LEARNING OBJECTIVES

Module A. Diamonds and Due Diligence

Lesson 5 - Key Geoscience Concepts

Learning Objectives

By the end of this Lesson, learners will:

- Using the concept of Earth System Science, describe why the Earth should be considered a interconnected system.
- Familiarize yourself with the steps involved in the scientific method.
- List the layers and basic characteristics of the Earth's Interior and their correct sequence.
- Summarize the basic concept of plate tectonics and describe processes that occur along the three types of tectonic plate boundaries
- Compare the thicknesses of continental and oceanic crust and their variability across the globe
- Define the terms rock, mineral, and gemstone.
- Describe the relationship between rocks and minerals.
- Describe the relationship between gems and minerals.
- Define the three main rock types (igneous, metamorphic, and sedimentary), how each are formed and their relative positions in the Rock Cycle.
- Appreciate the scale of geological time.

INTRODUCTION

Module A. Diamonds and Due Diligence

Lesson 5 - Key Geoscience Concepts

Introduction

In order to gain an understanding about the world of gemstones, precious gems and historical jewels, we first need to build a foundation by learning about the nature of scientific investigation and some basic geological and mineralogical concepts.

Essential readings and topics for this lesson in your textbook

Topic	Pages
Earth's Structure	14 - 19
Rock Types	28 - 31
Igneous Rocks	32 - 33
Sedimentary Rocks	52 - 53
Metamorphic Rocks	76 - 77
What is a gemstone?	104 - 105

The pages above contain basic information about rocks (the hosts of mineral gemstones!) and how they form. Keep the lesson's learning objectives in mind as you read through these short sections.

Optional readings for this lesson in your textbook

Topic	Pages
Granite	34 -35
Pegmatites	36
Kimberlite	41
Marble	78 - 79
Schist and gneiss	83

The pages above contain information about specific rocks types that commonly host gemstones. Getting familiar with them will be useful for the rest of the course, but do so at a leisurely pace.

Optional Web Resources

This Dynamic Earth: The Story of Plate Tectonics (a U.S. Geological Survey publication)

THE WORD "SCIENCE"

The word "Science"

What follows is an uninspiring dictionary definition of science:

> *"Branch of Knowledge, especially one dealing with material phenomena and based on observation, experiment and induction; systematic and formulated knowledge; pursuit of this; skillful technique."*

The field of science is very exciting with new discoveries being made each day with inextricable links to past ideas - an interweaving of new observations with historical data and interpretations. To some it can be a discipline filled with math and rambling facts with very little relevance to modern day life. It is our hope that we can turn this perception around with the exciting world of gemstones and precious metals and show you that science is a dynamic process of discovery and exploration involving the integration of many disciplines from both the sciences and the arts. Hopefully you will be able to appreciate science when it sneaks its way into many aspects of your daily life: from the ring on your finger, to gold wiring in your cell phone, to the latest fashion trends in Hollywood!

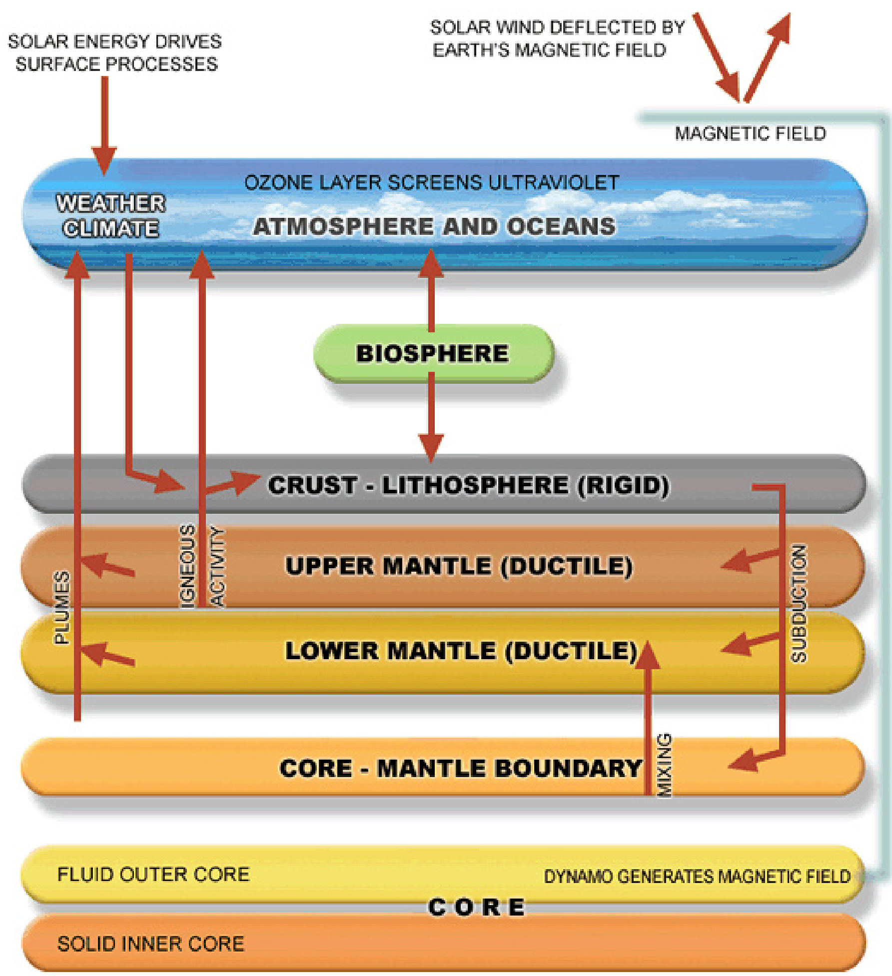
Earth System Science

In Earth Sciences the integrated approach to study is called "Earth System Science". Earth System Science views the Earth as a working system, each part having an impact and an effect on the other. The figure below attempts to illustrate this new way of looking at the Earth.

