1. Introduction

1.1. The scientific method

Science is about understanding how nature works. It is carried out by making ***hypotheses*** based on ***observations*** and/or ***experiments***. Hypotheses are confirmed, revised or refuted as scientists keep exploring nature, conducting new observations and performing new experiments. A set of hypotheses explaining some aspect of nature is called a ***theory***.

<u>Darwin's theory of evolution by natural selection</u>

One fundamental scientific achievement that greatly improved our understanding of nature is *Charles Darwin*'s (1809-1882) theory of evolution by natural selection[*]. Darwin's theory explains how new species can arise and how life evolved from simple microbial forms more than 3.5 billion years ago to the complex animals and plants we see today. Darwin's discovery is often refers to as the "Darwinian Revolution". *Stephen Jay Gould*, a famous American paleontologist, summarizes Darwin's theory in three points: (1) organisms belonging to the same species display variations (color, size…) inherited by their offspring, (2) organisms produce more offspring than can survive, and (3) as a consequence of (1) and (2), organisms with more advantageous traits have a greater chance to survive and reproduce (they are naturally selected).

Darwin tells us that if a population of organisms of a particular species becomes reproductively isolated from other members of the same species, the combination of new environmental constraints and random genetic mutations may lead to the formation of a new species after many generations. *Darwin*'s understanding of evolution came in part from his observations of species geographic distribution during his journey around the world on board HMS Beagle from 1831 to 1836. For instance, *Darwin* noticed a resemblance between the animals of the Galapagos Islands and those of the American continent. He hypothesized that the Galapagos Islands must have been colonized by organisms from America and that these organisms subsequently evolved in isolation to form new species by natural selection[**]. *Darwin*'s theory is also based on his study of domesticated pigeon breeds. He experimented with the artificial selection of different varieties of pigeons by crossing individuals with particular traits. He surmised that given enough time (after many generations) nature could produce different species much like a professional breeder can produce different varieties of domesticated animals, or farmers different varieties of fruits and vegetables.

The issue of time was crucial to *Darwin*'s theory. There was no consensus at that time about the age of the Earth and many still believed the Earth was very young, perhaps as young as several thousands of years, much too young for *Darwin*'s idea of natural selection. *Darwin*'s view of the geological time scale was influenced by a book he was reading on board HMS Beagle called "Principles of Geology" written by a prominent British geologist named *Charles Lyell*. This book recognizes the need of huge time

[*] Note that the same idea was proposed independently by another British naturalist: Alfred Russel Wallace (1823-1913).

[**] Darwin's finches famously illustrate how birds originating from the same species can evolve into distinct species by adapting to various environments (e.g. species with pointed beaks for picking fruits, species with shorter, larger beaks for eating seeds on the ground).

spans to explain the slow and progressive changes shaping Earth's landscape. This naturally appealed to *Charles Darwin* whose theory of evolution by natural selection requires long stretches of time (millions of years) to evolve new species by the slow and progressive accumulation of tiny modifications.

There are different ways of doing science. For instance, theoretical physicists do not draw conclusions from a set of data in the same manner that *Darwin* did to elaborate his theory. Theoretical physicists use the language of mathematics to explain how nature works. Their findings are then confirmed of refuted by observations and/or experiments. General, basic principles explaining how nature works are referred to as ***physical laws***. Examples of such laws are Newton's three laws of motion and his law of universal gravitation which explain the relationship between the motion of an object and the forces acting upon it.
When a natural system becomes relatively well understood, it is possible to create a ***scientific model*** explaining its behavior and predicting its response in different conditions. In geology for example, materials with different densities can be used to simulate rock layers in the lab and examine how they behave when exposed to different kinds of stress (analog modeling). Our understanding of natural systems can also be translated into computer models. Computer modeling has become a major tool to simulate natural processes. Computer models which are the most familiar to us are probably those used to predict the weather. We see the output of these models everyday in the news.

