000). These extremophiles might very well be descendants of the first cell.*

The critical reaction that converts organic monomers, produced in primitive earth conditions, into polymers can be catalyzed by minerals. Minerals can promote reactions by polarizing the functional groups on organic molecules and enhancing their electrophilicity. In fact, minerals are still used in modern life to facilitate reactions (Copley, Smith and Morowitz, 2010). For example, haemoglobin is a protein in human red blood cells that contains iron ions. The iron helps oxygen bind to the blood cell so that oxygen can be distributed throughout the body (Jonathan and Wittenberg, 1966). The use of minerals in modern life could be relics from ancestral life in hydrothermal vents.

Minerals also help overcome another big issue with the Miller-Urey experiment – the lack of sugars produced. Borate minerals from hydrothermal vents stabilize and promote the formation of pentose, which is the sugar component in nucleic acids. Without the Borate stabilizer, however, sugars produced in early-earth conditions would be rare and would decompose fairly rapidly (Copley et al., 2010). Minerals are the missing link between the formation of monomers and polymers.

Evolution of Abiogenesis

Historical abiogenesis has developed a solid foundation for its modern analogue by showing how organic molecules developed. The famous Miller-Urey experiment proved that methane and ammonia, which are present in hydrothermal vents, can create organic molecules in high energy conditions, such as lightening (Joseph, 2010). Although the Miller-Urey experiment had some flaws, its legacy was the multitude of similar, but significant, experiments that followed.

The Miller-Urey experiment only accounts for the production of simple organic molecules. The discovery of hydrothermal vents led to a better understanding of how polymers formed in early earth condition. The minerals, discovered at hydrothermal vents, can catalyze the synthesis of life-essential polymers from organic monomers.

Abiogenesis is an example of how science is a dynamic study. The rigorous standards of science are based on the doctrine of repeatable results in controlled experiments. The failure of spontaneous generation to meet this standard resulted in the birth of abiogenesis. Even within abiogenesis, experiments and discoveries continuously force scientists to rethink past conclusion and develop new ones. The constant breakdown and reconstruction of hypotheses is what progressed abiogenesis from spontaneous generation to the valid field of inquiry it is today.

Origin of Life

The historical contribution of abiogenesis to science is knowledge of how organic molecules formed in early earth conditions. Modern abiogenesis researches focuses on how these organic molecules become proto-life and then life. Although there are several theories for abiogenesis, the Vesicle First Principle (VFP) will be discussed here because it is well supported and is not as technical as other theories. For any abiogenesis theory to be valid, it needs to show how complex biological characteristics could have simpler chemical analogues.

The fundamental postulate of the VFP is that the first biological membranes were vesicles (Figure 4.74). Unlike cell membranes, vesicles are simple structures and can be spontaneously created when certain lipids are placed in water. Based on this assumption, several other chemical analogous for biological characteristics can be theorized.

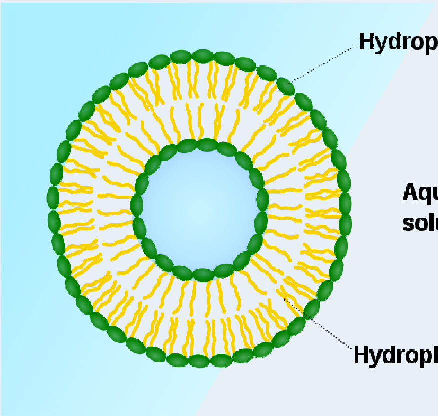
Synthesis of life-essential macromolecules is an important characteristic of life. Proto-cells are able to generate important macromolecules, such as RNA, by utilizing the selective permeability properties of vesicles. Vesicles are permeable to monomers but generally not to polymers (Koch, 2010). RNA nucleotides and minerals would enter the vesicle. Minerals would then catalyze the reaction to link RNA nucleotides and form RNA strands. Since the strands are polymers, they would be unable to exit the vesicle (Szostak, Bartel and Luisi, 2001). This structure, where the vesicle encapsulates RNA, is called a protobiont (Chela-Flores, 1985). Protobionts would have eventually evolved to have three important components: vesicles, template RNA and catalytic RNA (Szostak, Bartel and Luisi, 2001).

Protobionts, much like modern cells, have the ability to grow and divide. They grow spontaneously by incorporating nearby lipid molecules into their vesicles. Protobionts can replicate in two independent steps. First, the template RNA, which carries the genetic code, is replicated by catalytic RNA. Second, when the surrounding vesicle grows to a certain size, it divides spontaneously. This forms two protobionts, each with a copy of the parent template RNA. Mutations in template RNA usually occur during replication and can increase protobiont diversity (Szostak, Bartel and Luisi, 2001).

Finally, protobionts have the ability to evolve as well. The exact process of protobiont evolution is beyond the scope of this text. The basic concept, however, is that protobiont fitness is related to its complexity.

This selection for complexity led to the development of metabolic pathways and proteins (Szostak, Bartel and Luisi, 2001). Over time, protobionts became more complex and eventually evolved into prokaryotes (Correa and Correa, 2010), which are considered living cells.

Figure 4.32: *Vesicles form spontaneously when certain lipid molecules are placed in water (below). According to VFP, vesicles were the first biological membrane. Although they do not have the same complexity as modern cell membranes, there are still many similarities between them such as the lipid bilayer, selective permeability, and fluidity (Koch, 2010).*



Compatibility with Earth Science is of the utmost concern for any abiogenesis theory. It is believed that about 4.5 Ga years ago, Earth was very hot and was frequently struck by asteroids and comets. These space bodies brought with them several ingredients for life, such as carbon, nitrogen and water (Maurette et al. 2000). The heat and frequent collisions, however, prevented the formation of organic compounds. As the earth cooled and collisions decreased, simple organic molecules were synthesized, as demonstrated in the Miller-Urey experiment. The minerals deposited by hydrothermal vents then catalyzed the conversion of simple organic molecules to complex ones. It is believed that these complex molecules formed protobionts about 4.2 Ga years ago (Maurette et al. 2000). Note that the first fossilized life is 3.5 Ga years old (Brasier et al. 2005). Amazingly, within 700 Ma years, simple chemical protobionts had already become complex biological cells.

John Tuzo Wilson

John Tuzo Wilson (1908–1993) was a Canadian geologist and geophysicist who made many significant contributions to field of Earth science in the 20th century, especially towards developing the theory of plate tectonics. He completed his undergraduate studies in physics and geology at the University of Toronto in 1930. He earned a Masters degree from the University of Cambridge and later on, his Ph.D from Princeton University. (Strangway, 1997)

Figure 4.33 *The geological provinces of the west coast of Canada (above).*

Early on in his carer, in 1936, Wilson worked with the Geological Survey of Canada and developed two very valuable skills: field observations and geological mapping. During World War II (WWII), Wilson worked for the Canadian Army. In 1943, He was appointed as the director of Operation Research at National Defence Headquarters, where he directed Exercise Muskox, a series of exercises to improve the army's mobility in winter conditions (Strangway, 1997). During his trip to the Arctic in 1946 to test newly developed war equipments, Wilson realized that aerial photographs are a valuable source of data about surface geology. Towards the end of WWII, through his work with the military, he recognized the need for an international corporation to organise Arctic science (science relating to the processes and conditions present in the Arctic). Thus, he founded the Arctic Institute of North America (Strangway, 1997; Rowley and Rowley, 1994).

After the war, Wilson became a professor in the Department of Geophysics at the University of Toronto. He used his experiences from the military and started a research group that employed data from hundreds of thousands of aerial photograph and numerous on-site observations to develop and publish the very first Glacial Map of Canada. The map contained information about eskers, raised beaches, and many other quaternary characteristics of the surface geology (Rowley and Rowley, 1994). This map became an invaluable resource for many academics studying in the field of glaciology, permafrost and related studies. Other than academic uses, the Glacial Map of Canada was also very helpful for the planning of transportation routes, locating minerals and material, and identifying sites suitable for construction (Strangway, 1997; Rowley and Rowley, 1994).

In the 1950s Wilson initiated a research group and sponsored investigations pertaining to dating the age of the Precambrian Shield. The results of this research led to the distinct division of the Canadian Shield in to the geological provinces that we know today (Strangway, 1997).

In 1957, Wilson became the president of the International Union of Geodesy and Geophysics (IUGG) and was involved in the planning, organization and execution of the International Geophysical Year (IGY) in collaboration with other international organizations (Rowley and Rowley, 1994). The IGY was a joint effort between 67 nations to observe the Earth simultaneously with instruments set to the same standards in order to describe observable phenomena on a global scale. Prior to and during the IGY, Wilson travelled around the world to observe the geology and to meet scientists from different countries working on the IGY (Wilson, 1961).

Wilson was appointed as the director of the Institute of Earth Sciences at the University of Toronto in the year 1960. In the following years, he published a series of papers sharing the findings of his work dealing with plate tectonics. These played a key role in our modern understanding of many processes involving tectonic movements (Rowley and Rowley, 1994).

The Four Models

During that time, there were four major theories or models that were generally accepted and were used to explain geological features that resulted from plate tectonic activities such as formation of mountains, earthquakes, and volcanism.

The first theory, proposed by Sir Isaac Newton (1643-1721) and elaborated by Lord Kelvin (1824-1907), states that the Earth is a rigid body and the compressional features that can be observed in mountains and volcanoes are caused by the earth contracting through cooling, compaction, and extrusion of volcanic rocks and gases (Wilson, 1963).

The second theory proposes that the Earth is expanding either by radioactive heating (through the decay of radioactive elements such as uranium, thorium, and potassium) or due to the decreasing value of the gravitational pull exerted by the Earth (the gravitational constant). This theory offers an explanation of the tensional features observed in mid-ocean ridges (MOR) (Wilson, 1963).

The third theory was proposed by Alfred Wegener (1880-1930). He postulated that the Earth is mobile and the continents drift due to rotational forces on a spheroid. The exact mechanism that caused the drift was not known. This theory explains the non-uniform record of geomagnetism recorded in the rocks (Wilson, 1963).

The fourth theory builds on the theory of continental drift proposed by Wegener. The theory states that the plates are moved by currents of convection cell in the mantle rising under MOR and descending under young mountains and islands arcs. Based on this theory, the tension observed in the MOR is caused by the meeting of the currents of two cells rising then separating in opposite directions and the compression observed in the mountains are caused by two currents sinking and separating (Wilson, 1963).

It was difficult to determine which theory was correct because little of information was known about the Earth's interior and about the Earth's gravitational constant. Local observations could not prove any of the four theories because the observations are not made on the appropriate scale and not in enough places globally. However, most geologists agreed on the fact that there is a flow on the interior of the Earth. Now that technological advances were able to produce more information about the Earth's interior, the ocean floor, Antarctica, and rock magnetism, the rigid Earth theory became inadequate for explaining the newly collected data (Wilson, 1963).

Wilson supported the convecting mantle theory (the fourth theory) and he explained many processes using this model, including the formation of the Hawaiian Islands, classification of transform faults, and spreading of the ocean floor.

Figure 4.34 *Satellite image of the Hawaiian Islands (left). The islands are in increasing age from right to left.*

The Hawaiian Islands

It was observed by geologists that the Hawaiian Islands are in a linear formation. The age of each island, determined through radioactive dating, gets progressively older towards the northwest. It was also noted that islands were either active or previously active volcanoes, and each island has similar history of volcanism and erosion (Wilson, 1963).

The process by which these islands were formed was not completely understood. One of the generally accepted hypotheses, made under the rigid Earth model, accepted at the time was that the Hawaiian Islands were formed through extrusion of lava along a large fault due to a facture in the Earth's crust. The diminishing volcanic activity is thought to be due to the fact that the fault was extending and the extrusion of lava was more prominent at the extending end of the fault (Wilson, 1963). Subsequent studies pertaining to the sea floor along the Hawaiian Islands determined that there are no axial faults and no extension of faults as predicted by the hypothesis (Wilson, 1963).

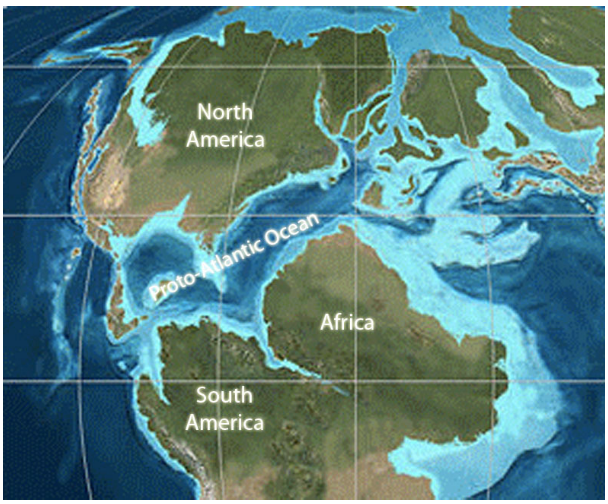


Figure 4.35 *The proto-Atlantic Ocean during the lower Palaeozoic era (above).*

Wilson proposed an explanation for the formation of the Hawaiian Island using the theory of convection in the context of the mantel. He postulated that a jet-stream, generated in a convection cell, flowing vertically towards the surface forms an active volcano. Then a convection current flowing horizontally in the northwest direction carries the volcano away from the jet-stream. Once the volcano is away from the lava source it slowly becomes inactive and a new active volcano will be formed directly above the jet-stream. This process will result in a chain of volcanoes with increasing age and erosion and decreasing volcanic activity towards the northwest direction like the current Hawaiian Islands (Wilson, 1963). This type of geological feature is named hot spots and there are over one hundred hot spots scattered around the globe (Wilson 1976).

New Class of Fault

In 1965, Wilson proposed a new class of fault called transform faults in addition to the existing transcurrent faults. Transform faults are a class of horizontal shear faults that can result in crustal displacement. The fault ends abruptly on both ends (Wilson, 1965). The motion of the crust along the transform faults is parallel to the fault and mostly horizontal (Wilson, 1973). The faults that now are classified under the transform fault were previously thought to be anomalies that existed among the transcurrent faults (Wilson, 1965).

Life Cycle of the Ocean Basins

In 1966, Wilson published a paper that proposed that a proto-Atlantic Ocean existed during the lower Palaeozoic era and this proto-Atlantic ocean closed throughout the middle and upper Palaeozic era and re-opened during the beginning of the Cretaceous era (Wilson, 1966). This paper marked the beginning of the developing theory about the life cycle of the ocean basins. Because new ocean basin is contantly being created through the MORs, causing the spreading of the ocean basin, the older and denser ocean crust gets pushed down into the Earth's mantle. The crust is then melted by the heat and gets recycled into the mantle. This process will create a cycle where the ocean basin, originating from a small MOR, continues to grow until a maxium size is reached, then it begins to decline until the continents on either side of the ocean basin come in contact with each other (Wilson, 1976; Wilson, 1973).

Age of the Scientific Revolution

The 1960s to the 1970s could be said to be the age of the scientific revolution in the Earth sciences. In Wilson's terms, a scientific revoution is the process of "changing the basic poing of view" to create "a new form of science with a different frame of reference" (Wilson, 1976, p. vi) and it is based on the "changes in basic premises and advances in theory that reinterpreted past obsevations without destroying their validity" (Wilson, 1976, p. vi).

The scientific revolution of the Earth sciences occurred when the continenal drift theory was accepted by the geologists. While the theory of was not widely accepted until the 1960s, emergence of technology and new evidence (such as the geomagnetism records on the rocks the ocean basins) strongly supported this idea. By the 1970s, the majority of the Earth scientists have accepted this theory as a valid explanation and they named the processes driven by continental drift as global plate tectonics (Wilson, 1976).

