Module 7
ORIGIN OF THE GEOSPHERE

Introduction

This module is about the origin of the planet we live in. The Earth is unique because it has liquid water, a well-oxygenated atmosphere, and most importantly, life. In the beginning, however, the Earth was not entirely conducive to life. It is important to understand the complex interplay of processes resulting in the formation of the world we live in.

This module discusses the main hypothesis about the formation of the geosphere, which is basically the physical Earth. First, the module relates the concept of self-assembly discussed in the previous module to the formation of the main "body" of the Earth. The process of self-assembly at the planetary scale (in the form of accretion and differentiation) allowed for the segregation of elements within the Earth, forming layers with different chemical and mechanical properties. Then we focus on the lithosphere, the mechanical layer consisting of the crust and the uppermost mantle. This sets the stage for the production and recycling of rocks at or near the surface. Lastly, dynamic superficial processes in the geosphere led to Plate Tectonics. We will examine how this concept was established from two main theories and explore evidence that supports Plate Tectonics theory.

We hope that as you study this module you will realize that many complex processes contributed to forming and shaping the Earth. In fact, all of the concepts you studied up to this point in this course were crucial in creating the Earth! To develop your understanding, it is important for you to read the key texts indicated and answer the study questions before going to class. Suggested enrichment readings are listed at the end of the module if you would like to explore further the origin of Earth.

Learning Outcomes

After studying this module, you should be able to:
1. Discuss ideas about the origin of the geosphere;
2. Describe the formation of the lithosphere and its components; and
3. Explain how Plate Tectonics Theory developed.

1.0 Planetary Accretion and Differentiation

The previous modules introduced you to the formation of the universe, the elementary particles that were created with it, and the coalescence of these particles to form atoms and light elements. The creation of heavier elements, which required more energy, was achieved through supernova nucleosynthesis (recall Module 4). These heavier elements combined to form molecules and compounds and, through self-assembly, formed into more complex molecules. But the process of self-assembly occurs not only at the atomic scale; the formation of protoplanets is also a type of self-assembly but on a planetary scale. More specifically, the protoplanets were formed through a process that is technically called **accretion**.

Recall that the nebular hypothesis states that a swirling cloud of gas and dust provided the materials for the formation of the protoplanets, which are the "seeds" from which the main planets of the solar system came to be. You also learned that elemental distribution is a function of the distance of a planet from the sun, with rocky, denser terrestrial planets being nearer to the sun, and large, less dense jovian planets being farther from it. As the protoplanets grew larger, their gravitational force also strengthened, and they became denser as heavier elements sank towards the center of each protoplanet. **Differentiation** describes the segregation of elements *within* a protoplanet.

The processes of accretion and differentiation led to the creation of the geosphere.

Activity 7-1

A. Read pages 102-110 of Chapter 6 (The Origin and Early Evolution of the Earth) of Dott & Prothero's (2004) book *Evolution of the Earth* (a copy of this reading is available at the SCIENCE 10 course site on your CU's VLE), and answer the following questions:

1. What were the early ideas on the probable origins of the Earth (and the solar system)?
2. Explain how distance from the sun influenced the major elemental assemblage of the Earth.
3. How did scientists determine that the interior of the Earth is zoned and not homogeneous? Enumerate the evidences that they studied and explain how these helped in determining that the Earth is layered.

B. Watch Naked Science – Birth of the Earth (at https://www.youtube.com/watch?v=XYHe5wQeA28) and prepare a comparison (similarities and differences) of the concepts introduced in the video with the ideas presented by Dott & Prothero (2004). Be ready to share your insights in class.

As discussed by Dott & Prothero, the nebular hypothesis (recall this from Module 3) is the most widely accepted explanation of the formation of the solar system. This hypothesis proposes the simultaneous origin of the sun and the planets, unlike earlier notions stating that the planets are derived from materials from a preexisting sun.