1.2. What is Earth Science?

Earth science is a multidisciplinary science and its purpose is to study the Earth. ***Geology*** is the study of the solid earth (e.g. its history, composition, internal structure, and surface features). Geology is composed of various disciplines. For example, ***paleontology*** is the study of past life based on fossils. ***Geophysics*** and ***geochemistry*** aims at understanding geological processes using tools and principles of physics and chemistry, respectively. Geology is based on the study of the ***geological record***, i.e. the information preserved in rocks formed at various times. Data of geological interest are primarily collected through field observations, rock sampling, lab analyses, geological and topographic mapping, seismic surveys, aerial photography, and satellite remote sensing (e.g. gravimetry).
Other branches of Earth science include ***oceanography*** —the study of the oceans—, ***meteorology*** —the study of the atmosphere—, ***glaciology*** —the study of ice and ice-related processes—, and ***geobiology*** —the study of the interactions between the biosphere, the lithosphere and the atmosphere—. Note that all these disciplines are themselves multidisciplinary. Over the past few decades, progress in space exploration has enabled us to look at the planets of our solar system at an unprecedented level of details. Our understanding of the geological

processes occurring on Earth combined with a wealth of data collected by satellites and land-based missions (e.g. Mars exploration rovers) are key to the study of the planets of our solar system (***planetary science***).

1.3. A brief history of geology

More than 2000 years ago, Greek philosophers were already trying to solve geological problems. For instance, they had noticed the presence of seashells in sediment layers well above sea level. *Erastosthenes* (3rd century BC) suggested that sea level may have fallen after the opening of the Strait of Gibraltar. *Strabo* (ca. 63 BC – ca. AD 24), on the other hand, proposed that catastrophic events such as earthquakes, volcanic eruptions, or landslides, had resulted in repeated sea level changes.

Another question exciting the curiosity of Greek philosophers was related to the more fundamental issue of the evolution of the Earth. By observing nature, they knew that rivers can carve deep valleys. They surmised that the process of erosion of hard rocks by water must be slow and progressive and must act over an extensive period of time to incise large mountains. Hence, Greek philosophers had already a sense of the ***long duration*** of the geological time scale. Moreover, they pondered about the continuous destruction of rocks by erosional processes which implies that mountains are meant to disappear on the long run unless they are regenerated by some other processes. This idea relates to the ***cyclic*** nature of geological processes which is central to modern geology (see plate tectonics and the rock cycle explained in the following chapters). Different scenarios were imagined by different schools of philosophers to explain the evolution of the Earth (see related slide). Although these ideas were inspired by observations, Greek philosophers were not scientists because they did not try to test their hypotheses.

Centuries later, a French philosopher named *René Descartes* (1596-1650), best known for his mathematical legacy (Cartesian coordinates) and philosophical work (e.g. Discourse on the Method and his famous “cogito ergo sum” —I think therefore I am—), elaborated a theory on the formation of the Earth and the origin of mountains and oceans. Based on his theory, the Universe is composed of three types of matter. One is the matter that composes the stars. Another is the matter that composes terrestrial bodies like the Earth. The third is the matter that composes the sky. Stars evolve into planets by forming an external crust. The Earth is thus a former star and possesses a central fire, remnant of its stellar origin. Various layers surround the central fire, including an internal ocean. The Earth’s landscape —mountains and ocean basins— is the result of the irregular collapse of the solid external layer. Although this idea has been completely refuted by later studies, it influenced generations of scientists who favored the idea of collapse rather than uplift to explain the formation of mountains. We know now that mountain chains can form by uplift where two tectonic plates converge but the theory of tectonic plates and our modern understanding

of mountain formation came to light only 300 years after the death of *René Descartes*!
An important step in the history of geology is marked by the achievements of a Danish anatomist named *Nicolas Steno* (1638-1686) who is considered to be the first "true" geologist. In the 17th century, the biological origin of fossils was not yet accepted. *Steno* identified a previously mysterious fossil called *Glossopetrae* as being the remains of the teeth of once-living sharks. He was also the first to formulate two fundamental principles of geology: the ***principle of horizontality*** and the ***principle of superposition***. The first states that sediments are originally deposited horizontally; the second that older layers are at the bottom and younger layers at the top. *Steno* also realized that different assemblages of fossils represent different environments, and therefore that fossils can be used to reconstruct past environments. This is a fundamental concept underpinning modern ***stratigraphy***, the study of layered rocks.