The Wilson Cycle

Today, the cyclic process by which the ocean basin opens and closes is known as the Wilson Cycle, in honour of the Canadian geophysicist J. Tuzo Wilson who first described this process. The Wilson Cycle can be divided into six distinct stages: growth of the ocean basin during the first three stages and decline in the later three. Throughout history, the Earth has gone through many cycles. The Wilson Cycle is the underlying process that governs the formation and breaking up of the supercontinents (Plummer et al., 2007).

The Wilson Cycle describes the life cycle of the ocean basin and it begins with a hot spot developing under a stable craton, thus causing an uplift of the continent as new crustal material is added, creating rift valleys. This stage is known as the embryonic stage (Jacobs, Russell and Wilson, 1973; Plummer et al., 2007). The second stage is known as the young or juvenile stage where a young and narrow ocean is created from the spreading of the ridges and depression of the coastal and central (at the mid-ocean ridges) crust (Jacobs, Russell and Wilson, 1973). The continuous spreading of the mid-ocean ridges leads into the third stage, the mature stage where a full ocean basin is created. (Jacobs, Russell and Wilson, 1973; Plummer et al., 2007)

As the ocean crust continues to expand, it cools and becomes denser, entering the fourth, declining stage of the cycle. The cool and dense ocean crust sinks into the asthenosphere where it meets the continental crust, creating island arcs and adjacent trenches (Jacobs, Russell and Wilson, 1973; Plummer et al., 2007). During the fifth stage, the terminal stage, the ocean crust continues to subduct into the asthenosphere, bringing the two continents on opposite sides of the ocean together and causing uplift of the continental crust resulting in the creation of young mountains (Jacobs, Russell and Wilson, 1973; Plummer et al., 2007). The collision of the two continents due to the continuous subduction of the ocean crust marks the final stage of the cycle, the suturing or relic scar stage. During this stage, the uplift of the continental crust continues to form young mountains (Jacobs, Russell and Wilson, 1973; Plummer et al., 2007).

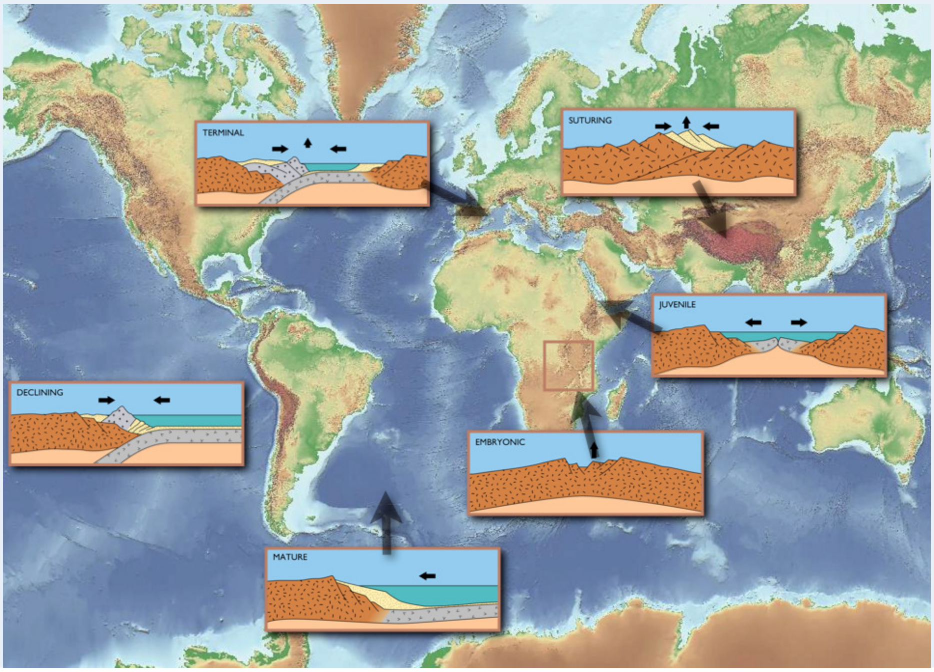


Figure 4.36 *Examples of the six stages of Wilson Cycle (left). Embryonic: East African Rift Valleys. Juvenile: Red Sea. Mature: Atlantic Ocean. Declining: Pacific Ocean. Terminal: Mediterranean Sea. Suturing: Indus Line in the Himalayas.*

Peter Vail: Torn Between Two Worlds

Figure 4.37 *An offshore oil platform in Brazil (above). Sequence stratigraphy has laid the groundwork for alternative stratigraphic measures, particularly useful in marine environments where other correlative techniques are difficult.*

The 1970s marked an era of change in petroleum exploration spearheaded by the multinational corporation, Exxon. The economic influence from industry triggered several advancements in the study of stratigraphy. However, associated with this race for knowledge, there was a wave of controversy concerning the leading theories. Exxon published theories by Peter Vail (1930-present), their leading geoscientist, without peer-review or validation. Thus, an era in stratigraphy began where new, unsubstantiated discoveries dominated scientific thought. Although seemingly a step backwards in understanding Earth's history, modern developments have salvaged Vail's findings to form a powerful working model in sequence stratigraphy.

Sequence Stratigraphy

Stratigraphy, the analysis of the layered structure of sediments, is a long-studied discipline in geology. English cartographer and geologist William Smith (1769-1839) invented the concept of stratigraphy in the late 18th century through his illustrative and correlative geological maps. Since then, geologists have focused on correlating strata from increasingly greater distances (Winchester, 2001). Stratigraphic methods traditionally relied on correlating grain sizes, fossils, isotopes, magnetic grains, or sedimentary structures to develop distinct rock units, or facies. The sequence stratigraphy method instead examines the relative age of disconformities within the rock record (Babcock, 2009).

Sequence stratigraphy attempts to model these abrupt changes in sedimentary facies by using a concept of 'eustasy', which considers long-term sea-level fluctuations. The theory uses historical Earth processes such as global glaciations to explain sea level changes. Continental glaciations cause regressions by sequestering water, but cause transgressions when icecaps melt and release water in warmer climates. The underlying theory of 'global eustasy' is that geological variations alter the amount of water volume in a given area, hence influencing both the movement of shorelines and periods of sediment deposition (Miall and Miall, 2002). The petroleum industry requires information on such eustastic relationships, as the distribution and characteristics of sedimentary successions help predict formations and layers containing oil or gas.

Seismic stratigraphy, a geophysical method for characterizing disconformities, materialized from oil companies in the 1960s (Miall and Miall, 2002). Peter Vail triggered academic enthusiasm for this method with his landmark publication in 1977 concerning the global eustasy model (Vail et al., 1977). Vail used a reflection technique akin to sonar to map underground structures. Although this technology was present since the 1920s, the computing power available from the 1970s led to previously invisible details such as bedding planes becoming visible as 3D shapes (Miall and Miall, 2002). Vail's paper debated that these bedding planes represented distinct timelines, and that the thicknesses of sequences represented a complete rise and fall of sea level. By correlating these cycles spatially, Vail developed the 'global cycle chart' (Vail et al., 1977), which created sweeping, albeit inaccurate, predictions of the deposition and formation of sedimentary strata, thereby providing a basic framework to explore oil-bearing structures (See Figure 4.91).

Understanding Peter Vail's convoluted journey with Exxon elucidates why the use of seismic methods to explain sequence stratigraphy permeated modern thought despite its controversy.

Vail's Indirect Journey

Science must deal exclusively with the real external world, and should not be dependent upon either non-inductive forms of knowledge or reflections of the social world (Miall and Miall, 2002). Peter Vail's work violated these rules many times by exercising bias, first by Vail himself, then by Exxon, and lastly by the public.

In Vail's memoirs, he cites his professors as promoting his scientific passions (Vail, 1992). First, his Ph.D. supervisor, Lawrence Sloss (1913-1996), provided the insights and exploration techniques in sequence stratigraphy that founded his scientific career. Secondly, Sloss's colleague, William Krumbein (1902-1979), taught Vail the computing aspect of geology, specifically the quantification of subjective data. Their work prompted Vail to pursue academic connections in sequence stratigraphy. Later employment with smaller oil companies affected both the way he interpreted his findings as well as the techniques he used for exploration. He saw how his pure scientific experience could reform the industrial standards. Vail's work led him to Exxon, who selected him to investigate the seismic stratigraphy of the North Sea (Miall and Miall, 2002; See Figure 4.92).

Vail led a team developing global eustasy, a tool for regional correlation (Vail, 1977). The intention was never for Exxon to develop a large-scale measure for geologic time, yet Vail made constant efforts to derive the global cycle chart (See Glossary; Miall and Miall, 2002). The supervisors in Exxon freely admitted his research would never be accepted due to Vail's insufficient skills in geophysics, and his presentations were at times met with derision (Vail, 1992). Yet with a dogged persistence, Vail continued work with his theory, constantly developing a mental image of a grand-scale correlation.

Exxon's Structural Problems

Industrial turmoil sprouting from the merger of smaller oil companies to form the conglomerate Exxon in the 1960s threatened Vail's work (Wilson, 1998). With the reshuffling of positions in the corporation, research scientists were forced to work with those with opposing views. This mandatory co-operation resulted in bitterness that played a part in influencing high-level decisions targeted against Vail's exploratory work (Miall and Miall, 2002).

The biggest structural shift in Exxon was the segregation of differing research fields such as geology, engineering, geophysics, and geochemistry into isolated divisions, which created miscommunication between specialists, fierceness over ownership, and growth of differing ideas within the same company. The greatest clash was between geophysics and geology, where geophysicists viewed their research as fundamental knowledge to solve geology's problems, whereas geologists perceived geophysics as a mere tool (Miall and Miall, 2002).

Therefore, in the late 1960s, when Vail's geological team approached the seismic stratigraphy assignment largely founded with geophysical data, opposition arose from all sides against Vail's eventual findings (Miall and Miall, 2002). Geophysicists correctly argued that the data was misinterpreted by stating that the sonar reflections were fluctuations in density. Paleontologists refused the notion that sequence boundaries followed discrete timelines, which also later proved to be true (See Figure 4.93). Amongst the harsh controversy, management had to intervene. The main issue, which himself Vail agreed with, was that he was more focused on developing his theoretical science than discovering operational utility (Vail, 1992). Vail, unable to assert himself and his findings within the industry, instead decided to pursue publication unaffected by his colleagues who he perceived were misinformed or envious.

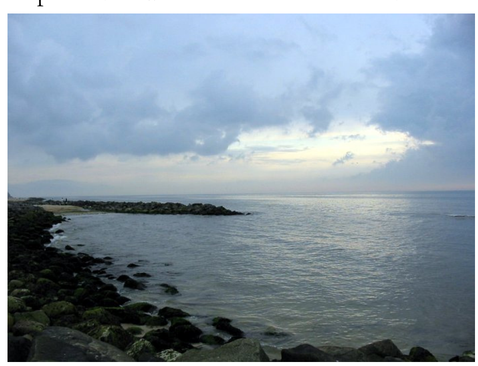


Figure 4.38 *North Sea Region (left). Vail's findings were based upon discoveries in this sea off the eastern coast of the British Isles.*

Vail published the bulk of his findings in the 1970s, though he required permission from Exxon officials to do so. Consequently, there were many contractual clauses preventing details to be revealed (such as the original data), largely for competitive reasons (Miall and Miall, 2002). In 1975, Vail presented his work at a symposium for the American Association of Petroleum Geologists, where, without any independent critical review, his theories fascinated other leaders in the field. Exxon provided funding for Vail's publications, a standard practice to support the reputation of their researchers, thus automatically providing prestige to the theories (Vail, 1975; Miall and Miall, 2002). So bolstered by the scientific community and with artificial support by Exxon, Vail's model was published in 1977 independent of peer review, and was immediately regarded as

Figure 4.39 *A palaeontologist inspecting dinosaur fossil (above). This field of study conflicted greatly with Vail's findings, as palaeontologists refused to believe sea-level changes could be recorded in the worldwide stratigraphy, as only catastrophic events such as the K-T boundary yielded global disconformities (Miall and Miall, 2001). However, because the public believed in Exxon, the new seismic methodology and the convenient model, critiques by palaeontologists were largely ignored.*

both a theoretical and technical breakthrough in the professional geological community (Kerr, 1987).

The Public Taking Control

After publication, the scientific community immediately attempted to analyze Vail's ideas. The charts and maps were irrefutable due to the withheld data. For example, the final observations of cycle charts for the entire Phanerozoic were present, but no detail on the original observations were provided, nor any discussion about the scientific method conducted or cross-referencing to other research (Vail et al., 1977). Thus, outsiders could not even interpret the decisions made by Vail. In fact, Exxon withheld all the specific locations and original analysis from the years of research Vail's team conducted and the data has never been released publicly to this day (Miall and Miall, 2002). In industrial sciences, secrecy is still common. For example, marine researchers must rely on confidential military data, and as such can only publish their final results (Mukerji, 1989). This confidentiality reinforced by the industrial superiority of Exxon, consequently led to Vail's research being taken as the final word to the public and subsequent industries who sought to emulate the findings.

Vail began a movement, where his global eustasy model formed the basis for both regional and global correlations. Through the 1980s, scientists were quick to adopt the breakthrough, to try to gain competitive advantages in either business or academia. In the process, they repeatedly cited Vail's research as a well-documented fact and it was not until the late 1980s when criticisms appeared (Miall and Miall, 2001; See Figure 4.93). However, *Science* published articles defending Vail in 1987, corroborating the original unchecked work and perpetuating the controversy (Kerr, 1987). Exxon's powerful reputation created assumptions that they compiled huge proprietary datasets and conducted critical analytical processes leading to the acceptance of the misinformation.

The support of other scientists turns statements into facts, and so human interpretation played a significant role in the erroneous acceptance (Miall and Miall, 2002). This grandness and simplicity of the model appealed to the fundamental human psyche, which strives for a predictable understanding of how the world works, and so there was a heavy psychological need in stratigraphy to find order within all the random successions (Miall and Miall, 2001).

Global Predictions: A Pipe Dream?

Consequently, science trivialized academic pursuits in deference to profitable ventures (Miall and Miall, 2002). Because these predictions seemed to reduce exploratory costs such as drilling dramatically, profits appeared to be increasing for all petroleum geologists. Geologists embarked on grand projects to explore offshore areas, typically with limited observational data, because they believed they had a template to proceed with knowledge when drilling. The dependency on this global cycle chart of sea level data heavily influenced the profession, only to be revamped within the past few decades with changing schools of thought (Miall and Miall, 2001; See Sequence Stratigraphy).

The sociologist Anselm Strauss (1916-1966) provides an explanation to this industrial acceptance of flawed science, with the social world and arena theory. The social world connects the groups with shared goals and resources, whom thus build common ideologies to conduct business, and the arena sets the stage where separate worlds interact to focus on debating a given shared issue (Strauss and Corbin, 2008). In this case, geologists and petroleum companies represented two distinct worlds (academic vs. economic), but because they were both concerned about stratigraphy, they met at a common arena. Vail represented the crossing of these worlds, as he attempted to solve the arena's conflict. Vail will forever be associated with this divide between the opposing worlds of industry and academia.

A Reconciliation

Although Vail's theories were initially flawed, he touched on a variety of important truths. He brought geophysics and geology together albeit erroneously, reshaping the view of geological architecture and industrial practises. His theories also provided a refreshing theoretical view of integrating wide ranges of data and interpretations over huge spatial and temporal scales, a process still being refined today. Understanding some of the premises of climatic, tectonic, and eustatic relationships on a grander scale has helped in the modern qualitative paradigms. Although Vail's unrefined scientific ideas percolated to common thought due to industrial confusion and mass public adoption, sometimes the indirect journey is the only possible journey for scientific advancement. Vail, in his memoires, provides apt thoughts when he yearns for his findings to serve as a reminder of the moulding that needs to take place between academia and industrial science.