In order to understand how the Earth created/creates beautiful and inspiring gems and metals, we must appreciate all aspects of the Earth system including the atmosphere, oceans, surface tectonic processes, processes deep in the Earth, and life.

The significance of these components will vary for the creation and preservation of different precious materials, but all aspects tend to be tied together in one way or another. Diamonds, for example, form deep within the Earth in a region called the Upper Mantle where very high pressures and temperatures exist. However, other processes are required to bring these diamonds through the mantle and crust to the surface in order for us to find and eventually mine them. Natural processes on the Earth's surface, such as glaciation, can move the diamonds away from their original source and leave a "cookie crumb trail" to where the real treasure lays (the 'primary deposit'). Alternatively, if enough diamonds were moved by natural processes (e.g. fluvial transport) from a 'primary source' to a new location, a 'secondary' diamond deposit would be formed far away from the original source.

Even in this very limited example, the complexity and "interconnectedness" of the Earth system is obvious. Get ready to explore many more complex systems that exist within the gem and precious metal world!



The Earth System. A schematic model of the Earth as a series of integrated systems. Drawing by G. Lascu.

THE SCIENTIFIC METHOD

Module A. Diamonds and Due Diligence

Lesson 5 - Key Geoscience Concepts

The Scientific Method

At the core of scientific investigation is the scientific method. Science is not a faith or belief system but a method of observing and attempting to interpret the physical universe. As such, science holds that every event has a physical explanation. The traditional process of scientific investigation involves a number of rigid steps:

1. Compile **observations**: Making detailed unambiguous and clear observations is vital to any scientific investigation whether that is recording results in a laboratory or describing the geology and mineralogy of a diamond-bearing rock.
2. Form a **Hypothesis**: This is a provisional theory to explain the observations made. We might first consider that the rock that contains the diamonds is what geologists call kimberlite.
3. Test the **Hypothesis**: For our diamond example, a way of testing if the rock is truly kimberlite is through the other minerals that exist in the rock.
4. **Repeated testing** raises the hypothesis to the level of a Theory. As such a theory is not a 'guess' but something that has been tested in many different ways and found to be true after each testing.
5. If a **Theory** or group of theories are always observed to happen it could be raised to the level of a **Law**. An example is the "Second Law of Thermodynamics", which states that heat flows from a warm body to a cooler body.
6. Continual **re-examination**. In science, everything can be tested and reinterpreted, even Laws! For example, some of the laws proposed by Isaac Newton have subsequently been called into question by the recent development of Quantum Theory.

In reality, however, this process is much too rigid and simple to be easily applied today. The principles and concepts that it conveys are valid, such as objective testing and interpretation, but the manner in which researchers navigate their experiments, data, and conclusions tends to be more flexible, creative and iterative. The following **optional** websites includes a great Flash animation describing one representation of "The Scientific Method", or rather, "The *Real* Process of Science".

The Real Process of Science - Flash Animation

A Blueprint for Scientific Investigations - Text Description and Static Images

EARTH'S INTERIOR

Module A. Diamonds and Due Diligence

Lesson 5 - Key Geoscience Concepts

Earth's Interior

One of the features of our planet is that it is not homogeneous but rather composed of a number of very distinct solid layers. These layers, from the exterior to the interior, are:

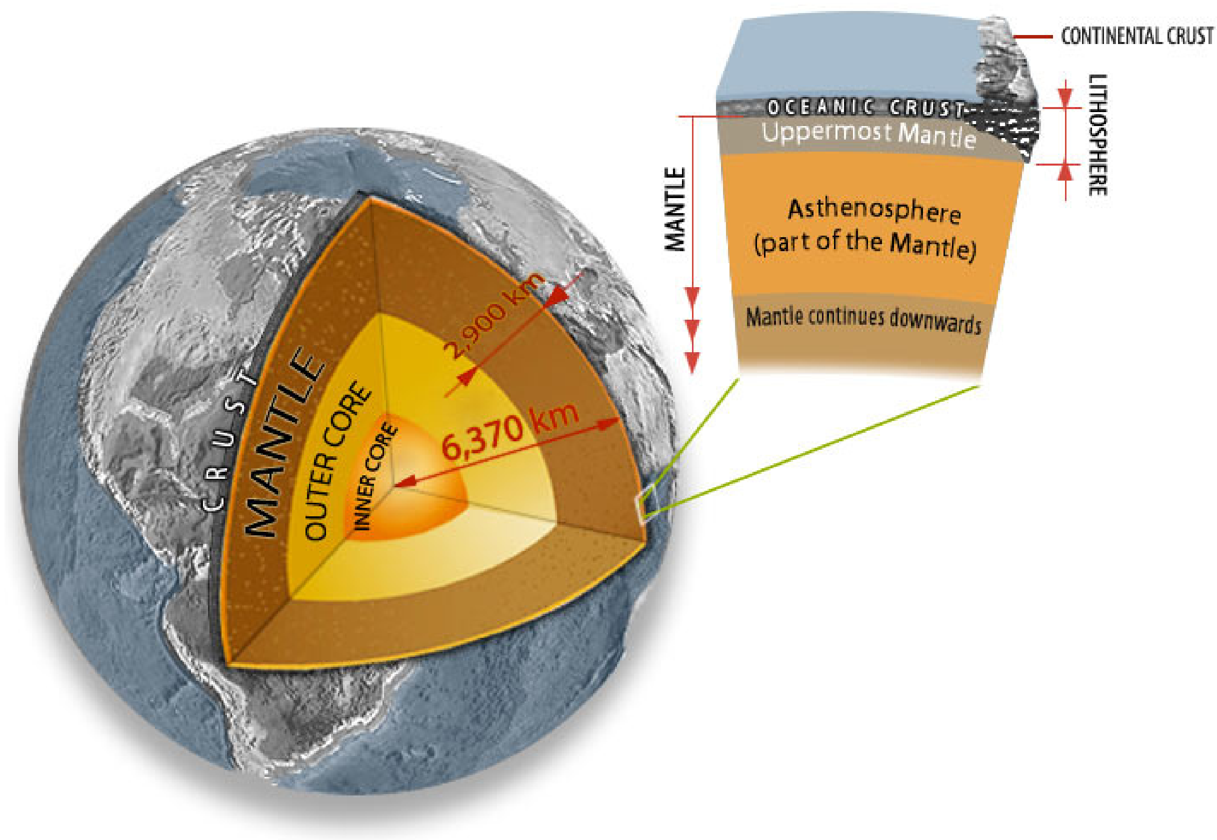
Lithosphere. The lithosphere consists of continental and oceanic crust and the uppermost part of the mantle. This layer is fractured into a number of rigid sections or plates. Continental crust and oceanic crust have different overall compositions; continental crust is much richer in minerals containing silicon (Si) while oceanic crust has a higher iron (Fe) content. Continental crust also tends to be much thicker than oceanic crust.