A hot debate which kept geologists busy in the 18th and 19th century opposed the *neptunists* and *plutonists*. The first school of thoughts was led by a German geologist named *Abraham Gottlob Werner* (1749-1817) and the second by a British geologist named *James Hutton* (1726-1797). Based on the neptunistic viewpoint, the Earth was originally covered by a global ocean. Most rocks found on Earth formed under water, including granites and basalts. We know now that granites and basalts form instead by crystallization of a cooling magma. The neptunists believed that mountains were formed by a combination of erosional and depositional processes in the ocean. For them, Earth's internal heat had little influence on the evolution of the landscape. Conversely to this view, the plutonists considered Earth's internal heat as the main driving force behind the formation of mountains and ocean basins. They correctly recognized the link between granites, basalts, and volcanic activity.

Another popular theory of the 19th century is called *contractionism*. It is based on the assumption that the Earth's interior is progressively cooling; as the Earth cools and contracts, the rigid external crust deforms. This deformation results in the creation of mountains and ocean basins, much like the wrinkles forming at the surface of a drying apple.

Another question that was central to geology in the 19th century was to know whether we can use our knowledge of present-day geological processes to understand the past. More simply put: ***is the present the key to the past?*** Two very different schools of thoughts emerged: *uniformitarianism* and *catastrophism*. The uniformitarianists, led by *Charles Lyell* (1797-1875), held the view that the history of our planet is characterized by geological processes that are still acting today. Hence, it is possible to understand the past based on a careful study of the processes shaping our modern landscape. The catastrophists, led by the French naturalist *Georges Cuvier* (1769-1832), emphasized the importance of catastrophic events which have no analogue with present-day phenomena to explain the evolution of our planet (cataclysmic earthquakes, volcanic eruptions or floods). Our modern understanding tells us that the basic idea behind uniformitarianism is true. We can indeed understand a great deal about the past based on our knowledge of geological processes occurring today. For instance, we can recognize beach deposits or river beds in the fossil record by analogy with modern sediments. We can recognize old mountain chains (e.g. Appalachian Mountains) and understand how they formed based on the study of active plate boundaries (e.g. Andes, Himalayas). However, the catastrophists were not entirely wrong because we know now that exceptional events like the impact of a very large meteorite or huge volcanic eruptions never witnessed in historical times have happened in the distant past and will happen in the future. For instance, the most widely accepted and best documented cause of the disappearance of the dinosaurs 65 million years ago is the impact of a very large meteorite off the Yucatan Peninsula.

The Newtonian revolution in physics took place in the 17th century. Geologists also have their revolution but it happened only recently in the mid-20th century. Although various theories explaining the formation of mountains and ocean basins, earthquakes and volcanoes have been proposed since the Greek antiquity, it is only in the 1950s that we began to understand the mechanisms behind these phenomena. The story begins with the discovery of ***continental drift*** by *Alfred Wegener* (1880-1930). Wegener compiled evidence supporting the fact that the position of continents is not fixed. However, he had no clue regarding the mechanism driving this movement. The time of Wegener’s discovery is also the time at which radioactivity was discovered by *Henri Becquerel* (1852-1902). Soon after, *Ernest Rutherford* (1871-1937) came up with a technique to date rocks based on the decay of radioactive isotopes which confirmed the old age of the Earth. The link between Earth’s internal heat and radioactivity was soon established, which led a British geologist named *Arthur Holmes* (1890-1965) to propose that heat produced by radioactivity could generate convection movements beneath the Earth’s crust and drive continental drift. The final pieces of the puzzle were put together in the mid-20th century when bathymetric surveys of the ocean floor led to the discovery of mid-ocean ridges. Dating of the ocean crust on both sides of these ridges showed that the age increases with the distance from the ridge. Based on this and other supporting evidence, geologists formed a theory known as the theory of ***plate tectonics*** (for details about plate tectonics, see chapter 3 of this course). Based on this theory, the Earth’s external rigid layer is divided into plates. Plates are moving relative to one another. New ocean plate is formed at mid-ocean ridges where two plates are pulled apart. Mountain chains form where two plates converge. Volcanoes and earthquakes are primarily located along plate boundaries where tectonic forces are concentrated. The theory of plate tectonics is at the core of modern geology and has revolutionized our understanding of the Earth and its history.

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