Sequence Stratigraphy

Sequence stratigraphy is evolving from Vail's preliminary work to form a well-grounded interdisciplinary study, which can create powerful connections, both locally and regionally. By observing trends in distally separated strata, inferences on depositional trends are developed based upon concepts such as sea-floor spreading, tectonic movements, and glaciations (Homewood et al., 2000). The interplay between eustatic relationships and the transgression or regression of seawater on continental surfaces is visible, at least on local scales. When sea level rises, covering the continental surfaces, there is a time of deposition, followed by a sea-level fall, causing exposure and erosion of sediment and the creation of a disconformity. Disconformities can be used to correlate sedimentary units across regions.

Current research is still sorting out the years of disorganized, unfounded research to develop an efficient workflow method for stratigraphic research (Vail, 1992). As Vail once envisioned, there are now attempts to develop a quantification of the large amounts of qualitative data available including seismic, outcrop, well log, biostratigraphic, and geochemical data. Expert human interpretation is required to correlate and interpret these data, judge the importance of different controlling factors and assess the quality of data on a case-by-case basis dependent upon each locality (Catuneanu et al., 2010; See Figure 4.94).

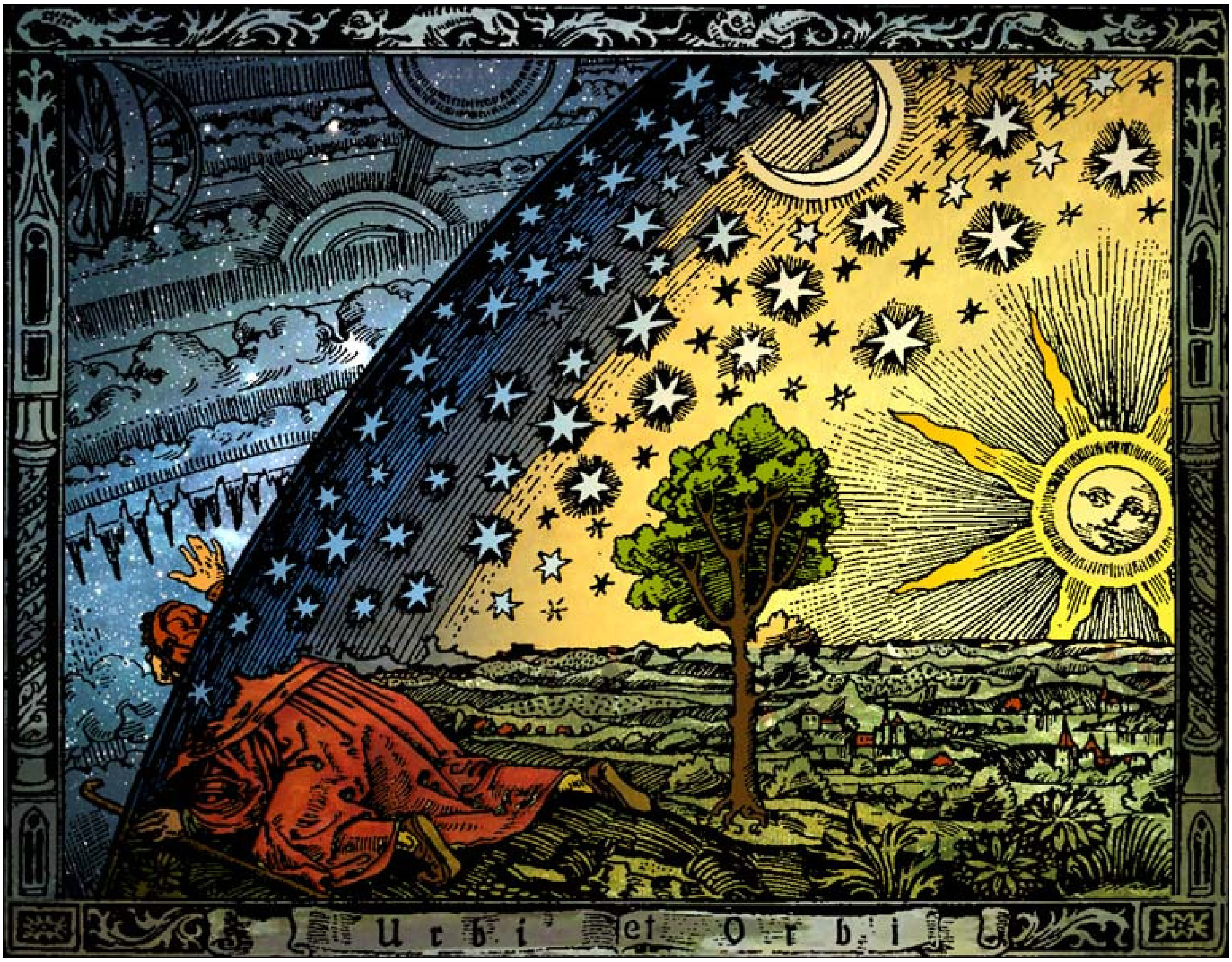
Figure 4.40 *Two geologists making qualitative observations of a Silurian limestone unit in Ohio (left). Qualitative analysis and expert observations by skilled scientists is, and will always be, a critical role in identifying sequences, boundaries, and time lines in the field of stratigraphy.*

Seismic Data and the Future

Seismic data are those based on geophysical observations and can provide spatially continuous information about subsurface conditions (Catuneanu et al., 2009). Whereas core and outcrop data are often of limited spatial extent, seismic data can provide the widespread, extensive template upon which to base regional correlations. The action of mutual interpretation and building simultaneous connections between the geophysical and sedimentological models is vital to eliminate bias in either field to form a complete picture (Spicer, 2010).

Research in geophysics focuses on empowering the basic methodology and providing clearer interpretations. Obstacles to generating accurate resolution of data collected at great depths frequently arise because reflection and feedback of units are often encountered (Catuneanu et al., 2009). Powerful computing devices can now dynamically tweak the frequencies input in cycles, which allows the bypassing of obstacles to penetrate deeper into the surface. The combination of seismic data with observational core or well log data can be used in mathematical 3D modelling software, which is evolving as the frontier of further geological understanding both academically and industrially (MacCormack, 2010).

All of these efforts attempt to calibrate Vail's original research, as improving data and reasoning continues to illustrate eustasy, albeit at local scales. Consequently, predictive strategies of sequence stratigraphy, in a modified, selective, yet equally powerful view, are changing the way scientists in all disciplines are both interpreting and integrating their information into Earth's history.



Camille Flammarion's woodcut. The picture depicts a medieval pilgrim who peers through a veil in the sky to look at the hidden inner workings of the universe. It is representative of a theme that is common throughout the book: humanity's curiosity about the Earth and the universe.

Conclusion

The research presented in this book pertains to a variety of cultures in a range of eras and locations. Despite this diversity, one common theme in the study of the Earth prevails: humanity's innate curiosity about the natural world. Although this ambition guided civilizations in the pursuit of obtaining a greater understanding of the Earth, progress in scientific research was by no means constant. Instead, the advancement of science was alternately impeded and stimulated by different cultural values of the evolving civilizations.

Scientific developments in the ancient world were governed largely by transformations in systems of thought. Rather than attributing the causes of natural processes to metaphysical beings, civilizations began to examine the world by using methodical deductive reasoning. Unfortunately, scientific advancement was greatly hindered by a lack of information exchange due to the relative scarcity of recorded information, prejudice among members of different classes, and the isolation of certain civilizations. Yet the introduction of formal empirical observations, along with increased travel and exploration particularly toward the end of this era, ultimately increased the rate at which science was developed and dispersed in the Middle Ages.

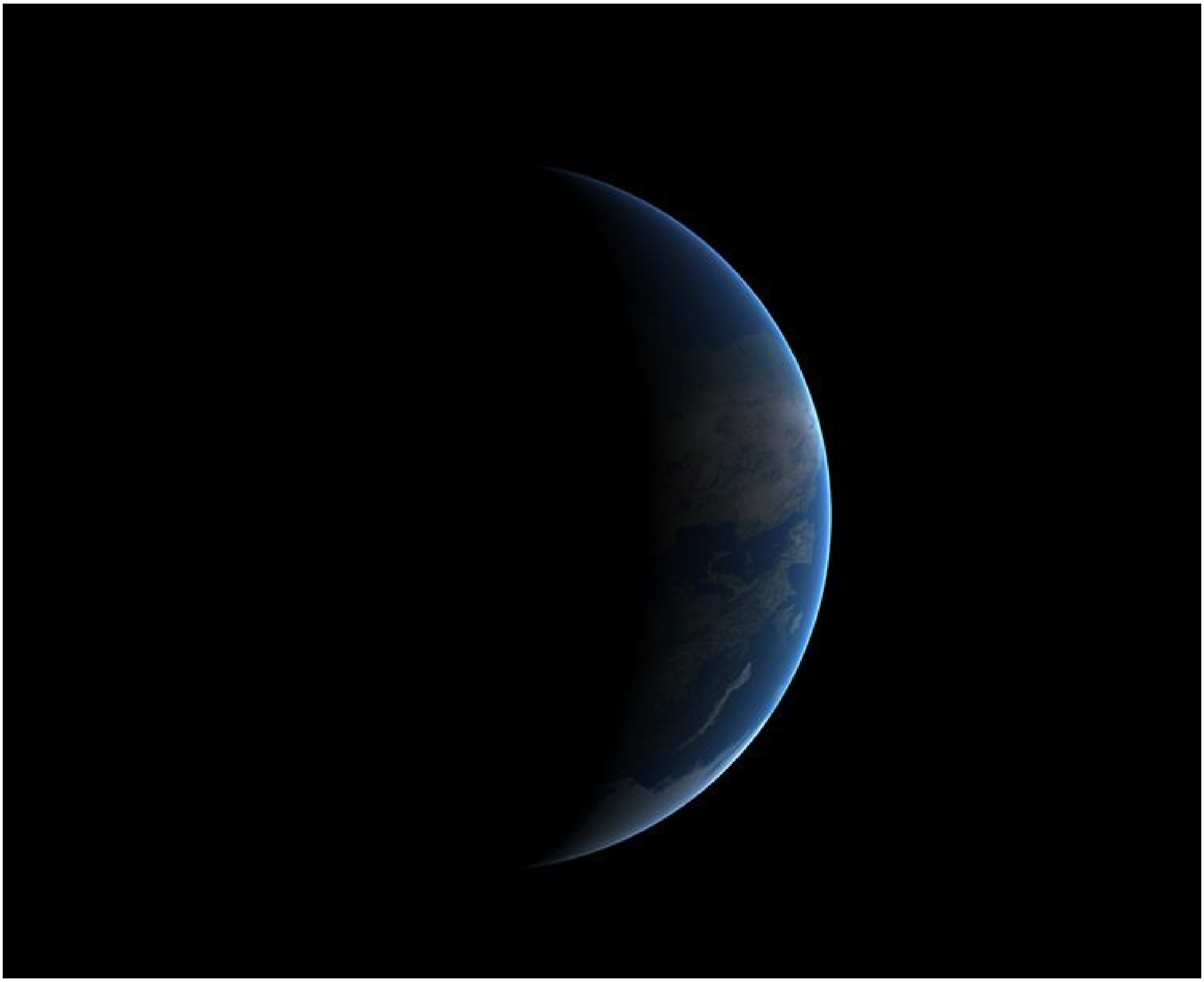
Although endowed with the invaluable insights of ancient scholars, the development of science in Europe during the Middle Ages was hindered due to major shifts in political and religious affairs. In particular, the fall of the Western Roman Empire isolated Christian Western Europeans from important sources of ancient knowledge. In contrast, China was experiencing a great deal of scientific development during the Song Dynasty (960-1279) attributed largely to the contributions of polymath Shen Kuo. The revival of science in Western Europe came with the reintroduction of Greek and Arabic geometry. The reform in thought was so drastic that this period is often referred to as the Scientific Revolution. Developments during this era diverged away from the doctrines of the ancient civilizations, and instead advanced scientific knowledge and reasoning that would prove to be essential for progress in the 1800s.

In the 19th century, significant advances in technology allowed for faster communication and therefore greater amounts of information to be exchanged between scientific communities. Additionally, scientists finally began to segregate religious dogma from the development of scientific theories. Mankind expanded their grasp to the ends of the Earth in the 19th century with various exploratory missions. Scientists also developed major theories about glaciation, evolution and geological time, which have become cornerstones for modern Earth science. Most importantly, scientific inquiry in the 19th century laid the foundations for the developments that came in the 20th century.

Technological advancements in the 20th century allowed scientists to test and refine past hypotheses. These developments led to new discoveries, which in turn inspired brilliant minds to establish new theories and guide further research. However, these valuable scientific and technologic progressions were often driven by government and corporate funding and had morally questionable applications. This led science to a greater sense of responsibility and ultimately aided in the understanding of how humanity affects the environment. Although several important questions about Earth's history remain unanswered, the knowledge gathered during the 20th century paved the way for modern research.

The current state of Earth sciences is very promising. Albeit the product of thousands of years of revolution, the modern conflict between science and religion is comparatively minimal. Furthermore, the firm establishment of the Information Age has provided scientists with the abilities to transfer information both freely and instantaneously, and to access knowledge that was previously difficult or impossible to find. The institution of the modern scientific method has increased the efficiency, and accuracy of scientific thought. Similarly, current technology has granted scientists the opportunity to refine previous theories and develop new ones through vigorous experimentation and strict observation. Although there are still many open questions in the Earth sciences, sufficient understanding of our planet has guided humanity toward a new stage of scientific exploration: the planetary sciences. By extrapolating information about the Earth, researchers are now discovering the geologic processes of other celestial bodies, Mars prominent among them. Indeed, the innate characteristic of our species to learn about the Earth and its position in the universe has not yet diminished, as humanity stands upon the brink of uncovering not only the history of the Earth, but the time course of our universe as well.

Science is a dynamic body of knowledge that constantly evolves to accommodate new observations and discoveries. One can see that each major time period brought sweeping changes in scientific thought. These changes were necessary to bring humanity a step closer to understanding Earth's history. Although the topics in this book are diverse, they all have an underlying theme: as science evolves, so does our knowledge of Earth's history. The book demonstrates that our perspective on Earth's history is intrinsically bound to our understanding of science – no complete appreciation for one can be had without the other.



Earth as seen from outer space. With the advent of space exploration, scientists continue their eager pursuit to unravel Earth's history. As entities in a common solar system, the history of other planets may yet reveal a great deal about the history and origin of our own planet.

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Glossary and Index

a priori reasoning 9
Information or justifications drawn through means that are independent of observation and experience. This method relies only on logical connections between ideas (Ross, 2004).

abiogenesis 69,115
A theory that states life arises from non-living material. or the study of how life can arise from inorganic matter.

absorption spectra 107
Qualitative indicator of the ability of a substance to absorb certain wavelengths of light. Can be used to identify unknown compounds (Treibs, 1936).

accrete 11
In astrophysics, accretion is defined as a process by which a massive object gains more mass by gravitationally attracting more matter (esp. gaseous matter) (Levin, 2009).

aerial photography 103-105,118
Aerial photography includes the various techniques of taking photographs of natural or cultural features from the air, using balloons, airplanes, satellites, and other sources, in order to study the features in their entirety from a top-down (bird's eye) view.

aerology 95
Branch of meteorology associated with the study of the entire atmosphere, especially the upper layers.

Agassiz, Louis (1807-1873) 76
A Swiss naturalist who was a leading advocate of the glacial theory in the 19th century (Imbrie and Imbrie, 1979).

aggregates 103
Aggregates are materials such as sand or gravel used with cement and water to make concrete, mortar, or plaster.

airgun 87
A device used to create energy signals (sound waves) for geophysical applications.

Al-Biruni (973-1048) 13
10th century Persian scholar known to have visited and studied in India.

alchemy 50-53
A philosophy of nature with the goals of transmutation, creation of the Philosopher's Stone and Elixir of Life.