Although distance from the sun is one factor in elemental availability, we must note that elemental segregation does not *fully* segregate the elements such that light elements are found only in the jovian planets and heavy elements, such as iron and nickel, are found only in the terrestrial planets. Chemical theory suggests that heavy elements decrease in abundance as distance from the sun increases. This is governed by the temperature of the solar nebula, as most of the heavy elements condense in hotter environments. The density of the Earth is greater than the density of the rocks found in the crust. Therefore, there should be *heavier* materials *inside* the Earth. This led to the speculation that the Earth's interior is zoned. Further evidence of the Earth's internal structure is presented by differences in the behavior of waves as they travel through the Earth, and the existence of the magnetic field. The compatibility of elements in certain phases determines the components available for each zone in the Earth's layers. The differentiation of the Earth's compositional layers allowed the segregation of elements and thus influenced the availability of materials on the surface. As gravitational strength increases near the center, the behavior of the Earth's layers also differs even if some of these zones are of similar composition. Thus, the interior of the Earth is classified based on its composition and its mechanical properties.

Activity 7-2

Visit the USGS website at https://pubs.usgs.gov/gip/dynamic/inside.html and study the different compositional and mechanical layers of the Earth. Answer these questions:

1. How many compositional layers does the Earth have? Describe the composition of each layer.
2. How many mechanical layers does the Earth have? Describe the phase (solid, liquid, gas) and strength (rigid, ductile) of each layer.
3. The mesosphere is a mechanical layer that is rigid and composed mainly of iron and magnesium. In which part of the figure in the USGS website is the mesosphere located?

Be ready to share your answers in class.

1.1 Formation of the Lithosphere

We now focus on the uppermost mechanical layer of the Earth which includes the crust and the uppermost mantle — the lithosphere. The mantle is relatively heavier in composition (magnesium and iron) compared to the crust and is further differentiated based on its mechanical property. The upper mantle is more ductile in nature and can flow; the crust "rides" on top of the uppermost mantle. The crust is further divided into two based on composition — the continental and oceanic crust. Their composition has implications on the density and distribution of the two kinds of crusts on the lithosphere.

Activity 7-3

Read pages 111-114 (Dawn of Earth's History) of Chapter 6 (The Origin and Early Evolution of the Earth) of Dott & Prothero's (2004) *Evolution of the Earth*, and the introduction (on pages 57-58) of Condie's (1989) paper *Origin of the Earth's Crust* (a copy of the readings are available at the SCIENCE 10 course site on your CU's VLE). Answer the following questions:

1. Why is the creation of the continental crust more complicated than the creation of the oceanic crust?
2. Explain why the inhomogeneous accretion and impact models introduced by Condie (1989) are problematic as an explanation for the formation of the Earth's crust.
3. Explain why the terrestrial model of Condie (1989) is the most successful in explaining the origin of the Earth's crust.

Be ready to discuss your answers in class.

You may have noticed that the discussions concerning the lithosphere focus mainly on the Earth's crust rather than the whole lithosphere. It is the crust that is the most affected by the surface dynamics of the Earth. The segregation of the more brittle crust and the more ductile upper mantle is discussed by Dott & Prothero in terms of chemical differentiation. The relatively lighter elements (e.g., oxygen, silicon, aluminum) are retained in the continental crust while the heavier elements (e.g., iron, magnesium) are concentrated in the oceanic crust.

Condie (1989) presented three models to explain the origin of the Earth's crust. The inhomogeneous model suggests that the last elements to condense in the solar nebula were the lightest, which may have produced the first crust rich in silicon, oxygen, and aluminum. Although this model adheres to the notion of chemical differentiation of the elements, the model states that the crust was formed from the condensation of the *solar nebula*. The impact model proposes that asteroids with a similar composition to the crust produced the first continents, with the impact creating intense heat that led to the melting of the Earth's crust, which resulted in the production of both oceanic and continental crusts. But while it is true that innumerable asteroids have plummeted towards the Earth's surface, clues from the rocks in the Earth's moon suggest that basalt, a key component of the Earth's oceanic crust, formed on the surface of the moon *after* the impacts. The exponential increase in pressure for a very short time caused by impacts from asteroids should result in a peculiar form of the minerals exposed to the event — however, this is absent in rocks of similar age. Finally, the terrestrial model points to processes that operate *within* the Earth, which corroborates Dott & Prothero's discussion of the formation of the crust.