Asthenosphere. The upper mantle material acts as a relatively soft, lubricating layer over which the crustal lithospheric plates move.

Mantle. A relatively hot viscous "taffy-like" layer. The mantle is in continual motion with hot mantle material rising from the depth and cooler upper mantle material sinking to the lower areas. These motions are called convection currents and may in part help drive the motion of the lithospheric plates. Next time you are eating Miso soup, check to see if you can see the convection currents!

Outer core. This layer is a liquid.

Inner core. This layer is a solid and has a metallic composition.

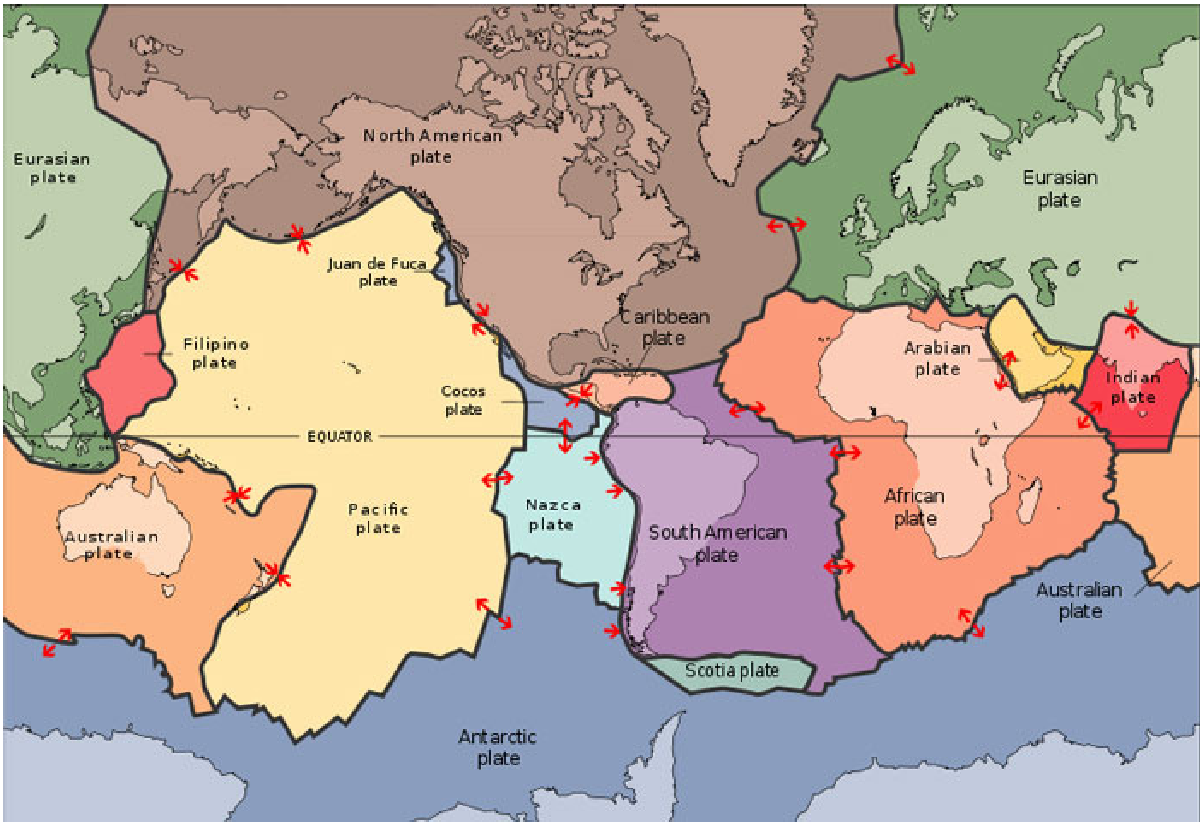


The geological layers of the Earth (not drawn to scale). Drawing by G. Lascu.