Alexander the Great (356-323 BC) 5,10
King of Macedon, pupil of Aristotle. His conquest over surrounding kingdoms (most notably that of the Persians) led to the creation of one of the largest empires in history (Ross, 2004).

Alfred Wegener (1880-1930) 33
Notable German geophysicist and meteorologist. Famous for his theory of continental drift, which proposed that continents slowly drift around the world.

algebra 38
A branch of mathematics that uses equations to represent the relationships between variables.

Algonquin 38
A language family of the First Nations people in central North America. Algonquin refers to both the languages and the people who speak them.

alidade 31
Instrument used to measure the angle bwteen a location and a reference point. In this context it is the vertical angle of a star in relation to the ground.

alluvial deposits 7
Soil or sediments which have been transported and deposited by streams or rivers.

American Association of Petroleum Geologists (AAPG) 123
The world's foremost professional geological society involved in advancing the scientific field of geology. Often publishes highly regarded papers and reports.

Americas 38,39
The landmasses of North and South America, located in the Western hemisphere.

amphitheatre 16
A round building, typically unroofed, with a central space for dramatic or sporting events.

Anaximander (611-547 BC) 4
A pre-Socratic Greek philosopher born in Miletus. One of his pupils was Pythagoras.

ancient Greek philosophers 8, 10
A group that arose in 6th century BC. They abandoned the common use of Greek mythology to describe the world in favour of evidence and reason. Their primary focus included ethics, metaphysics and studies that sought to describe the natural world, paralleling the modern field of science (Lloyd, 1974).

andesite 113
An extrusive igeneous rock composed of feldspars and ferromagnesian minerals; andesitic magma is an intermediate magma between mafic and silicic magma.

Ångström, Knut Johan (1814-1874) 91-92
Swedish physicist who disproved Svante Arrhenius's theory of carbon dioxide's warming effect. However, his experimental data was later found to be inaccurate.

angular unconformity 57
An unconformity where younger rocks cover an erosion surface on an older layer of folded or tilted rock.

angulum 13
Ancient unit of length, approximately 1.763 cm.

anthraquinone 107
An aromatic organic molecule consisting of three fused six-membered carbon rings.

anthropomorphic 48
Attribution of human characteristics to animals or inatimate objects. Some of Leonardo da Vinci's landscape sceneries featured anthropomorphic features.

anticline 109
An upward fold in a rock formation. The oldest beds are at the core of the structure.

aragonite 45
Mineral composed of $CaCO_3$. Same chemical forumla as calcite, but with a different crystal lattice. Orthorhombic crystal system, metastable. Often converted to calcite through diagenic processes.

Arctic Institute of North America 118
An institute that aims to advance the study of the North American and circumpolar Arctic to acquire, preserve, and disseminate information on physical environmental and social conditions in the North (AINA, 2010)

Arcticon 38
A book on nautical navigation, written by Thomas Harriot and published between 1893 and 1896 (exact date unknown). No copies have survived.

Aristarchus (310-230 BC) 5
Born in Samos, Greece, Aristarchus was a Greek astronomer and mathematician. He proposed the first known theory that the Earth revolved around the Sun.

aristocracy 8
A council in ancient Greece in which the most prominent citizens or the ruling class formed a government (Ross, 2004).

Aristotelian logic 8
Also known as syllogisms. This logical argument essentially reasons that facts are determined through the combination of existing statements (or axioms). It provides the basis for classical deductive reasoning (Ross, 2004).

Aristotle (384-322 BC) 5,6,30,32,95
Greek philospher, a student of Plato and teacher of Alexander the Great.

armillary sphere 28
Early astronomical device for representing celestial features.

Arrhenius, Svante (1859–1927) 90-92
Swedish physicist and chemist who was the first to quantitatively define the influence of greenhouse gases on the surface temperature of the Earth.

Arthasastra 13
Treatise by Kautilya that described units of measures, along with other political and economic topics.

artificial horizon 73
Instrument used to provide simulated horizon for navigation.

Artis Analyticae Praxis 38
Thomas Harriot's book outlining some of his influential work in the field of algebra. It was published posthumously in Latin in 1631.

Aryabhata (476–550) 14
5th century astronomer and mathematician from India, credited with propagating many ideas in the subcontinent.

Aryabhatiya 14
Aryabhata's magnum opus, published in AD 499. *Aryabhatiya* is divided into four chapters, the first three that primarily deal with mathematical ideas while the last involves astronomy.

asthenosphere 53,101
The upper region of Earth's mantle, below the lithosphere (rigid outer shell) that behaves plastically.

asthenospheric mantle 113
The portion of the mantle below the lithosphere that is ductile.

astronomy 28,38-41
The study of celestial bodies and other non-terrestrial phenomena.

atomic bomb 102,104
An atomic bomb is a nuclear weapon in which enormous energy is released by nuclear fission (splitting the nuclei of a heavy element like uranium 235 or plutonium 239).

atomic theory 38
The theory that all matter is composed of tiny, indivisible atoms, and that the combinations and arrangements of these atoms are what determine the properties of a given material.

back-staff 39
A modified cross staff, invented independently by Thomas Harriot (1560-1621) and others that does not require users to look directly at the sun, as does a conventional cross staff.

Bactria 12
Ancient region that is now part of present day Afghanistan and Central Asia.

Barringer crater 64-67
The first crater to be properly identified as a meteoritic crater. Was initially called Canyon Diablo Crater until it was renamed to Barringer Crater to recognize the influence D. M Barringer had in determining the true origin of the crater. Was initially discovered in the 1870's and known to contain extensive amounts of iron ore.

Barringer, Daniel Moreau (1860-1929) 65, 66
An American mining engineer. Investigated the origin of Barringer Crater and determined that it was meteoritic in origin. Presented a paper in 1905 outlining 9 points proving the impact origin of Barringer Crater. These points were not conclusively validated until 1960 by Eugene Shoemaker.

basalt 113
An igenous rock composed of ferromagnesian minerals; basaltic magma is mafic.

Bathybius haekelii 69
A protoplasmic substance discovered by T.H. Huxley. It has a gelatinous structure with organic properties.

Bauer, George (1494-1555) 50
German physician and geologist who wrote De Re Metallica.

biomarker 109
Organic molecule found in sediment that can be used to correlate one deposit or formation to another (Hunt, Philp and Kvenvolden, 2002).

biosynthesis 114
A type of enzyme-catalyzed synthesis reaction in cells where complex products are produced from simpler molecules (Fondi, Giovanni and Fani, 2010).

bitumen 106
Naturally-occurring hydrocarbon deposits, excluding gases, which are soluble in organic solvents (Killops and Killops, 1993).

Black Sea **106**
Inland sea located in between the continental borders of Europe and Asia. Green pigments similar to chlorophyll have been discovered in clay sediments from this body of water (Treibs, 1936).

boreholes **7**
A narrow hole or well that is drilled into the earth. Boreholes have many uses such as extracing water or gases out of the earth or for environmental site assessments.

Boyle, Robert (1627-1691) **50-53**
English natural philosopher, considered a founder of modern chemistry. Author of *The Sceptical Chymist*.

Buchan, David (1780-1838) **72**
Naval officer and Arctic Explorer. Captain of Sir John Franklin's first expedition to Northern Canada.

Buchanan, John Y. (1844-1863) **68,69**
A European chemist who conducted the chemical research on the *H.M.S. Challenger* Expedition in 19th century. He was known to work alone and improve the equipment on the ship.

Buckland, William (1784-1856) **78**
A well-known and influential English geologist who became one of the first major supporters of Agassiz's Glacial Theory (Imbrie and Imbrie, 1979).

calcite **45**
Mineral composed of $CaCO_3$. Same chemical formula as aragonite, but with a different crystal lattice and more stable. Trigonal crystal system, stable.

calcitization **45**
Replacement of aragonite by calcite across a thin film, with dissolution of aragonite on one side of the film and precipitation of calcite on the other.

caldera **19**
A large volcanic crater (>1km wide), typically formed by a major eruption leading to the collapse of the mouth of the volcano.

Cambrian explosion **23**
The rapid appearance of complex organisms in the fossil record that occurred at the beginning of the Cambrian period (544 million years ago).

camera obscura **47**
An optical device consisting of a box with a hole in one side which allows light to pass though and strike a surface inside. The image is reproduced on the rear wall, upside down but preserving colour and perspective. Used by early artists to display a scene on a wall so that it could be more easily traced (Kemp, 1991).

Canadian Shield **23**
The exposed portion of the North American craton.

carbonate **91**
A mineral commonly found in chemically formed sedimentary rocks such as limestone and dolomstone.

Carey, Samuel (1911-2002) **110,111**
Geologist who made large contributions to the Earth expansion theory.

Carpenter, William Benjamin (1813–1885) **68-71**
A European biologist who specialized in marine zoology in the 19th century. He proposed an expedition around the world's oceans to further human knowledge of marine conditions.

cartography **4-6, 27,28**
The study and practice of making maps. Cartography is an art and science used to express natural and social features of the earth. Someone who practices cartography is called a cartographer.

Carvendel Mountains **107**
Mountain formation near the upper Isar River, which flows through parts of Germany. Treibs discovered porphyrins in a bituminous oil shale from a rock formation that is part of this mountain (Treibs, 1936).

Cavendish, Henry (1731-1810) **53**
British chemist, discovered hydrogen and calculated the mass of the Earth.

Cenozoic era **71**
A geological era spanning from 65.5 million years ago to the present. During this time the continents moved into the positions they are found in today.

Chac **21**
The Mayan god of rain, thunder and lightning.

Challenger Expedition **68-71**
A three and half year expedition on marine conditions. It lasted from 1873 to 1876 and made many discoveries and contributions to oceanography.

de Charpentier, Jean (1786-1855) **77**
Played an important role in the development of the Glacial Theory. He helped give it a foothold in scientific fact and convinced Louis Agassiz of its truth by showing him evidence of past extensive glaciations. He lived from 1786 to 1855 (Imbrie and Imbrie, 1979).

Chicxulub Crater **67**
The crater created by the meteorite believed to have caused the mass extinction event at the end of the Cretaceous period.

chlorophyll **106-108**
A green, photosynthetic pigment found in almost all plants and cyanobacteria. Structurally similar to porphyrins (Treibs, 1936).

Cigoli, Lodovico (1559-1613) **47**
Italian painter and architect who wrote about methods of achieving correct perception in his treatise *Prospettiva Pratica*.

circumference **5,6**
The distance around a closed curve; a derivative of perimeter. Circumference can be calculated using the following equation: $C = \pi d$, where d is the diameter of the closed curve.

Claudius Ptolemaeus (90-168) **4**
(see *Ptolemy*)

cleavage **26**
Specific patterns of how minerals split. Used as a classifying feature.

climate change **71**
A change in weather conditions that occurs over time and area. Climate change can refer to a gobal change or a local change.

climatology **94-97**
The study of the statistical properties of the atmosphere averaged over a period of time, including measures of average temperature, moisture, precipitation and winds.

cloud atlas **94**
A pictoral key to the nomenclature of clouds.

codex **20-22**
A Mayan "book of knowledge" whose pages were made from long strips of fig tree bark. They contained numerous tables keeping track of various cycles and were used to predict astronomical events.

Codex Leicester **34-37**
A collection of scientific writings and drawings written by Leonardo da Vinci, based on his thoughts and observations from 1506-1510.

coevolution **83**
The evolution of one species directly leads to the evolution of a related species.

coition **32**
The attractive force produced my magnets. Different from the attraction observed from static electricity.

comet **67**
An icy extraterrestrial object that rotates around the sun in a highly eliptical orbit.

comet Halley **40**
A comet (also known as Halley's Comet) with a period of 75 years, as determined by Edmund Halley in 1705. It was the first comet recognized to be periodic, and remains one of the best known comets.

comet Shoemaker-Levy 9 **67**
Discovered by Eugene Shoemaker, collided with Jupiter in 1994. Sparked interest in detecting all extraterrestrial objects that could possibly collide with earth.

compass **38,39**
A device consisting of a magnetized needle that aligns with the Earth's magnetic field, orienting the user.

conduction **61-62**
The transfer of themal energy from a higher energy molecule to an adjacent lower energy molecule.

cone **16**
A conical mountain or peak of volcanic origin.

cone sheet **19**
A dyke shaped in cross-section like a cone dipping inwards to a central pluton. It is usually explained by reference to a stress field generated by the parent pluton.

conical projection **6**
A projection used in GIS that is used to transform data points from a sphere onto a tangent or secant cone which is wrapped around the globe creating a cone. The cone is then sectioned from top to bottom and flatten into a plane (ESRI, 2010).

consolidation **55, 56**
The process of fusing loose sediments to form rocks, with the help of pressure and heat.

continental drift **98-101,110,113, 119-121**
Theory proposing that continents have moved on the surface of the Earth, proposed by Alfred Wegener in 1912.

continental plate **19**
Lithospheric plate consisting primarily of continental crust. These plates are generally older and more complex geologically than the oceanic plates.

continentality **96**
A measure of the difference between continental and marine climates due the differences in evaporation rates and heat capacities of land and water.

convection **61-62**
The cyclic movement and heat transfer of a heated fluid.

convection **119-120**
Fluid movement in the mantle of the earth

Copàn **21**
A Mayan city where stelae are distributed in a manner that corresponds to the movement of constellations and planets.

Copernicus, Nicolaus (1473-1543) **40,46,50**
A Polish Astronomer who proposed a heliocentric model of the universe, in contrast to the former Earth-centered model. Copernicus' model was not widely accepted until much later.

core, of Moon **41**
The centre of the moon, composed of heavy metallic elements and probably consisting of liquid and solid portions.

Crater **16,64-67**
Depression on the surface of the earth, usually circular or ellipitcal in shape. A large, bowl-shaped depression at the mouth of a volcano created by the eruption of a volcano.

craton **121**
Part of the continent that has been stable for a long peroid of time

Cretaceous Era **120**
145-65 million years ago

Crimean Peninsula **94,95**
Peninsula located on the northern coast of the Black Sea. Currently under the jurisdiction of Ukraine.

Croll, James (1821- 1890) **70**
A European scientist who made contributions to the field of climate change in the 19th century. He engaged in a debate with Carpenter during the *H.M.S. Challenger* expedition in 1873.

cross staff **38-40**
A device, consisting of two bars arranged in a cross, that measures the angle between two points of interest. The longer bar is pointed from the viewer's face in the direction to be measured, and the shorter bar slides along it until the two ends eclipse the two points of interest. The corresponding angle is recorded on the longer bar where it is crossed by the shorter.

cross-cutting relationships **23**
A unit of rock that has been disrupted is older than the rock causing the disruption.

crust, basaltic **41**
Dense crust composed of mafic material on the surface of a planet or other body. Examples include Earth's 10 km thick oceanic crust and the Moon's 50 km thick Lunar crust.

crust, of Moon **41**
(see *Crust, basaltic*).

cylindrical projection **6**
A projection used in GIS that is used to transform data points from a sphere onto a tangent or secant cylinder. The cylinder is sectioned from top to bottom and then flattened into a plane (ESRI, 2010).

Darwin, Charles (1809-1882) **44, 61-62,114**
British naturalist who proposed that natural selection was the mechanism for evolution. (1809-1882).

Darwin, Erasmus (1731–1802) **80**
Darwin's grandfather on his father's side. A prominent physician who wrote *Zoonomia* which speculated on biological evolution.

declination **39**
The difference, in degrees, between true north and magnetic north from any point on the Earth's surface. It must be added or subtracted to compass readings to obtain accurate geographical positioning .

deism **54**
An intellectual movement popular during the 17th and 18th century,that acknowledged the existence of a Creator but denied that the Creator interfered with the laws of the universe.

del Monte, Guidobaldo (1545-1607) **47**
Italian mathematician, philosopher, and astronomer of the 16th centruy. Published Perspectivae Libri VI in 1600 – an influential book about perspective viewed geometrically. Many artists used this knowledge in their work.