Our understanding of the first hundred million years of the Earth's history is speculative and based on limited evidence. Only isolated exposures of Hadean (~4.60-4.00 billion years old) rocks have ever been found, and most information is obtained through the study of undifferentiated meteorites. When the geosphere and lithosphere were formed cannot be determined exactly, which is why the mechanisms of their formation are subject to much research and debate. Current models will surely be improved as more data become available through scientific investigation.

2.0 Continental Drift and Seafloor Spreading

You may have learned in your earth science class in high school that the dynamics occurring in the Earth's crust is primarily due to plate tectonics. **Plate Tectonics Theory** includes the movement of the continents, creation of mountain ranges, and occurrence of hazards such as volcanic eruptions and earthquakes. Although this theory is now called the "unifying theme of geology", earlier works that bolstered the idea of plate tectonics were faced with great skepticism.

Early ideas on surface dynamics came from observations that igneous rocks are usually found parallel to the axis of mountain ranges. Scientists like James Hutton and Leopold von Buch believed a so-called vertical force pushed the rocks from the interior. Others argued that the contraction of the crust caused folding and the creation of mountains, which are horizontal forces. However, two of the most important concepts in laying the foundation for plate tectonics are the Continental Drift Theory and the Seafloor Spreading Theory by Alfred Wegener and Harry Hammond Hess, respectively. We will take a close look at these two theories.

Activity 7-4

Read Wegener's (1912; 2002) *The Origins of Continents* and Hess's (1962) *History of Ocean Basins* (a copy of this reading is available at the SCIENCE 10 course site on your CU's VLE), and answer the following questions:

1. What types of evidence were presented by Wegener and Hess to support their respective hypothesis on continental drift and seafloor spreading?
2. Why were their hypotheses not accepted by other scientists during their time?
3. Why were their respective ideas considered "revolutionary" at the time they were proposed?

Wegener's Continental Drift Theory explained several phenomena that puzzled scientists during his time, such as (1) the fit of the South American and African coastlines; (2) the presence of similar mountain ranges across continents; and (3) the presence of coal deposits near the poles (which are otherwise cold places). Wegener proposed that all of the continents were joined into one single landmass, which he called Pangea, and the movement of the continents plowed against oceans. Some of Wegener's suggestions for explaining the movement of the continents include tidal friction and the Earth's rotation. Although the exact mechanisms for these drifts were not yet understood at that time (as acknowledged by Wegener himself), Wegener's paper presented unequivocal evidence suggesting that continents were probably once joined together in the past and they subsequently drifted to their present-day location, which resulted in such features as mountain ranges and mid-ocean ridges, among others. However, despite the evidence, the mechanisms proposed by Wegener were rejected by physicists because these forces were thought to be too small/weak to drive crustal movement.

It was only in the 1960s that seafloor exploration began, providing new data on the oceanic crust. Hess (1962) published a paper proposing the mechanism for continental drift that Wegener failed to provide in his paper, namely, seafloor spreading. Instead of continents plowing through the oceanic crust, it was proposed that the continents "rode passively on a convecting mantle". In Hess's paper, mid-ocean ridges are postulated as areas representing the rising limbs of mantle convection cells, the area where mantle materials come to the surface, pushing the continents away from each other at a particular rate. This is supported by the age and thickness of the sediments on top of the ridge, which become older and thicker towards the edge of the basins. This contrasts with the circum-Pacific region, which represents the descending limbs of the convection cell, and where deformation and volcanism are prevalent. The relatively thin cover sediments on the seafloor, the absence of rocks older than the Cretaceous period, and the relatively small number of seamounts suggest a young seafloor, contrary to the idea of "ocean permanence," which was also addressed by Wegener (1912; 2002).

2.1 Plate Tectonics

Since the publication of the papers by Wegener (1912; 2002) and Hess (1962), numerous studies have provided compelling evidence of continental drift and sea floor spreading, now collectively known as the **Plate Tectonics Theory**.

Geomagnetism, the study of the Earth's magnetic field, provides support for the idea of magma generation along mid-ocean ridges as predicted by Hess. The simplified illustration in Figure 1 (next page) shows how magnetic imprints are developed along mid-ocean ridges. As the magnetic field of the Earth reverses in direction (i.e., the magnetic north is transferred to the south), minerals within the rocks will align themselves to that field. It has been shown that these magnetic reversals are strikingly symmetrical (albeit not perfect) parallel to the mid-ocean ridge axis, providing strong evidence that magma generation does happen along these ridges.