THEORY OF PLATE TECTONICS

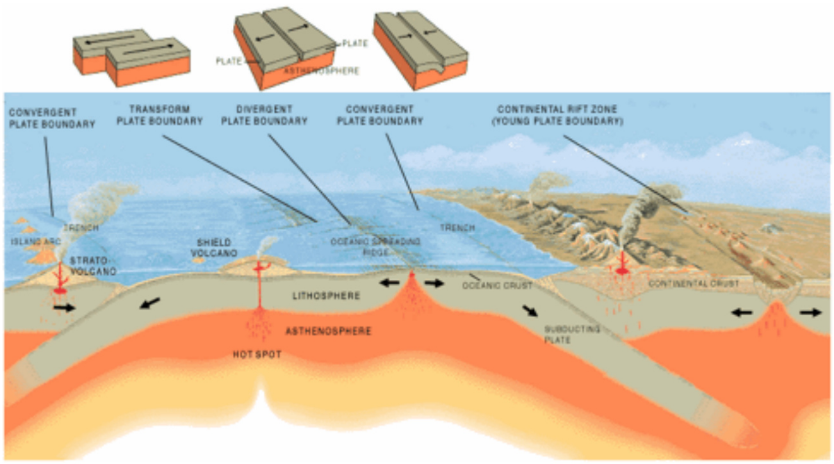
Theory of Plate Tectonics

The Theory of Plate Tectonics is often called the geological Grand Unifying Theory. It explains many of the geological phenomena that have puzzled scientists for so many years, such as the processes that build mountains and the patterns of distribution of earthquakes and volcanoes. The theory describes how the plates and the continents they contain are pushed and pulled around the surface of the Earth. The surface of the Earth resembles a fractured eggshell with each fragment of that "shell" (the Earth's crust) being a plate.



The Major Lithospheric Plates. The layer of the Earth we live on is broken into a dozen or so rigid slabs (called tectonic plates by geologists) that are moving relative to one another. Map from Wikipedia.

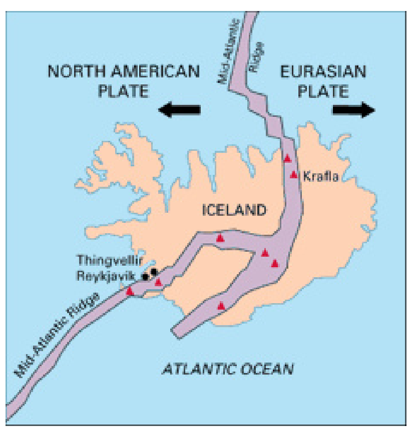
In general, most geological activity (such as earthquakes, volcanic activity, and mountain building) that affects the surface of the Earth occurs at the plate boundaries whereas the central portions of the plates tend to be quite 'stable' and experience little larger scale geological activity. The three main types of plate boundaries are convergent, divergent, and transform.



The Types of Plate Boundaries. A cross-section illustrating the main types of plate boundaries: convergent, divergent, and transform. This figure is a wall map produced jointly by the U.S. Geological Survey, the Smithsonian Institution, and the U.S. Naval Research Laboratory.

Divergent (Constructive) Plate Boundaries

Tectonic plates move away from each other at these boundaries and new crust is produced ("constructed"). These boundaries can form within a continental plate to ultimately form a new ocean basin. An example of a constructive plate boundary is the Mid-Atlantic Ridge (MAR). This feature has been widening the Atlantic Ocean at an average rate of about 2.5 cm per year (this rate varies along its length). The MAR is notable in that it is one of the few that can be observed on land.



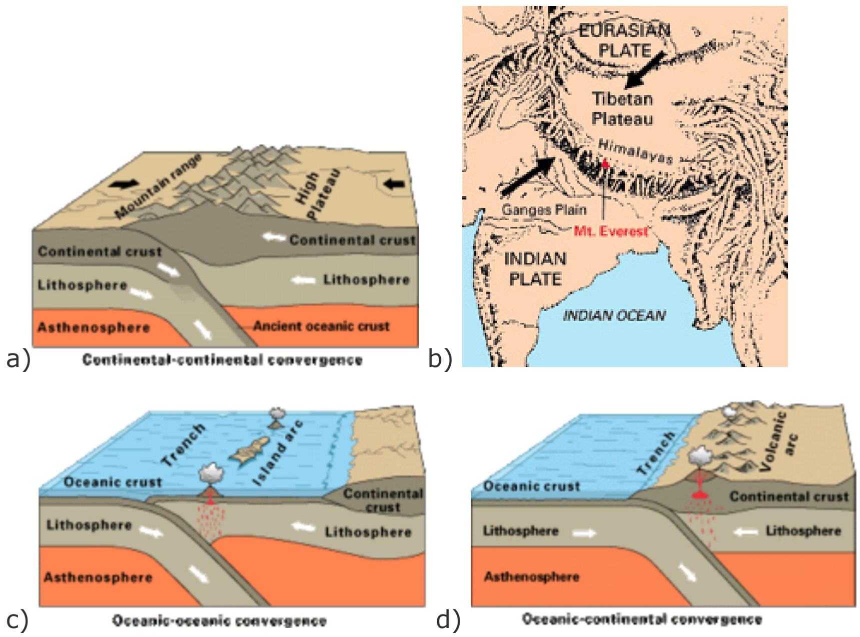
The Mid-Atlantic Ridge at Iceland. The Mid-Atlantic Ridge (MAR) is mostly an underwater feature. On Iceland, portions of the MAR are above sea level. This section is known as the Reykjanes Ridge. Map from the U.S. Geological Survey.