Democritus (460-370 BC) **4,5,8**
Greek philosopher who lived in Thrace, Greece. He made significant contributions to mathematics, ethics, biology, anthropology, and politics, but is perhaps most notable for his contribution to the development of the atomic theory (Ross, 2004).

deoxophylloerythrin **107**
A derivative of chlorophyll (Treibs, 1936).

deposition **56, 57**
Occurs when transported material comes to rest or settles out of suspension.

Descartes, René (1596-1650) **38, 52**
A French philosopher, mathematician, physicist, and mechanical philosopher best known for his work in the nascent fields of calculus and analytical geometry.

diagenesis **45**
The chemical alteration of the minerals in a sediment after initial deposition and before metamorphism.

Dicaearchus (350-285 BC) **5**
Born in Messina, Dicaearchus was a Greek philosopher, cartographer, geographer, and mathematician. He was another of Aristotle's students.

Dieulafait, Louis (b. 1830) **69**
A 19th century French geologist. He contributed theories regarding the appearance of manganese in the sea floor clay.

differentiation **41**
The process of separation of materials by gravity within a planet or similar body. Dense substances fall into the center of the mass, while lighter ones float to the surface.

digital elevation model (DEM) **7**
A digital representation of the Earth's surface or terrain. It is used in GIS.

diluvial **42**
Relating to a flood, specifically the universal deluge described in the Book of Genesis when the term is used in reference to the origin of fossils and geological structures.

diluvial theory **76**
The idea that geological history should be interpreted on the basis of a catastrophic flood, typically connected with the biblical Great Flood described in Genesis (Rudwick, 1969).

diluvialism **43**
The theory that geological structures were formed by the universal deluge described in the Book of Genesis.

Dirac, Paul (1902-1984) **110**
English theoretical physicist and Nobel prize winner who studied quantum mechanics and proposed an expanding Earth in 1937.

direction, magnetic **32**
Magnets have directionality. There exists a North and South pole.

disconformities **57,122-125**
Specific surfaces in stratigraphic records that represent erosion or non-deposition where strata below and above are parallel. Predicted to be related to large-scale geological processes such as glaciations.

Discourse of Neuchatel **77**
The name given to Louis Agassiz' presentation of the Glacial Theory at the annual meeting of the Swiss Society of Natural Sciences in 1837. This presentation shocked his colleagues and began heated arguments and disputes for many years to come (Imbrie and Imbrie, 1979; Rudwick, 1969).

doctrine **8**
A collection of teachings on particular principles or policies that are taught or advocated.

double-entry bookkeeping **46**
Accounting system in which every transaction changes at least two different accounts or classifications. First codified by Luca Pacioli in a mathematics textbook.

dredge **68**
A device that scrapes and collects sediment from the sea floor.

drift theory **76**
A modified version of the diluvial theory. Explains erratic deposits as being deposited by boulder-laden icebergs that drifted about in a major flood (Imbrie and Imbrie, 1979).

earth expansion theory **119**
A theory stating that the earth is expanding either by radioactive heating or decreasing gravitaional force

earthquake **16-18**
A sudden and violent shaking of the ground as a result of movements within the Earth's crust and/or volcanic action.

Egyed, László (1914-1970) **110,111**
Geophysicist who supported Earth expansion theory; published *Physics of the Solid Earth* in 1956.

ejecta **41**
Material displaced from a planet or other body during impact by a meteorite or larger body. It can normally be found surrounding the impact crater, but can be discharged into space if the impacting body is very large.

electrometer **73**
Instrument used to measure electrical charge or electrical potential.

electrophilicity **116**
A measure of how attracted the reactant is to bonding electrons: higher electrophilicity, implies higher reactivity.

Elixir of Life **50**
Theoretical alchemical substance capable of granting eternal life.

empiricism **9**
The theory of knowledge which suggests that knowledge can be extracted from sensory perception, experience, and evidence. Emphasizes that all theories must be tested through observations of the natural world (Ross, 2004).

endemic **80, 81**
An adjective used to descirbe a species native to a specific geographical area such as an island.

English Channel **102,103**
The English Channel is an arm of the Atlantic Ocean that forms a channel between France and Britain.

enzymes **116**
Biological catalysts that increase the specificity and speed of a biological reaction.

epicentre **11,87**
The point on the Earth's surface that is directly above the centre from which the shock waves of earthquakes originate.

epigenetics **83**
The study of changes in genetic expression not due to a change in the genetic sequence.

Eratosthenes (275-195 BC) **5,6**
Born in Cyrene, Eratosthenes was a Greek mathematician, poet, geographer, and astronomer. He worked as a librarian in Alexandria.

erosion **19,27-29,35,55-57**
The weathering and removal of rocks through the action of running water, ice or wind.

erratic boulders **76**
Extremely large boulders transported by glaciers that are far removed from their areas of origin. (Hansen, 1970; Imbrie and Imbrie, 1979).

ethnology **72**
An anthropology-related area of study, focusing on investiagtion of origins, culture and social structure of divisions of humanity.

etioporphyrin **107**
A violet-coloured porphyrin pigment (Treibs, 1936).

Etna **18**
The highest and most active volcano in Europe.

Euclid's *Elements* **48**
A mathematical treatise written by Greek mathemetician Euclid of Alexandria in 300 B.C. Comprised of definitions and axioms from which propositions or theorems are then deduced. The principles presented form what is now called Euclidean geometry. (Dauben 1998).

eustasy **122,125**
Positions and changes in sea level. In geology, linked to processes of regression and transgression, which can be observed in sedimentary layers.

evaporation **71**
The vaporization of a liquid. For example, the change of sea water to water vapour.

evapotranspiration **97**
The combined quantity of moisture lost through evaporation from the soil and transpiration from vegetation.

Exercise Muskox **118**
A demonstration of the use of mechanical transport during winter during WWII

extremophiles **116**
Organisms that thrive in extreme conditions.

Exxon **122-125**
A multinational, global petroleum corporation. Founded officially in 1973, but working under the 'Exxon' label for a large period in the 1960s, it represented the unification of many other oil companies under an umbrella organization. Their active involvement in science shaped the relationship between academia and industry.

facies **122**
A sedimentary unit with characterisable units. Often can be linked to a specific environment or origin. Useful in correlations.

fathom **68-70**
A unit of length that measures depth of water (1 fathom = 1.8288 metres).

fathometer **100**
A sonar-based tool used to measure water depth.

features **7**
In GIS, a feature is a representation of a real-world object on a map (ESRI, 2010).

Fischer, Hans (1881-1945) **106**
German organic chemist who won the Nobel Prize for Chemistry in 1930 for his study of hemin and chlorophyll, two biological pigments whose structures contain porphyrin rings (Kvenvolden, 2006).

fitness **117**
A relative measure of how well the individual can survive and reproduce to pass on its genetic information.

Florencian Accademia Del Cimento **42**
"Florencian Academy for Experimentation", a group of natural philosophers, notable members incude Nicolaus Steno, Francesco Redi and Giovanni Borelli.

fluvial system **29**
Physical interaction of flowing water and resulting channels of rivers and streams. Plays an essential role in transport of sediment and shaping the land's surface.

focus **11**
Refers to the literal position at which the earthquake originated, or the point where the fault begins to rupture. This position is the location where the strain energy stored in the rocks of the two plate tectonics is first released.

foraminifera **68.69**
A group of single cell marine organisms with fine strands of cytoplasm.

fossil **23,42-45,97**
Remnant or trace of an organism preserved in rock formations and sedimentary layers.

Fourier, Jean Baptiste Joseph (1768–1830) **90**
French mathematician and physicist who attributed heat receiving and conserving properties to water vapour in the atmosphere.

Fu Yin (fl. 1160) **27**
Chinese cartographer who mapped the Yellow river.

gabbro **19**
A dark, coarse-grained plutonic rock of crystalline texture composed predominantly of ferromagnesian minerals.

Galapagos **80, 81**
A group of volcanic islands in the Pacific Ocean west of Ecuador.

Galileo Galilei (1562-1642) **40,50**
An Italian astronomer, physicist and mathematician, who discovered many significant and controversial phenomena, especially with regards to the nature of gravity and the organization of the solar system.

gas chromatography **108,109**
Similar to paper chromatography, except the liquid mixture is vapourized prior to separation.

Geiger, Rudolph (1894-1981) **95,96**
German meteorologist and climatologist.

Geisel Valley **106,108**
Saxony-Anhalt, Germany. Green leaf remains and crocodile feces have been found in lignite coal deposits from this valley (Treibs, 1936).

geographic approach, the **7**
A new way of thinking and problem solving that integrates geographic information into how we understand the Earth (ESRI, 2010).

geographic information system (GIS) **7**
GIS merges cartography, statistical analysis, and database technology. It integrates hardware, software, and data for capturing, managing and analyzing and displaying all forms of geographically referenced information. It produces maps, reportas and charts that are used to show relationships, patterns, and trends in geographic data (ESRI, 2010).

geographically referenced information **7**
Information that describes the locations and attributes of things such as their shapes. These data are the composite of spatial and attribute data (ESRI, 2010).

geologic extraction **107**
A process used to isolate and study the components of a sediment sample. The desired components of the sample are extracted using appropriate solvents (Treibs, 1936).

geologic time scale **23**
A chronology of geologic time divided into eons, then eras, then periods and finally epochs.

geological maps **122**
Visual representations showing features of the subsurface on a two-dimensional figure. Useful for explaining trends and correlations.

Geological Survey of Canada **118**
Part of the Earth Science Sector of Natural Resources Canada.

geomagnetic field **12**
Earth's magnetic field that plays a role in climate and allows the use of a compass.

geomagnetism **75,119-120**
Study of magnetism or properties of the Earth's magnetic field.

geomorphology **7,29,105**
The study of the nature and the origin of landforms, including the relationships to underlying structures and processes of formation (Tinkler, 1985).

geopetal structure **49**
Sedimentary structres which can indicate whether a rock strata is oriented the right way up. Include sole marks, rain drop impressions, mudcracks, etc (Levin, 2006).

geophysicist **123,125**
A scientist using physical, often quantitative, methods and principles to study the earth's surfaces and subsurfaces.

geothermal gradient **37,61**
The increase of the Earth's temperature with depth.

giant impact hypothesis **41**
The leading theory of lunar formation, involving the collision of a large body with the proto-Earth early in Earth's history. The ejecta from the impact assembled in Earth's orbit to form the moon.

Gilbert, William (1544-1603) **30-33**
Early English physicist and natural philosopher. Notable for his contributions to the study of magnetism and electricity.

GIS **7**
(see *geographic information system*)

glacial map of Canada **118**
A map of Canada showing characteristics of surface geology

glacial theory **76**
The theory developed by Ignace Venetz, Jean de Charpentier, and further expanded and established by Louis Agassiz in the late 1830s. The theory states that glaciers were much more extensive in the past than observed at present and was used to explain phenomena such as striations in bedrock and the location of erratic boulders (Imbrie and Imbrie, 1979).

glaciation **75**
Process of covering with glaciers or masses of ice.

glaciers **29,93**
Masses of ice that move slowly. Glaciers are capable of eroding and transporting sediments.

glacitectonite **79**
A rock or sediment deformed by subglacial shearing that retains the characteristics of the parent material (Evans et al., 2006).

global climate change **105**
Changes in global patterns of rainfall and temperature, sea level, habitats and the incidences of droughts, floods and storms, resulting from changes in the Earth's atmosphere.

global cycle chart **122-124**
A large correlative chart published by Vail (Vail et al., 1977). Provides extrapolations based on local eustatic changes to model disconfomities as worldwide events. Information was used to develop geological models and predictions across the world.

global eustasy **122-125**
World-wide changes in sea-level due to events in Earth's history. Because the world's water supply is connected, a variation in one area affects all other areas.

global warming **92-93**
The increase in the Earth's surface temperature due to various natural and human-induced factors, such as the rise of atmospheric carbon dioxide.

globigerina 68,69
A type of plankton that belongs to the group foraminifera.

glossopetrae 42
Latin for "tonguestones". Rocks shaped like tongues, believed to have magical and medicinal properties until Nicolaus Steno established that they were ancient sharks' teeth.

Gould, John (1804-1881) 81
An ornithologist that helped Darwin classify the finches he observed.

GRACE 15
Gravity Recovery and Climate Experiment (NASA), an experiment that began in 2002 with the launch of two satellites. The purpose of GRACE is to collect data on the Earth's gravity field.

graebite 107
An organic arthraquinone pigment originally found in blocks of shale from Olsnitz, Germany (Mineralogical Society of America, 1934).

gravitational constant 110.119
A constant, *G*, that describes the gravitational pull (force) of the earth

great ocean conveyor 71
The global circulation of ocean water that occurs at great depths due to the changes in salinity and temperature.

greenhouse effect 91
The process by which greenhouse gases trap thermal infrared radiation from the Earth's surface, leading to an increase of the Earth's surface temperature.

greenhouse gases 90
Gases that absorb and reflect thermal infrared radiation from the Earth's surface.

ground penetrating radar 125
A geophyiscal computational method using pulses of radar (in the microwave spectra) to generate imaging of the subsurface. Can detect changes in rock types, voids, cracks, and disconformities.

Grove, Karl Gilbert (1843-1918) 64, 65
An American Geologist that created the initial theory that the craters present on the Moon's surface were created by meteorite impacts. Also known for research concerning the origin of Barringer Crater in 1891. His conclusion that Barringer Crater originated from a volcanic event was challenged in 1905 by D. M Barringer.

Gulf Stream 69
An Atlantic ocean current that carries warm water from the equator to the North Atlantic.

Gunpowder Plot 38
A failed attempt to assassinate King James I of England in 1605. Memory of the gunpowder plot has retained a presence through the centuries, particularly through the annual celebration of Guy Fawkes Day.

H.M.S. Beagle 80-81
A former ship of the Royal Navy, later used in expeditions. Darwin was on the second of these voyages.

halos 10
Optical phenomena caused by refracted and reflected light off of tiny ice crystals in the atmosphere (Aristotle and Webster, 2006).

Harappa 12
Another major city of the Indus Valley civilization.

Harriot, Thomas (1560-1621) 38-41
(also spelled Hariot, Harriet, Hariet). An English scientist who made important contributions to renaissance science, particularly in mathematics and optics.

Harvey, William (1578-1657) 50
English physician who first correctly described the circulatory system.

hasta 13
Ancient unit of length. Equal to 24, 28, 32, 42, or 52 angulum, depending on the time period and context.

Hawaii 19
A state in the United States of America that is comprised of a group of islands created by volcanic activity.

Hawaiian Islands 119-120
A chain of volanic islands produced by hot spots

ibn Hayyan, Jabir (721-815) 50
Arab alchemist, developed many early chemical processes.

van Helmont, Baptista (1579-1644) 114
A belgian scientist whose experiments attemtped to disprove spontaneous generation (Paweletz, 2001).

hemin 106-108
An iron-containing porphyrin that is structurally similar to hemoglobin (Treibs, 1936).

hemoglobin 107
An oxygen-carrying protein found in the red blood cells of almost all vertebrates. Structurally similar to mesophoryns extracted from bituminous oil shales (Treibs, 1936).

Henslow, John Stevens (1796-1861) 80
A Cambridge botany professor that introduced Darwin to science.

Herculaneum 16-18
An ancient Roman town on the lower slopes Vesuvius. It was buried along with Pompeii in the eruption of AD 79 under volcanic ash which largely preserved it until its accidental rediscovery.

Hercules 17
A hero of superhuman strength and courage in Greek and Roman mythology.

Herodotus (484-424 BC) 4,5
Born in Halicarnassus, Herodotus was a Greek historian who travelled over much of the known land to research for his works.
longer and more detailed than an essay (Aristotle and Webster, 2006).