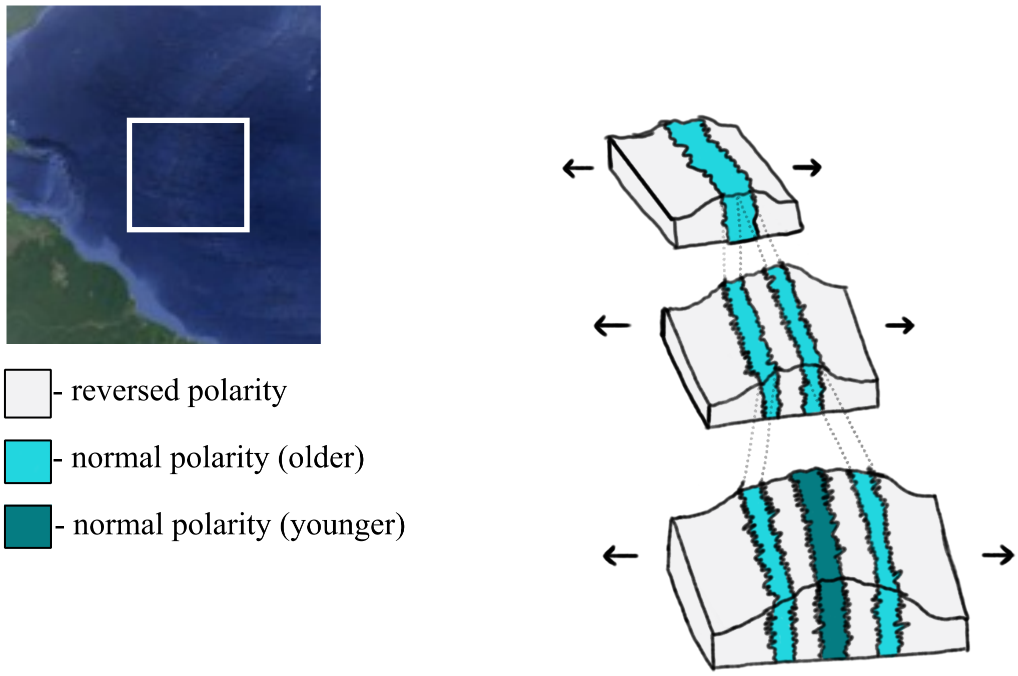


Figure 1. Magnetic reversals recorded on the seafloor

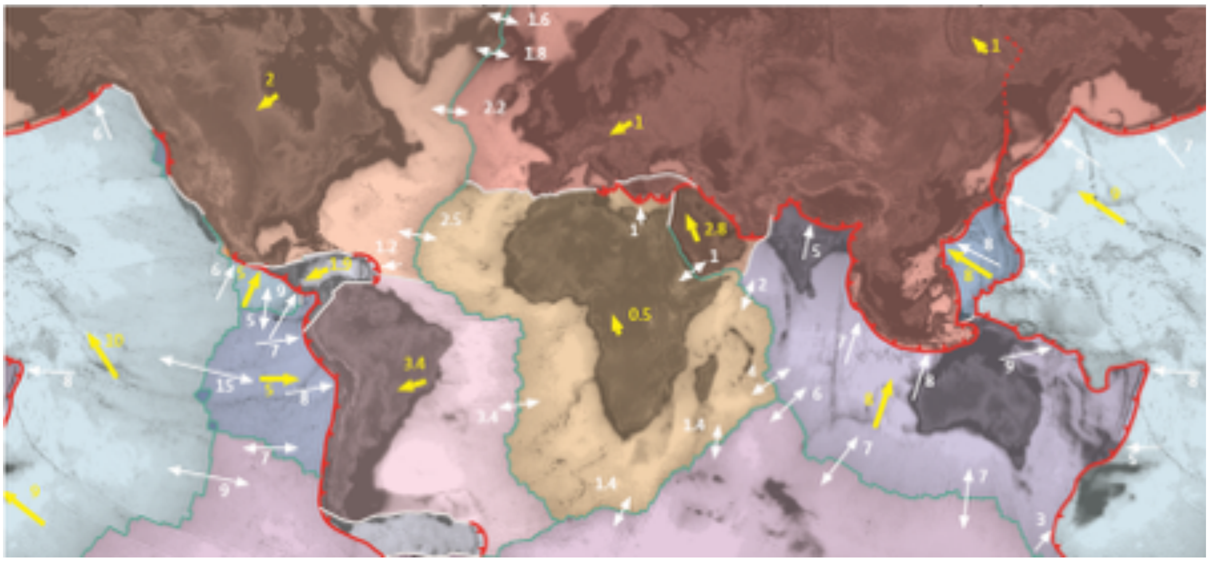
Seismology, the study of earthquakes, provides information on constraints to the geometry of the plates as well as the Earth's internal structure. Conspicuous concentrations of seismic activity are manifested along trenches and mountain ranges. The Plate Tectonics Theory suggests that these are zones of plate collision causing some crust to subduct beneath another or to be deformed intensely and rise in height.