Convergent (Destructive) Plate Boundaries

At convergent boundaries, two plates move toward each other and collide. The Himalaya mountain range was formed when two continental plates, the Indian and Eurasian plates, collided (continental-continental collision).

When two oceanic plates or an oceanic plate and a continental plate are in collision, one plate is pushed under or **subducted** below the other. When two oceanic plates collide, a chain of volcanic islands develops above the zone of subduction.

In the case of oceanic-continental plate collision, the oceanic plate is always subducted below the continental plate because oceanic crust is denser than continental material. In this case mountain ranges that run along the edge of a continent, such as the Cascades in North America, will be produced.



a) Schematic diagrams of continental-continental convergent plate boundary and b) the examples of the collision of the Indian and Eurasian (continental) plates which has pushed up the Himalayas and the Tibetan Plateau. Schematic diagrams of a c) oceanic-oceanic collision, and d) oceanic-continental plate convergence. Figures from the U.S. Geological Survey.

Transform Plate Boundaries

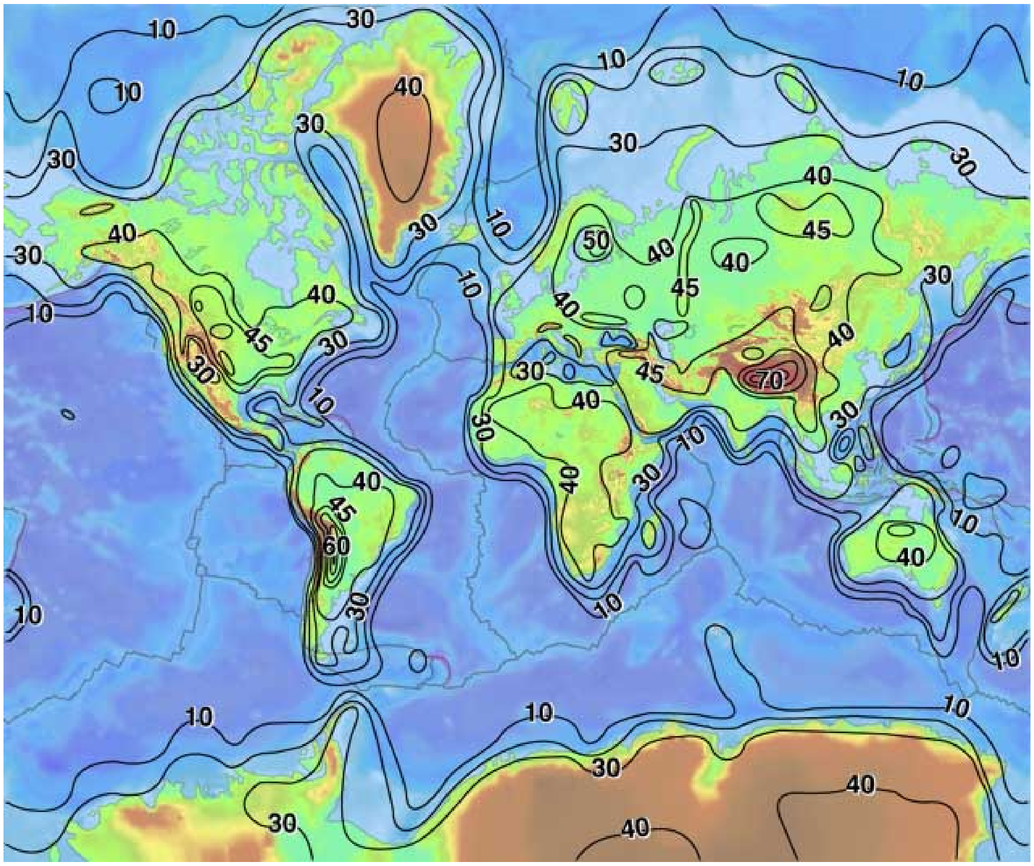
At transform boundaries the plates move past each other without the creation or significant destruction of crustal material. The most famous transform plate boundary is coincident with the feature known as the San Andreas Fault where the North American Plate is moving past the Pacific Plate.

Map of San Andreas Fault. The Blanco, Mendocino, Murray, and Molokai Fracture Zones are some of the many transform faults that scar the ocean floor and offset ridges. The San Andreas Fault is one of the few transform faults exposed on land. Figure from the U.S. Geological Survey.

Aerial view of the San Andreas Fault slicing through the Carrizo Plain in the Temblor Range east of the city of San Luis Obispo. Photograph by Robert E. Wallace, U.S. Geological Survey

Crustal Thicknesses

As alluded to previously, the thickness of the world's crust varies in time and space as geological processes incessantly march forward. The following image from the USGS is a map of the world with the thickness of the crust mapped out - each line traces areas of equal thickness as measured in kilometers. Colour corresponds to altitude of the Earth's surface (blue=below sea level, green=low lying, yellow=mid elevation, brown=high elevation). Roughly, the continents and their margins are outlined by the 30 km contour. Continental crust with a thickness greater than 50 km is rare and accounts for less than 10% of the continental crust!



Thickness contour map of the of the Earth's crust, developed from the CRUST 5.1 model with a contour interval of 10 km with greater detail on the continents above 45 km thickness. U.S. Geological Survey. Colours indicate surface elevation above average sea leavel.