Hess, Harry Hammond (1906-1969). 33,100
American geologist and Rear Admiral in World War II who proposed a mechanism for seafloor speading, which provided the evidence needed to substantiate the theory of plate techtonics.

hieroglyphs 21-22
Representative characters that are part of a logographic writing system which is generally not in use today.

Hilgenberg, Ott (1896-1976) 110,111
Scientist who supported Earth expansion theory; worked with the past size of the Earth and created the bud-petal model of expansion.

Hipparchus (190-120 BC) 5,6
Born in Nicaea, Hipparchus was a Greek astrologer, astronomer, geographer, and mathematician.

Hitler, Adolf (1889-1945) 104
Adolf Hitler was an Austrian-born German politician and the leader of the National Socialist German Workers Party, commonly known as the Nazi Party.

Högbom, Arvid (1857-1940) 91-92
Swedish geologist who worked with Svante Arrhenius in the early 20th century. He and Arrhenius were the first scientists to recognize that the industrial use of coal could amount to a net increase in atmospheric carbon dioxide level.

Holmes, Arthur (1890-1965) 99
British geologist. Proposed convection in the mantle as a mechanism for continental drift.

hominid 23
A member of any upright, bipedal primate family. Modern examples are humans, orangutans, gorillas and chimpanzees.

Hooker, Joseph Dalton (1817–1911) 81
British botanist and friend of Charles Darwin.

hot spots 120
A locatin on the crust, away from faults, that experiences volcanic acvitiy due to rising mantle plumes

Hsi, Chu (1130-1200) 27
Chinese scholar who made hypotheses about the origins of fossils.

humus 16
The organic component of soil, formed by the decomposition of leaves and other plant material by soil microorganisms.

Hun Hunahpu 21
The Mayan god of maize.

Hutton, James (1726-1797) 44,54-57
Scottish geologist known as the founder of modern geology. His most notable contributions included his hypotheses regarding the formation of rocks, the age of the earth and the uniformity of geological processes.

Huxley, Thomas Henry (1825-1895) 44, 61-62,69,82
English biologist and supporter of Darwin. contributed information to the theory of abiogenesis. Engaged in a series of debates with Lord Kelvin regarding his theory on the age of the earth.

hydrogeology 102
Hydrogeology (*hydro* meaning water, and *geology* meaning the study of the Earth) is the area of geology that deals with the distribution and movement of groundwater in the soil and rocks of the Earth's crust.

hydrophone 87
A hydrophone is a device that receives sound waves. It is towed behind a survey ship.

hygrometer 73
Instrument used to measure relative humidity of atmosphere.

ice age 75
Period of time where the earth is largely covered by glaciers.

ice cap 75
Mass of snow and ice covering a large region of land. Smaller than 50,000 km^2.

igneous Rock 16,65
A rock formed, or apparently formed, from the solidification of magma. Examples of igneous rocks include obsidian and basalt.

impact craters 64-67
Depressions formed by the impact of a meteorite.

impact event 64-67
Describes an event in which a meteorite decends into earth's atmosphere, causing an impact with the surface, and potentially creating an impact crater.

Imperial College of Tokyo 85
Now called the University of Tokyo. It is one of the most prestigious universities in Japan (Clancey, 2006).

Imperial Earthquake Investigation Committee 85
A committee that was formed in 1892 to study seismology. This group of people initiated the study of seismology in Japan (Clancey, 2006).

inclination 32
The inclination, or dip, of a compass needle. The angle which the needle varies from the plane of reference of the compass.

Indus Valley 12
Temperate valley formed by the Indus River that sustained the civilization of the same name.

International Geophysical Year (IGY) 118
A collaboration between 67 nations from July 1957 to December 1959 to observe the earth with sychronized equipments to obtain global data

International Union of Geodesy and Geophysics (IUGG) 118
An international organization dedicated to advancing, promoting, and communicating knowledge of the Earth system, its space environment, and the dynamical processes causing change (IUGG, 2010)

iron ore 67
A rock from which iron can be extracted.

island arc 113,119-121
A line of volcanoes in the shape of an arc; formed by subduction processes, associated with convergent plate boundaries.

isostasy 98
Idea that crust of the Earth is isostatic. Namely, the crust can move up and down vertically, but not side-to-side.

isostatic movement 29
Vertical movement of sections of Earth's crust to achive equilibrium.

isotherm 95
A contour line on a map joining locations of equal temperature. Temperature gradients are perpendicular to isotherms.

isothermal 61
A body or surface of uniform temperature.

Ito Chuta (1868-1954) 86
A Japanese architect who studied ancient Japanese shrines and temples. He is well-known for the first modern national style, *shajiyo* (Clancey, 2006).

Ito Tamekichi (1864-1943) 86
A Japanese architect who created the Triangular House. The goal of his architectural career was to build earthquake-proof buildings (Clancey, 2006).

Jameson, Robert (1774-1854) 57
Scottish naturalist and mineralogist known for his mapping of the mineralogy of Scotland.

Japan Weekly Mail **85**
Newspaper published in the 18th and 19th centuries. It was originally published by *Japan Times*, Yokohama (Clancey, 2006).

Jupiter **16**
The chief god of the Roman state religion, originally a sky god associated with thunder and lightning.

Kautilya (350–283 BC) **13**
Advisor to first Gupta Emperor Chandragupta Maurya and author of Arthasastra. Also known as Chanakya.

Kelvin, Lord (1824–1907) **60-63**
(see *Thomson, William*)

Kepler, Johannes (1571-1630) **38,50**
German astronomer; discovered a set of rules that govern the motion of planets, among other contributions to math and science.

kerogen **109**
The polymer precursor to petroleum. Can be changed into petroleum products if exposed to appropriate temperatures for appropriate periods of time during compaction and burial (Killops and Killops, 1993).

Kinich Ahan **21**
The Mayan sun god who became a jaguar at night and descended into Xibalba to do battle with the evil deities who lived there.

Kirwan, Richard (1733-1812) **44**
Irish scientist who disputed James Hutton's geological theories.

Köppen climate classification system **94-97**
Mapping system dividing global climatic zones. Devised by Wladimir Köppen.

Köppen, Wladimir (1846-1940) **94-97**
Russian-born climatologist, paleoclimatologist, geologist, meteorologist and botanist during the late 19th to early 20th centuries.

Kotō Bunjiro (1856-1935) **86**
A Japanese geologist and seismologist. His major research areas were earthquakes and volcanoes (Clancey, 2006).

Krumbein, William C. (1902–1979) **123**
A mathematical geologist with research in the field of sedimentology.

Kuo, Shen (1032-1095) **26-28,30**
Influential Chinese scientist who made early hypotheses about erosion and the change of environmental conditions over time.

de Landa, Fray Diego (1524–1579) **20**
A Spanish bishop who burned most of the Mayan codices in the 1500s.

landslide **84**
The general term used to describe the downslope movement of rock or soil. Examples of landslides include rock falls, and debris flows.

Langley, Samuel Pierpont (1834-1906) **90-91**
U.S. physicist and engineer who led an expedition to Mount Whitney to collect data on the infrared radiation emitted by the moon. His experimental data was later used by Svante Arrhenius for calculations of the effect of carbon dioxide on the Earth's climate.

lapilli **16**
Rock fragments ejected from a volcano.

latitude **5,6**
The angular distace north or south of the equator measure in degrees. Lines of latitude are also referred to as parallels.

latitude **38,39**
A measure of distance from the equator, given in degrees from the Earth's core. Thus, the equator has latitude 0° and the poles have latitude 90°.

lava **16**
Hot molten, semifluid or solid rock erupted from a volcano or fissure.

Lavoisier, Antoine (1743-1794) **52**
French chemist, considered a founder of modern chemistry.

layers **7**
A visual representation of a geographic dataset in a digital map environment. A layer can be thought of as a slice of geographic reality in a particular area. For example, on a road map, a layer could be considered the roads, national parks or rivers. (ESRI, 2010).

Lehmann, Johan Gottlob (1719-1767) **44**
German minerologist and geologist, conducted significant research in the area of stratigraphy..

Leonardo da Vinci (1452-1519) **34-37, 42,46,48**
Italian polymath living during the Renaissace age, author of *Codex Leicester*.

lignite **106**
Often referred to as brown coal. A soft, brown, low-quality coal.

Limestone **20,91**
A sedimentary rock composed of calcium carbonate.

linear perspective **47**
A form of perspective in drawing and painting based on the idea of a vanishing point. Parallel lines converge to a common point on the horizon. Allows for the depiction of depth and distance.

lipids **117**
A subset of organic molecules that includes fats, vitamins and phospholipids.

lithification **57**
Creation of sedimentary rocks through the consolidation of sediments.

lithosphere **101**
Rigid outermost layer of Earth, also known as the crust.

lodestone **30**
Naturally magnetised rock due to the presence of magnetite. Magnetic alignment of these stones corresponds to the Earth's magnetic field at the time when the rock solidified.

longitude **5,6**
The angular distance of the location of a point on the Earth's surface that is east or west of an arbitrarily defined meridian. It is measured in degrees, minutes, seconds.

lunar eclipse **22**
Astronomical event when the moon passes through the Earth's shadow.

Lyell, Charles (1797-1875) **61-62, 80-82**
British geologist, friend of Charles Darwin, author of *Principles of Geology,* and founder of the theory of uniformitarianism

Macedonia **8**
Ancient kingdom (800-146BC) in what is now northern Greece. Because of conquests led by the

kingdom's monarchy, the kingdom was the most powerful state in the Western world, controlling much of modern day Europe (Harper, 2004).

Maclaurin, Colin (1698-1746), 54
Scottish mathematician, who is best known for his work on Taylor Series.

Magoules 7
A term refering to the settlements established in the Neolithic period in Thessaly, Greece.

de Mandeville, Jean (fl. 1350-1370) 47
An anonymous French illuminator and court artist during the Middle Ages. Among his works was a depiction of St. John at Patmos.

Manhattan Project 103,104
Codename for a project conducted during World War II to develop the first atomic bomb. Led by the United States, with participation from the United Kingdom and Canada.

mantle 101
A thick sphere of rock that separates the Earth's crust from the Earth's core.

mantle plume 19
A localized column of hot magma rising by convection in the mantle, known to cause volcanic activity in hot spots, such as the Hawaiian Islands, away from plate margins.

mantle, of Moon 41
The portion of the moon between the central core and outer crust. Little is known about the Moon's mantle.

maria 40,41
Large flows of basaltic lava on the moon, which are visibly darker than the surrounding highlands. They were once believed to be oceans, as reflected by their name, *maria* being Latin for "seas".

mass extinction 23
A global event in which more than 20% of marine genera become extinct.

mass spectrometry 108,109
A technique that can identify substances by their differing charge-to-mass ratios.

Matthews, Drummond (1931-1997). 33
British marine geologist and geophysicist. Together with Fredrick Vine provided geomagnetic evidence which confirmed the theory of seafloor spreading.

Maya 20-23
An ancient civilization and culture that was located in present-day Belize, western Honduras and El Salvador, and the Chiapas and Yucatán peninsula of Mexico. They had significant knowledge of astronomy, mathematics and time cycles.

Mayan Calendar 20-23
Three interlocking calendars used by the Mayans to keep track of time.

Mayan Mathematics 22
A system of mathematics used by the Mayans that was base twenty and the first recorded to use the concept of zero.

McClintock, Sir Francis Leopold (1819-1907) 73
Arctic explorer who found a page on King William Island with notes from Franklin's crew and the date of Franklin's death.

mechanical philosophy 52
Renaissance metaphysical theory, suggesting that living things are like machines, composed of inanimate parts lacking order or intrinsic relation to one another.

Meiji Restoration 84
A revolution that modernized Japan's economy and politics. It started in 1868 when Emperor Meiji overpowered the former rulers of the Tokugawa government (Clancey, 2006).

melt-out till 79
Sediment released by the melting of slowly moving, debris-rich glacier ice that lacks subsequent transport or deformation before it is deposited (Evans et al., 2006).

meridian 6
An imaginary, arbitraly defined line on the Earth's surface from the North Pole to the South Pole. It conects all locations the same longitude. An example of a common meridian is the Greenwich prime meridian (ESRI, 2010).

mesoporphyrins 107
Another name for a series of blood pigments that includes hemin (Treibs, 1936).

Mesozoic era 71,111
A geological era spanning from 250 million years ago to 67 million years ago. The break up of Pangea occurred in this time.

metallurgist 104
A metallurgist is an engineer trained in the extraction, refining, alloying and fabrication of metals.

metamorphic rock 57
Rock produced by metamorphism, the process by which a pre-existing rock is converted into a new rock due high temperature and pressure.

meteorite 64-67
A meteoroid that has reached the earth's surface.

meteoroid 64-67
A stony or metallic extraterrestrial object that enters the earth's atmosphere.

meteorology 94,95
The study of the atmosphere focusing on weather processes and short term forecasting.

microcosm-macrocosm 46
Ancient schema of seeing the same patterns reproduced at all scales of the cosmos. A micrococm is something that represents the universe, or humanity, in miniature. Microcosm is the converse – the universe or some other entity that contains smaller structures (Rosenberg, 2009).

mid-ocean ridge 53, 100,101,105,110,112,119-121
A mid-ocean ridge is an underwater mountain range, typically having a valley known as a rift running along its spine, formed by plate tectonics. This type of oceanic ridge is characteristic of what is known as an oceanic spreading center, which is responsible for seafloor spreading.

Milanković cycles, theory 93,95
Mathematical model describing the effects of Earth's orbit on its surface temperature proposed by Serbian mathematician Milutin Milanković during the First World War. This theory has been revised many times by later scientists, and is now the most important theory in prediciting glacial/interglacial cycles. Milanković theory describes the collective effect of the Earth's movements (Milanković cycles) on the amount of solar radiation reaching the Earth and thus facilitating climate changes.

Miller, Stanley (1930-2007) **115**
American scientist who poineered the Miller-Urey experiment (Joseph, 2010).

Mohenjo-daro **12**
Key city in the Indus Valley civilization.

Moon **36-37,40,41**
The single natural satellite of the Earth, with an orbital period of 29 days. Moon can also refer to the natural satellites of other planets. Leonardo da Vinci presented the theory of planetshine, explaining the moon's luminosity, years before it is proven and accepted.

Moon, formation of **41**

Murray, John (1841-1914) **68,69**
A European naturalist who led the biological research on the *H.M.S. Challenger* Expedition in the 19th century. He made many important contributions to life and Earth science.

naksatra dina **14**
Sanskrit term for sidereal day.

Nalanda **14**
Buddhist center of higher learning in Eastern India from AD 427-1197.

Naniwa Cotton Textile Mill **85**
A three-story red brick building built in the usual English factory style. It collapsed in the Nōbi Earthquake of 1891 (Clancey, 2006).

Nares, George Strong (1831- 1915) **68**
A British navel officer and explorer. He was the captain of the *H.M.S. Challenger* in the 19th century. He lived from 1831 to 1915.

natural philosophy **50-51**
Philosophy of nature. Term used prior to definition of modern science; a precursor to natural and physical sciences.

navigation **38-39**
The set of tasks required to determine one's location on the globe and manage a route to a destination while avoiding hazards, primarily as concerns maritime travel.

New World **38,39**
(see *Americas*)

Newton, Isaac (1642-1727) **50-54,118**
English natural philosopher, physicist, mathematician, astronomer, alchemist, and theologian; developer of calculus and classical mechanics.

Nōbi Earthquake **84**
A powerful earthquake that hit the Nōbi Plain in 1891. It is also known as Mino-Owari Earthquake (Clancey, 2006).

Nōbi Plain **84**
An extensive plain in Japan that covers from the Mino region of southwest Gifu to Owari region of northwest Aichi (Bolt, 2003).

nonconformity **57**
An unconformity where younger sedimentary or volcanic rocks overlie much older plutonic or metamorphic rocks.

North America **38,39**
A New World continent in the Northern Hemisphere.