Finally, the development of the Global Positioning System (GPS) paved the way for a more precise documentation and measurement of plate motion and their internal deformation.

These methods solidified the status of Plate Tectonics Theory as one of the most important ideas in geology, which will be improved and refined as more data becomes available. The Plate Tectonics Theory describes the creation, motion, and destruction of the uppermost portions of the Earth. It is also a good example of how a scientific method works — i.e. Plate Tectonics Theory is a revolutionary idea in geology that synthesized earlier hypotheses regarding the mechanisms for large-scale movements of continents and the formation of ocean basins through seafloor spreading, and it now provides the framework within which geologic phenomena like earthquakes and volcanic eruptions can be understood.

Activity 7-5

Given the map below showing the different tectonic plates and the direction and rate of their movements, “construct” what the continents and ocean basins would look like in the future. Using the information on plate boundaries, identify areas where new mountain ranges, volcanoes, and ocean basins can form.



NOTE: The map focuses on the following areas – Hawaii (hotspot volcanism), Red Sea and Afar Triangle (continental rift, divergent plate boundary), Iceland (mid-oceanic ridge, divergent plate boundary), California (San Andreas Fault, transform fault boundary), and Southeast Asia. Your teacher may refer you to a different map.

Conclusion

In this module, we explored the concepts of accretion and differentiation in the formation of the geosphere and lithosphere. The lithosphere is broken up into major tectonic plates in which material are created, displaced, and destroyed.

The release of heat from the Earth’s interior through outgassing produced volatiles, which paved the way for the creation of the atmosphere and the hydrosphere. In the next module, you will learn how these spheres came to be and their evolution through the early Earth.

Required Readings

1. Dott, R.H. and Prothero, D.R. (2004). Chapter 6. The Origin and Early Evolution of the Earth. In: *Evolution of the Earth*, 7^{th} ed.

2. Condie, Kent C. (1989). Origin of the Earth's Crust. *Palaeogeography, Palaeoclimatology, Palaeoecology* (Global and Planetary Change Section) 75. pp 57-81. (Introduction only)
3. Wegener, A. (2002). The origins of continents. Geol Rundsch 3: 276-292 (R von Huene, Trans.) *International Journal of Earth Sciences* 91: S4-S17. (Original work published 1912) DOI 10.1007/s00531-002-0271-1.
4. Hess, H.H. (1962). History of Ocean Basins. *Petrologic Studies: A Volume to Honor A.F. Buddington*: 599-620.

Supplementary Readings

1. Ross Taylor, S. and McLennan, S.C. (2005). *The Evolution of Continental Crust*. Available at https://www.scientificamerican.com/article/the-evolution-of-continental-crust-2005-07/
2. Hough, S. (2003). *Earthshaking Science: What We Know (And Don't Know) about Earthquakes*. Chapter 1. Plate Tectonics Princeton University.
3. An Introduction to the Formation of Earth. TEDEd lesson by Shannan Bennett. Available at https://ed.ted.com/on/yRWszobe
4. Frisch, W., Meschede, M., and Blakey, R. (2011). Chapter 1: Contractional Theory, Continental Drift and Plate Tectonics. In: *Plate Tectonics: Continental Drift and Mountain Building*. Springer-Verlag Berlin Heidelberg. pp. 1-13.