For more background information on this topic, visit the excellent web site "This Dynamic Earth" published by the U.S. Geological Survey, as well as their Crustal Thickness subsite within the Earthquake Hazards Program

Check Your Understanding

Consider the following questions using the maps of lithospheric plates and crustal thicknesses:

- In general, where are mountain ranges (or the thickest parts of the crust) located in relation to plate boundaries?
- Where are the thinnest parts of the crust? Are they continental or oceanic? Explain why.
- Where do you think the most earthquakes in North America occur?
- What do you notice when you compare the map of plate thickness to the map outlining the different tectonic plates?
- Can a stable plate be made of both continental and oceanic crust?

Similarly, consider and answer the following questions:

- What happens when two continental plates converge?
- What happens when two oceanic plates converge?
- When a continental and oceanic plate converge, which plate is subducted? Why?
- Name the kind of plate interaction that results in the formation of island arc chains.

GEMS, ROCKS, AND MINERALS

Module A. Diamonds and Due Diligence

Lesson 5 - Key Geoscience Concepts

Gems, Rocks, and Minerals

As a general statement, gems are valuable minerals that originated from an original source rock. There are exceptions.

The definition of the term 'gem' is in reality much more broad. A gemstone (the words gem and gemstone are commonly interchanged) is any mineral that is highly valued for its beauty, durability, and rarity. Included in the mineral-focused gemstone definition are non-mineral gemstones that are organic or biological in origin, such as pearls and amber. Furthermore, there are a few rocks that are also considered gemstones.

Ok then, so what is the difference between a rock and a mineral? Well, rocks can essentially be thought of as (i) naturally occuring aggregates of (ii) minerals. A lengthy definition (but concise at the same time) of the term mineral is as follows:

> *"A mineral is a (i) naturally occurring (ii) homogeneous solid with a (iii) definite (but generally not fixed) chemical composition and a (iv) crystalline structure. It is usually formed by (v) inorganic processes"*

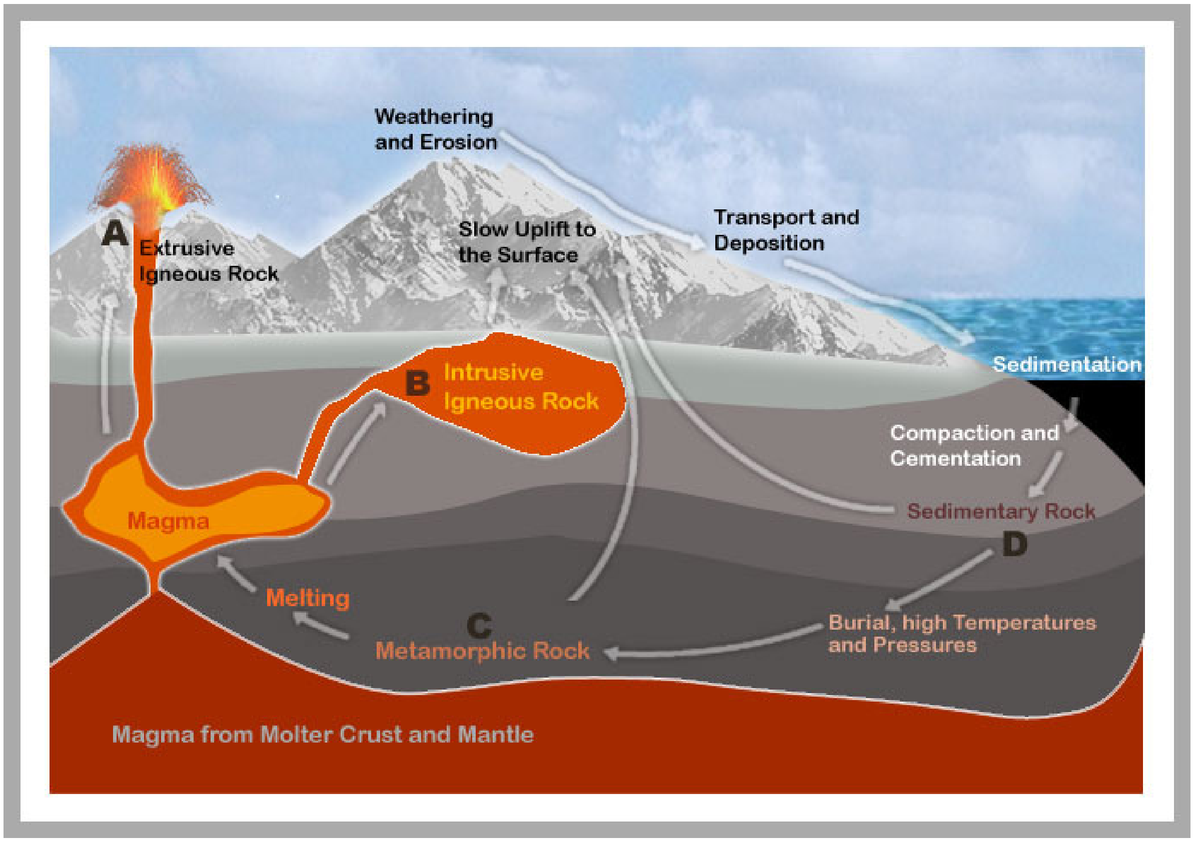
It is important to note that rocks and minerals are NATURAL, so if something is made by people in a lab or elsewhere, it is not a rock or mineral. We will come back to these items later, but it is important to remember since these parameters are what we use to classify and study rocks and minerals. And since most gems are minerals, this clearly defined way of looking at minerals allows us to easily differentiate a valuable ruby gemstone from common red glass!