North Sea **123**
A shallow sea off the coast of Great Britain, spanning the Atlantic Ocean until Scandanivia. Considered an epeiric sea, or one that lies atop continental crust. Vail's research was conducted here.

North Star **39**
(see *Polaris*)

nuée ardente **16**
An incandescent cloud of gas, ash, and lava fragments ejected from a volcano, typically as part of a pyroclastic flow.

numerical dating **23**
Dating techniques used to find the actual age of a rock or fossil.

O, Shan (fl. 1059) **27**
Chinese cartographer who mapped rivers and lakes.

ocean basin **120-121**
An area on earth that is covered or filled with seawater

ocean current **69-71,75**
Movement of ocean water not related to tides that is continuous and directed, based on temperature and salinity changes.

oceanic trench **112,113**
A trough found at convergent boundaries; site where subduction takes place.

oceanography **71**
A field within earth science that studies the biological, physical and chemical properties of oceans.

oikoumene **4**
The term used by the Greeks to denote the habitable areas of the known world.

Omōri Fusakichi (1868-1923) **85**
A well-known seismologist who served as president of the Imperial Earthquake Investigation Committee. He was a professor of seismology in the Imperial College of Tokyo (Clancey, 2006).

Omōri's Law **85**
A theory argued by Omōri Fusakichi about the occurrence of earthquake aftershocks. He argued that the aftershock frequency decreased with increasing time after the initial shock.

Oparin, Alexander (1894-1980) **117**
Soviet scientist who developed the Oparin-Halide thoery (Joseph, 2010).

Operation Overlord **103**
'Operation Overlord' was the code name for the invasion of western Europe during World War II by Allied forces. The operation began on 6 June 1944 with the Normandy Landings (commonly known as D-Day) when an airborne assault preceded an amphibious assault.

optical isomers **115**
Molecules of the same composition and structure, but mirror images of each other (much like the right and left hand). Biological systems only use L-amino acids. D-amino acids, which are optical isomers of L-amino acids, are incompatible with cellular machinery and are, therefore, biologically inactive (Joseph, 2010).

organic compounds **114**
A molecule consisting of carbon typically bonded to oxygen, nitrogen and hydrogen.

organic geochemistry **106,108**
A branch of science that studies the origin, composition, and distribution of organic substances in rocks and sediments (Durand, 2003).

ornithologist **81**
A scientist that specializes in the study of birds.

outer planets 115
Refers to Jupiter, Saturn, Uranus and Neptune.

P and S Waves 87
P and S waves are types of seismic waves or energy waves produced by an earthquake. They have different travel velocities, and these differences are used to locate earthquake epicenters.

Pacioli, Luca (1446-1517) 46
Italian mathematician and Franciscan friar who worked with Leonardo da Vinci. Known as the "Father of Accountring". First codifed the system of double- entry bookkeeping in a mathematics textbook published in 1494.

palaeontologist 123,124
A scientist observing Earth's past, usually by looking at and correlating fossils.

Palaeozoic era 120
542-251 million years ago

paleoclimatology 94-97
The study of climate on the scale of the entirety of earth history.

paleoclimatology 98,99
Study of ancient climates, also known as paleoclimates.

paleomagnetism 110,111
The study of the Earth's past magnetic fields.

Paleozoic era 111
The time period 542-251 million years ago in which Pangea was formed.

Pangea 71,98,99, 110,111
Supercontinent that existed during the Paleozoic and Mesozoic era and contained almost all of the present continents into a single landmass. Began to separate 225 million years ago.

paper chromatography 108
A technique that separates a liquid mixture of substances by their differing polarities.

parallel 5,6
An imaginary east-west line that encircles the Earth and is parallel to the equator. A parallel connects all lines of equal latitude.

Pasteur, Louis (1822-1895) 117
French scientist and the father of modern bacteriology (Joseph, 2010).

Percy, Henry (1564-1632) 38
The 9th Earl of Northumberland, given the moniker "Wizard Earl" for his interest in the sciences and mysterious personality.

Peregrinus, Peter (fl. 1269) 30,31
Early French academic who conducted and recorded experiments on magnetism. Author of the first documented scholarly journal.

Perraudin, Jean-Pierre (1767- 1858) 79
A mountaineer from the Southern Swiss Alps who conceived the theory of glaciation. He brought his ideas to the attention of Charpentier, who initially was unconvinced, and Ignace Venetz (Imbrie and Imbrie, 1979).

Perry, John (1850-1920) 61-62
British geologist and student of Lord Kelvin, who argued against Kelvin's assumption of an entirely solid earth.

Persians 4
An ethnic group native to Iran, Tajikstan, and Afghanistan. The Persian language is their mother tongue.

perspectograph 47
An instrument for obtaining, and transfering to a picture, the points and outlines of a given object so as to represent that object with proper geometric proportions (Kemp, 1991).

petrification 26
Fossilization of organic material.

petroleum 106-109
A term used to describe a broad variety of hydrocarbon-rich liquids and gases that originated from organic material and evolved over time through biological and thermal processes (Killops and Killops, 1993).

Phanerozoic Eon 23,124
The portion of geologic time from 542 million years ago to the present with an abundant fossil record; made up of the Paleozoic, Mesozoic and Cenozoic eras. The targeted eon in the rock record to find fossil fuel reserves.

Philosopher's Stone 50, 52
Alchemically theorized substance capable of transmuting base metals into gold.

Phoenician 4
Civilization that spread across the Mediterranean during 1550-300 BC. The Phoenicians were heavily involved in the maritime trading culture.

photometer 73
Instrument used to measure the luminous intensity of a light source by comparing it to a standard light source.

piezometer 68
A device that measures water levels at a specific depths below the Earth's surface.

planetshine 36
The phenomenon that occurs when sunlight is reflected from a planetary body to illuminate the dark side of a nearby moon.

plate tectonics 75, 105,110-113, 118,120
A theory explaining continental drift in which the Earth's surface is composed of plates that move and collide.

Plato (429-347 BC) 8,10
Greek philosopher, writer, mathematician and founder of the first institution of higher learning in the Western world, the Academy in Athens. He studied the subjects of philosophy, logic and mathematics most extensively (Harper, 2004).

Plato's Academy 8
School founded in Athens by Plato in 387 BC that taught many famous philosophers (Harper, 2004).

Pleistocene epoch 93
The Earth's most recent glacial period that began around 2.5 million years ago (Armitage, 2005).

Pliny the Younger (61– ca. 112) 18
A Roman senator and writer that was the nephew of the Roman statesman and scholar Pliny the Elder. Pliny the Younger's letters to Tacitus provide a detailed description of the eruption of Vesuvius in AD 79.

Polaris 39
A star nearly aligned with the axis of rotation of the Earth. As a consequence, its position is fixed in the sky above the North Pole and it can be used for navigation.

polymath 26
Individual whose knowledge and studies cover a broad range of topics.

Pompeian **17**
Citizen of the ancient Italian city of Pompeii.

Pompeii **16-18**
Ancient Italian city that, with Herculaneum, was buried by the eruption of Vesuvius in AD 79.

porphyrin **106-108**
Aromatic organic compound consisting of four modified pyrrole subunits. Forms the bases of the structures of chlorophyll and hemin (Treibs, 1936).

Posidonius (135-51 BC) **6**
Born in Apameia, Posidonius was a Greek philosopher, politician, astronomer, geographer, historian, and teacher.

positive feedback **93**
A system in which the response to an environmental disturbance increases the magnitude of the disturbance. For example, low atmospheric carbon dioxide level leads to the cooling of the Earth, which reduces the rate of weathering of geological materials. Slow weathering processes further decrease the amount of atmospheric carbon dioxide.

Precambrian era **23,111**
The time period 4500-542 million years ago, made up of the Hadean, Archean and Proterozoic eons, when the surface of the Earth began to cool and form a crust. The era represents 87% of the geologic time scale and precedes the Phanerozoic eon.

Precambrian Shield **118**
The exposed part of the North American craton.

precipitation **69-71**
Water in the atmosphere condenses and falls to the Earth as rain, snow and various other forms. It is also a type of chemical reaction where a nonsoluble substance is formed from a solution.

precision **15**
A measure of distribution of repeated measurements. Measured values that are close to each other are more precise.

principle of lateral continuity **23**
States that an original layer of sediment will extend laterally and thin at the edges.

principle of original horizontality **23**
States that sediment deposited in water will originally form horizontal or nearly horizontal beds.

principle of superposition **23**
States that the layers of a sequence of volcanic or sedimentary rocks will decrease in age from bottom to top so long as the sequence is undisturbed.

printing **26**

Prodromus **42**
Latin for "The Forerunner", title of Nicolaus Steno's dissertation. The dissertation was intended to be the forerunner for a later, more detailed work that was never written.

progenitor **80, 83**
Another word for ancestor often used in reference to an evolutionary ancestor.

projection **6**
A method by which a curved surface of the Earth is portayed on a flat surface. GIS software can apply a systematic mathematical transformation of the Earth's lines of latitude and longitude onto a plane (ESRI, 2010).

Prospettiva Pratica **47**
Treatise published in 1583 by Lodovico Cigoli addressing several themes crucial to perspective drawing, including the use of mathematical instruments.

proto-Atlantic Ocean **120**
An ocean basin that existed prior to the opening of the Atlantic Ocean that is in the same location as the current Altanic Ocean

protobiont **117**
Organic matter contained within a membrane (Chela-Flores, 1985).

protoplanets **11**
Large, moon-sized celestial bodies, precursors to planets, surrounded by a planetary disc that eventually aggregate together under the influence of gravity, increasing the mass, leading to the eventual formation of planets (Levin, 2009).

protoplasm **68,69**
Cell material such as the cytoplasm, proteins and nucleic acids contained in a plasma membrane.

proxy data **97**
Information used for indirect measurement of past climate (or other) characteristics.

psudotachylytes **67**
Melted and fused rocks found at nuclear and impact craters. The high pressure environments created by these events cause the surrounding rock to fracture and fuse together, creating this type of rock.

Ptolemy (90-168) **4-6**
Roman citizen of Egypt who wrote in Greek. He was culturally Greek and was therefore considered a Greek mathematician, astronomer, geographer, astrologer, and poet.

pumice **18**
Very light and porous volcanic rock formed when a gas-rich froth of glassy lava solidifies rapidly.

Puranas **12**
Collection of religious texts on various topics including the Earth, similar to the Rig Veda.

pyramid temples **21**
Sacred stone Mayan temples built to resemble mountains, which the Mayans believed housed the souls of ancient ancestors. These temples were used for worshipping and as tombs.

Pythagoras (570-495 BC) **4**
Born in Samos, Pythagoras was a Greek philosopher and mathematician.

Pytheas (4th century BC) **5**
Born in Massillia, Pytheas was a Greek geographer and explorer. His exact dates of birth and death are unknown.

radioactive decay **63**
Process by which larger atomic nuclei split into smaller nuclei via the release of energy and ionizing particles

radiocarbon dating **97**
Using measurement of the radioisotope carbon-14 in carbonaceous materials to estimate the age of the organism.

radiometric Dating **23**
Dating technique that determines the age of a rock based on ratios of its isotopic elements to their decay products.

Rae, John (1813-1893) **74**
Doctor and explorer of arctic regions and Northern Canada. Brought first news of Franklin's expedition's fate to British authorities.

Raleigh, Sir Walter (1552-1618) **38,39**
English explorer who funded expeditions to the New World. He fell out of favour with King James I and was executed for atheism.

von Rebeur Paschwitz, Ernst (1861-1895) **87**
German scientist, who first observed the seismic waves created by an earthquake.

Redi, Francesco (1626-1697) **114**
Italian scientist who attempted to disprove spontaneous generation (Ruestow, 1984).

regression **122,125**
Drop in sea-level causing water to recede from the land, extending shorelines seaward. Represented by disconformities in the rock record.

relative age dating **23**
Dating techniques that sequence events by looking at when they occurred relative to one another.

relief map **27**
Map with raised, vertical representations of topographical features.

remote sensing **7,104,105**
Remote sensing is the science of acquiring information about the Earth using instruments which are remote to the Earth's surface, usually from aircraft or satellites. Instruments may use visible light, infrared or radar to obtain data.

reservoir rock **109**
A porous and permeable rock through which petroleum can migrate. If the migrating petroleum encounters a structural or stratigraphic trap, it can accumulate to form a new petroleum reservoir.

revelation **9**
In religion and theology, the revealing of some form of information through active or passive communication with supernatural beings.

Oldham, Richard Dixon (1858-1936) **87**
British geologist who initiated the use of P and S waves to study interior of the earth.

rift **112**
A valley created at divergent plate boundaries when two plates are pulled apart.

Rift Valley **121**
Valley found at diverging plate boundaries on continents

Rig Veda **12**
Collection of Vedic hymns on various topics including the Earth; part of the Vedas.

Ring of Fire **84**
Areas fringing the Pacific Ocean characterized by collisinal plate margins where frequent earthquakes and volcanic eruptions occur.

ring-dyke **16**
Intrusive igneous body that has either a concentric or radial geometric distribution around a centre of volcanic activity.

rotation, magnetic **33**
Magnetic rotation is the movement seen by object when placed in a magnetic field. The object rotates to align with the magnetic field.

Royal Society **52**
Learned society formed in London in 1660 for the discussion and advancement of science.

satellite altimetry **15**
The measure of terrain elevation and oceanic depths by satellites that bounce microwave signals off land or the ocean floor to measure the time difference.

de Saussure, Horace-Bénédict (1740-1799) **55**
Swiss physicist and geologist who was also an early alpine explorer.

Scientific Revolution **50**
Period of 16th and 17th century development of scientific theory that witnessed the birth of the modern fields of science and overturned the theories held since ancient Greece.

Scotland **19**
A country in northern Great Britain and the United Kingdom whose landscape was highly influenced by volcanic activity.

sea floor spreading **100,101**
Concept proposed by Harry Hess that ocean floor is moving away from mid-ocean ridges.

sea floor spreading **110-113**
Process of creating sea floor at mid-ocean ridges.

seafloor **87**
The solid surface underlying seas or oceans comprised of basaltic lava with variable sediment cover.

second law of thermodynamics **60-61**
Every transformation of energy results in the loss of usable energy in the form of heat.

sediment **28,29**
Particles of rock of varying sizes created by erosion and transported by water, ice or wind.

sediment **56**
Loose fragments that are produced by weathering and erosion of pre-existing rocks.

sedimentary rock **57**
Rocks that form through the lithification of sediments, the precipitation from solution, or the consolidation of plant and animals remains.

sedimentary strata **92**
Layers of sedimentary rocks that are studied by geologist to understand the orgin, composition and changes of the layers.

seismic reflection **87**
A technique used in geophysical exploration that analyses the reflection of seismic waves from subsurface geological boundaries.

seismic refraction **87**
A technique used in geophysical exploration that analyses the refraction or bending of seismic waves as they pass between different types of subsurface geological materials.

seismic stratigraphy **122-125**
A methodology in stratigraphy using geophysics to model and predict the subsurface. Used primarily in the oil industry.

seismic wave **87**
A wave of energy generated by an earthquake.

seismic waves **11**
Radiating waves of energy created by the sudden breaking of rock within the Earth due to stress induced by the differential movement of rock masses.

seismograph 87
Seismograph is a measuring instrument that can measure and record the direction, intensity, and duration of ground motions.

seismologists 9,11
Scientists who study the creation and propagation of seismic waves in geological material.

seismology 85
The study of earthquakes and related occurrences such as tsunami.

seismometers 11
Instruments used to measure and record the motion of the ground at specific locations.

sequence stratigraphy 122-125
A specific study of straigraphy focussed on a timescale, connecting repetitive, environmentally-related strata by observing disconformities. Eustatic principles are used to describe stratigraphy in this field.

sextant 73
Instrument used to measure angle between celestial objects.

shale 106,107
A fine-grained rock consisting of fissile silts and clays. Commonly forms in deep marine environments.

shatter cones 67
V-shaped geologic structures created under high pressure during impact events and nuclear explosions. The apex of a shatter cone points toward the source of the pressure.