To finish off this activity, read pages 104 and 105 of your textbook that addresses the question of **'What is a gemstone?**'

THE THREE-FOLD ROCK CLASSIFICATION SYSTEM

The Three-fold Rock Classification System

The basic three-fold classification of rocks are igneous, metamorphic, and sedimentary. These rock types are related to each other via processes that change from one type to another over time. Our textbook expands on what is presented below about three rock types, be sure to have read the appropriate pages as indicated in the Introduction!



Illustrating the Rock Cycle.

At **A**, extrusive igneous rocks form from magma that cools as it reaches the surface of the Earth. At **B**, Intrusive plutonic igneous rocks intrude from below the subsurface, cool, crystallize, and eventually are exposed by erosion at Earth's surface. At **C**, metamorphic rocks form as a result of the transformation of existing rock. At **D**, sedimentary rock forms from sediments such as chalk, limestone, dolomite, sandstone, conglomerate, and shale that are then compacted and converted to rock by the process of lithification.

Igneous Rocks

Igneous rocks crystallize (a process sometimes called solidification) from a molten material (called a melt or magma) to form a rock composed of interlocking crystals. The melt is generated from a process called "partial melting" of mantle material or of rocks deep in the crust. If this melt cools to form a rock at the surface of the Earth, it is called volcanic or extrusive. If the melt cools and solidifies inside the Earth it is called plutonic or intrusive.

Metamorphic Rocks

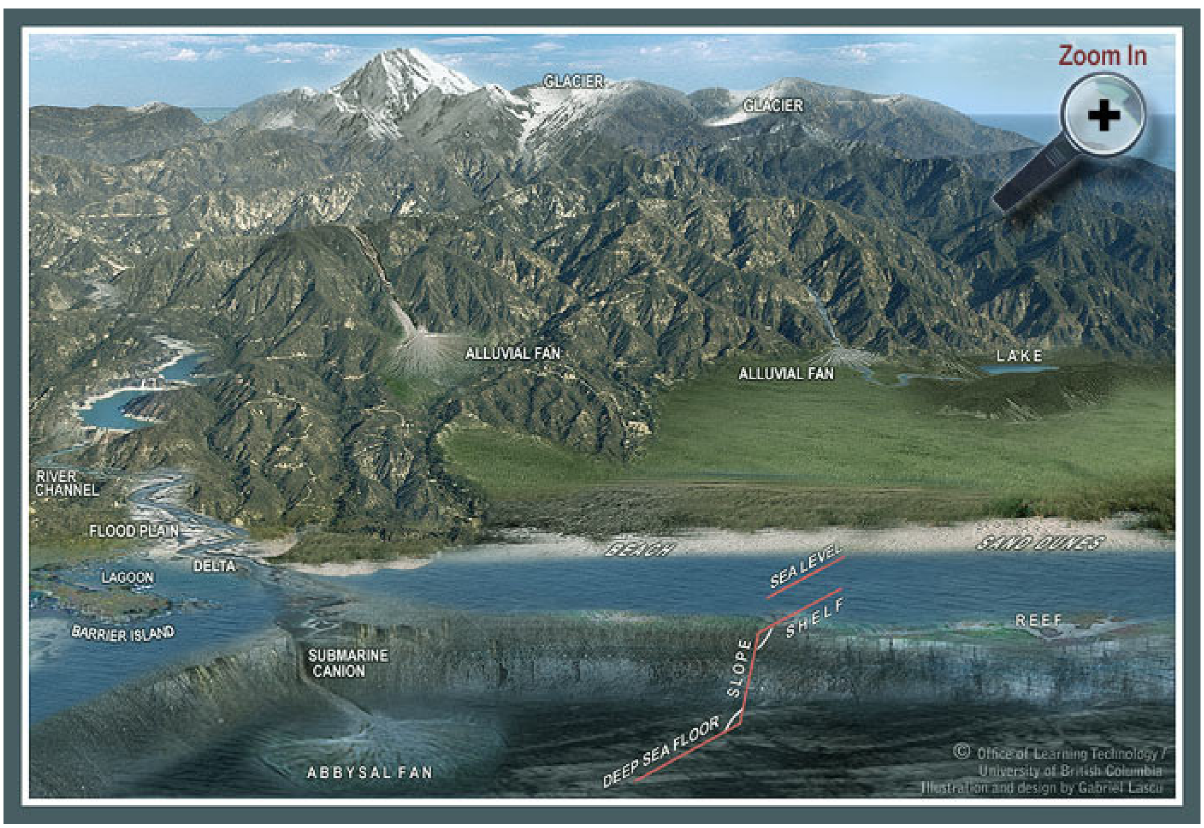
Metamorphic rocks are formed by the alteration of pre-existing rocks (igneous, metamorphic, and sedimentary) via metamorphism. The processes that transform or metamorphose rocks involve heat and/or pressure and very often fluids percolating through the subsurface. Rocks can be compressed and flattened and new minerals may be generated that are more stable under the new temperature and/or pressure conditions. Pressure is often the result of compressional tectonic forces generated when plates collide; this can also generate heat. In addition, pressure and temperature will increase with depth.