Shoemaker, Eugene (1928-1997) 66, 67
An American geologist who validated Barringer's theory concerning the origin of the Barringer Crater. Co-discovered Comet Shoemaker-Levy 9 which collided with Jupiter in 1994.

sial 110-112
Term for continental crust composed of silica and aluminum.

Siccar Point 56,57
A rocky point that juts into the sea in Scotland. It is famously the site of James Hutton's 1788 recognition of an unconformity.

sidereal day 14
Period of time it takes for the Earth to rotate exactly 360°; c.f. solar day in which the Earth's revolution around the sun is taken into account.

sima 111
Term for oceanic crust composed of silica and magnesium.

Sloss, Lawrence (1913-1996) 122,123
A sedimentary geologist, Peter Vail's Ph.D. supervisor. Founded theories of eustasy and straigraphy in North America as well as research in cratonic relationships.

Smith, William (1769–1839) 122
An English geologist known as "the Father of English Geology," famous for collecting geologic history of the United Kingdom and compiling the data in visual representations.

social arena 124
Defined by Strauss (Strauss and Corbin, 2008), it is a sociological construct whereby opposing social worlds must meet to debate an issue (not an element of culture or background, but rather a future issue) that concerns them both. Often, a lack of meeting at the social arena causes miscommunications.

social world 124
Defined by Strauss (Strauss and Corbin, 2008), it is a sociological construct of a collection of groups sharing similar resources, goals, or principles. A specific group can be part of many social worlds based on this definition. A social world thus encompasses a sphere of groups of common backgrounds.

Socrates (469-399 BC) 10
Greek philosopher, who became famous both for his teachings of logic and ethics, and for his many famous students, including Plato (Harper, 2004).

solar eclipse 22
When the moon passes between the Sun and the Earth, blocking it from view.

sonar 100
Sound-based navigation and ranging technique.

Song Dynasty 26-27
Ruling Dynasty in China between 960 and 1279.

source rock 107-109
A fine-grained sedimentary rock that has generated and released enough hydrocarbons to form an accumulation of oil or gas (Hunt, Philp and Kvenvolden, 2002).

species disparity 83
The morpholigical differences between species. The physical differences between species.

species diversity 83
The number of species present.

spheroid 119
A three-dimensional eplipse

spontaneous generation 114
A theory that states that life can emerges from matter other than seeds, eggs or parents.

stellae 21
Tall stone Mayan structures with histories of rulers and cities carved into them. Also called "tree stones."

Steno, Nicolas (1638-1686) 42-44,48,49,57
Danish pioneer in anatomy and geology. Formulated three Principles of Geology which initiated the science of Stratigraphy. Author of *The Prodromus*.

Strabo (63 BC-AD 23) 18
A Greek geographer and historian.

strata 55, 57,122
Layer of rock or soil that has consistent internal characteristics that distinguishes it from the surrounding rock layers. Each strata typically represents a unique environment, and can be correlated regionally.

stratigraphic trap 109
A succession of sedimentary rocks that traps petroleum in a certain strata and prevents it from migrating.

stratigraphy 23,49, 122-125
Branch of geology that studies the layering of rock, known as stratification, as well as layered rocks in general (Levin, 2006). The study includes analysis of the composition, ages, and environments of these layers.

Strauss, Anselm (1916-1996) 124
An American sociologist who developed the qualitative analysis of grounded theory, used in explaining sociologist principles across disciplines.

structural trap 109
A rock structure that traps petroleum and allows it to accumulate, such as an anticline.

subduction **101,112,113,121**
The process in plate tectonics where one plate slides underneath another at a convergent boundary.
subduction zone **87**
The area in which one tectonic plate slides beneath another. Relatively dense plates consisting of oceanic crust are subducted beneath lower density continental plates.
subglacial processes **76**
Processes which occur in the region underneath a glacier. They ultimately depend on the interaction between water, ice, bedrock and sediment in the region of ice-bed contact (Evans et al., 2006).
subglacial traction till **79**
Sediment deposited from a glacier base by frictional drag on sediment within the basal ice and by pressure melting of sediment-rich basal ice (Evans et al., 2006).
suevites **67**
Sedimentary rock structure formed when airborne rocks settle to the surface of the earth. Primarily created in nuclear and meteoritic events.
sunspots **40,41**
Dark spots on the surface of the sun, visible from Earth. Sunspots are due to magnetic anomalies at the surface of the sun.
surveying **41**
The act of determining the precise positions of terrain points, often for the purpose of making maps.
Tacitus (AD 56-120) **18**
Roman historian.
taxonomy **46**
The practice and science of classification.
Taylor, Frank Bursley (1860-1938) **98**
American geologist. First to describe relation in shape between the coastlines of continents.
tectonic plates **29**
Large scale crustal layers that make up surface of Earth. Plates move on plastic materials of the asthenosphere and shift over long periods of time.
telescope **40,41**
A set of lenses used to magnify distant objects so that details can be observed that are normally too small to distinguish from one another..
Tennant, Smithson (1761-1815) **53**
English chemist, discovered elements iridium and osmium. Proved diamond is made of carbon.
terrain **102,103**
Terrain is a piece of ground having specific geological characteristics or military potential.
terrella **32**
"Little Earth." Spherical magnet, invented by William Gilbert, used as a representative of the Earth and its magnetic field.
Tertullian, Quintus (ca. 160-ca. 220) **42**
Christian author from Carthage.
Thales of Miletus (624-546 BC) **30**
Pre-socratic philosipher from Asia Minor. Considered the first of philosopher in Greek Tradition.
The Nine Chapters on Art of Mathematics **48**
Chinese mathematical text written by generations of scholars beginning from the first century BC Comprised of problems accompanied by solutions, algorithms and explanations of solving the problems (Dauben 1998).
The Sceptical Chymist **51**
Treatise by Robert Boyle, published in 1661, rejected alchemical theory and promoted the modern definition of chemistry.
Titans **17**
Any of the older gods who preceeded the Olympians and were the children of Uranus and Gaia. Led by Cronus, they overthrew Uranus and then Cronus's son, Zeus, rebelled against his father and eventually defeated the Titans.
Theory of the Earth **54, 55**
James Hutton's paper exploring his hypotheses on the age of the earth, and the uniformity of geological processes. Originally published in 1778.
thermohaline circulation **71**
The circulation of ocean water that occurs at great depths due to the changes in salinity and temperature.
Thomson, William (1824-1907) **60-63, 119**
Prolific British scientist, mathematician and physicist. Made Baron Kelvin of Largs, Ayrshire in 1882 for his achievements.
Thomson, Wyville (1830-1882) **68,70**
A European naturalist who was part of the team of scientists on the *H.M.S. Challenger* Expedition in the 19th century. He contributed theories for the movement of Antarctic water in 1875.
Thornthwaite, Charles (1899-1963) **96,97**
American geographer and climatologist during the 20th century.
three dimensional (3d) modelling **125**
The use of computing to generate visualizations in three dimensions. Clarifies the realistic relations between subsurface layers.
tides **41**
The gravitational attraction between the Moon and terrestrial bodies of water.. The bodies of water rise and fall in a twelve hours cycle in accordance with the Earth's rotation upon its axis.
Tikal **21**
A Mayan city known as the "city of the dead" which had the most impressive stone pyramid temples of this region.
timelines **122,125**
A specific word to describe disconformities emphasizing that it represents a point in time.
Titus (AD 39-81) **16**
Roman emperor from AD 79-81.
Tokugawa government **84**
A government that ruled Edo, which is now called Tokyo, from 1603 to 1868. The government was not open to western countries (Clancey, 2006).
topography **102-105**
The configuration of a surface and the relations between its man-made and natural features.
Torporley, Nathaniel (1564-1632) **38**
An English mathematician and clergyman, Torporley was a student of Thomas Harriot.
Tower of London **38**
A castle on the river Thames, London, that was initially a royal residence, but was then transformed into a heavily guarded prison, holding many notorious political prisoners.

transform faults **119-120**
Horizontal shear faults along which movement occurs that results in crustal displacement paralled to the faults

transgression **122,125**
A rise in sea-level causing water to submerge the land. Pushes shorelines landward. Represented by sediments in the rock record.

transitional form **80**
Extinct species that illustrate a major evolutionary change by posessing charecteristics of both an older ancestor and its successor.

trawl **68**
A net that is pulled through the water by a boat. It is used for fishing.

treatise **9**
A systematic and formal written discourse about the principles of a subject, generally

tree rings **97**
Also known as growth rings. Visible rings seen in horizontal cross-sections of tree trunks in which approximately one ring grows annualy.

Treibs, Alfred E.(1899-1983) **106-108**
German scientist who, in 1936, isolated and identified porphyrin molecules from bituminous oil shales. These molecules closely resembled the biological molecules chlorophyll and hemin (Treibs, 1936).

Trewartha, Glenn (1896–1984) **96,97**
American geographer during the 20th century.

***Tria Prima* (Three Primes)** **51**
Alchemical philosophy of three spiritual and physical traits of matter: Mercury (liquid/solid transition and spirit of life), Sulphur (expansive force) and Salt (contractive force).

Triangular House **86**
A building that was designed by Ito Tamekichi. Ito built this building, hoping that it would withstand earthquakes (Clancey, 2006).

triangulation **39**
A surveying technique that uses angles and distances to uniquely identify a triangle and precisely determine relative positions of multiple points.

trilobite **23**
An ancient, extinct marine arthropod that first appears in the fossil record during the Cambrian explosion of life.

tuff cone **16**
A steep, conical volcanic hill with a deep, wide crater composed of thin layers of fine pyroclastic fragments.

Tyndall, John (1820-1893) **90**
British physicist who demonstrated the high heat absorbency of water vapour, carbon dioxide and ozone. He reasoned that a drop in atmospheric carbon dioxide content would lead to an ice age.

U-boat **105**
Military submarines operated by Germany during World War I and World War II.

U.S. Geological Survey **103**
The United States Geological Survey (USGS) is a scientific agency of the United States government. The scientists of the USGS study the landscape of the United States, its natural resources, and the natural hazards that threaten it.

unconformity **57**
A surface where the rock stratum directly above the surface will be much younger than the rocks beneath it. It represents a gap in the depositional sequence and geologic record.

uniformitarianism **54, 55, 61-63**
The theory that the natural processes that operate now are the same as the processes that occurred in the past.

universal deluge **42**
Flood described in the Book of Genesis, Chapters 6 to 9. Only animals and humans on Noah's ark were said to have survived.

University of Toronto **118**

upper alpine Triassic strata **107**
Part of the Carvendel Mountains in Germany. Treibs studied samples from this formation and later identified porphyrins in these samples (Treibs, 1936).

upwelling **71**
The movement of cold, dense water to the sea surface due to wind movements.

Urey, Harold (1893-1981) **115**
Nobel-prize winner for chemistry who helped develop the Miller-Urey experiment (Joseph, 2010).

Ussher, James (1581-1656) **44,54**
(also spelled Usher). Irish Archbishop, claimed that the date of creation was October 23rd, 4004 BC by analyzing the events of the Bible.

Vail, Peter (b. 1930) **122-125**
An American geologist and geophysicist known for his work in sequence stratigraphy and developing the model for global eustasy and global cycle charts.

vanishing point **47**
Point in a perspective drawing at which all imaginary lines of perspective converge.

Vedic period **12**
Period in Indian history ranging from around 1500-500 B.C., and characterized by the religious texts written during this time that are collectively known as the Vedas.

Venetz, Ignace (1788-1859) **76**
A Swiss naturalist who wrote a paper describing what can be considered as the first true glacial theory (Imbrie and Imbrie, 1979).

Venus **21-22**
A sinister Mayan god whose appearance was considered to be a bad omen.

Verhaecht, Tobias (1561-1631) **48**
Painter and draughtsman who focussed primarily on landscape painting. Among his many works was a Renaissance depiction of St. John at Patmos.

vesicles **117**
Closed structures that form spontaneously when certain lipids are placed in water. Formation is due to hydrophilic and hydrophobic interactions between the non-polar lipid molecules and polar water molecules (Koch, 2010).

Vesuvius **16-18**
An active volcano in southern Italy whose eruption in AD 79 buried the towns of Pompeii and Herculaneum.

Vine, Fredrick (b. 1939) **33**
Marine geologist and geophysicist. Together with supervisor Drummond Matthews provided

geomagnetic evidence which confirmed the theory of seafloor spreading.

Virginia **39**
An American state. The term was used broadly in 16th Century England to describe a significant portion of the North American coast and inland regions.

visual pyramid **47**
A concept of linear perspective which maintained that a group of light rays converge precisely onto a single point in the eye (Kemp, 1991).

Vitruvius (fl. 1st century BC) **18**
Roman architect and military engineer.

volcanic craters **64**
Depression formed on top of a volcano due to volcanic activity.

volcanism **64, 65**
A phenomenon asscociated with volcanoes and volcanic activity. Typically involving the eruption of lava and the effects of lava on its surroundings.

volcano **19**
A mountain or hill, typically conical, constructed by the extrusion of lava or rock fragments from a vent.

Wallace, Alfred Russel (1823-1913) **82**
British naturalist that independently derived the theory of natural selection

water, movement of **34-35**
Leonardo da Vinci studies the properties of water in his *Codex Leicester*.

weather telegraphy **94**
Transmission of weather-related information over long distances.

weathering **90-91**
Physical and chemical processes that change rocks at the Earth's surface.

Wedgwood, Emma (1808-1896) **81**
Darwin's wife. They had 10 children together.

Wegener, Alfred (1880-1930) **95,98,99,119**
German geophysicist and meteorologist. First to propose theory of continental drift and existence of the supercontinent Pangea.

Western Front **102,103**
Western Front was a term used during the First and Second World Wars to describe the "contested armed frontier" between lands controlled by Germany to the East and the Allies to the West.

Wedgwood, Josiah (1730-1795) **80**
Darwin's maternal grandfather and founder of industrialized pottery.

wholesale dissolution **45**
The process whereby aragonite dissolves and leaves an impression of its shape in a sediment. The mold is filled by precipitated calcite (Donovan, 1991).

Wilberforce, Samuel (1805-1873) **82**
Bishop of Oxford; opposed Darwin`s views.

Wilson cycle **120-121**
Cycle of closing and re-opening of ocean basins.

Wilson, John Tuzo (1908-1993) **118-121**
Canadian geologist and geophysicst

Wöhler, Friedrich (1800-1882) **114**
German scientist who synthesized urea.

woodblock painting **84**
Technique called woodcut in Western printing. It was first used in China, but adopted in Japan in the Edo period (1603-1867) (Clancey, 2006).

World Tree (wakachan) **20**
A tree connecting the Mayan Earth to the celestial realm above and to Xibalba below, which facilitated the passaged of souls between these three realms.

World War I **99,102-105**
A military conflict that lasted from 1914 to 1918 and involved most of the world's great powers, assembled in two opposing alliances: the Allies (centred around the Triple Entente) and the Central Powers.

World War II **100,102-105,118**
A global military conflict lasting from 1939 to 1945 which involved most of the world's nations, including all great powers, organised into two opposing military alliances: the Allies and the Axis.

Xibalba **20-21**
The Mayan underworld.

Yaxchilán **21**
A Mayan city with many stelae around its pyramid temples to mirror the trees around the city.

yojanam **13**
Ancient unit of length, equal to 16,000 *hasta*. The Vedas gave the circumference of the Earth as 5,000 *yojanam*, which is 39,491.2 km around if a *yojanam* is taken to equal 28 *angulum*.

zenith **39**
The highest point in the sky reached by a celestial body, such as the sun, moon or stars.