Sedimentary Rocks

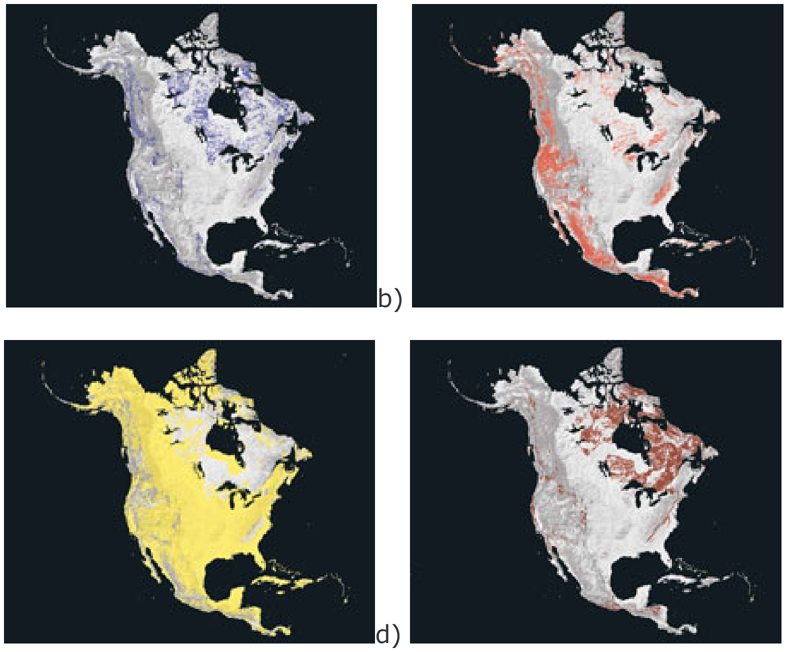
Sedimentary rocks form by a number of processes and can generally be classified by:

- Physical erosion and weathering of another rock to form a clastic sedimentary rock such as a sandstone, siltstone, or mudstone. These rocks are composed of the fragments and grains of the rock(s) that were being eroded to form the sediment.
- Chemical precipitation to form an evaporite. These form when a body of water such as a lake or inland sea evaporates to form layers of salt.
- Biological precipitation of minerals includes the production of coral reefs, sediments composed of shells, and deposition of plant material in swamps to form coal.

Sediments are transformed into rock via a process called diagenesis or lithification which physically cements the sedimentary grains together. Like metamorphism, this process involves heat, pressure, and percolating fluids but not to such a degree that the rocks mineralogy or structure is drastically transformed.



Formation of Sedimentary Rocks. Examples of environments where sediments are being deposited. Click on 'zoom' for a more detailed view. Drawing by G. Lascu.

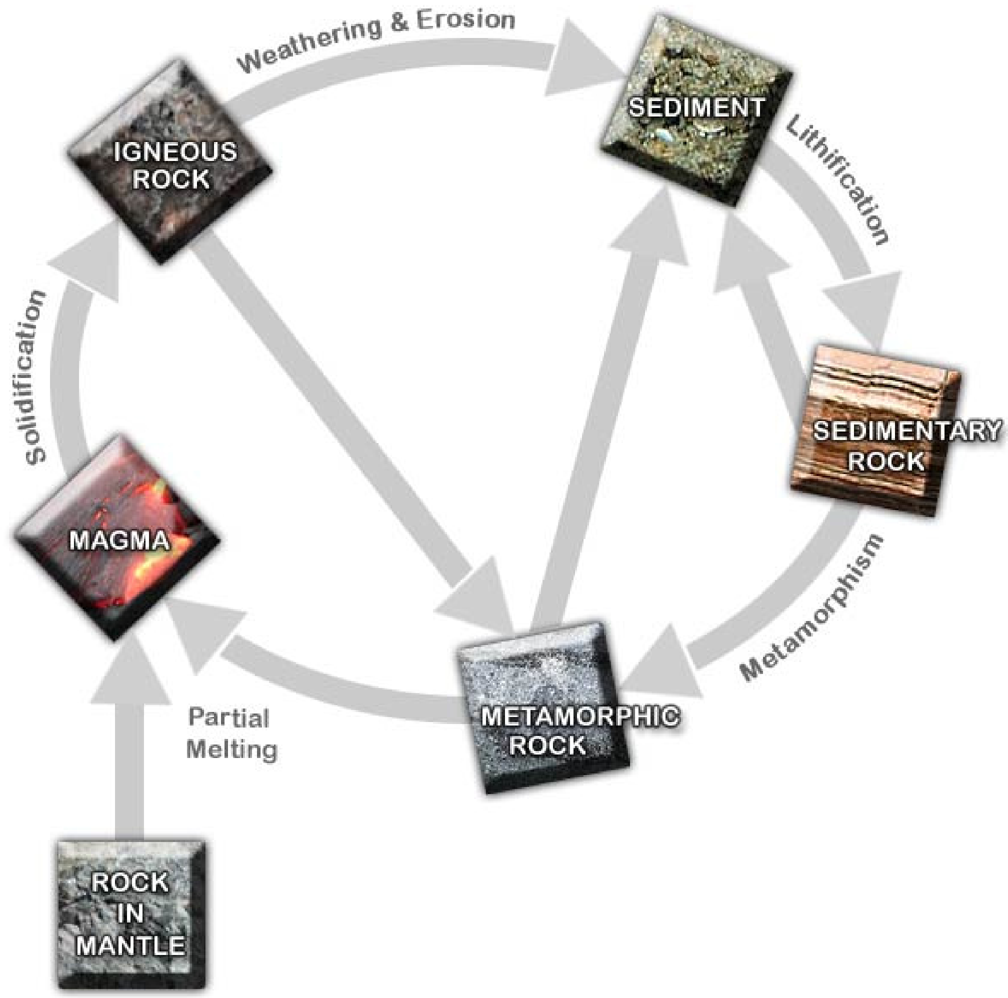

a) b) c) d)

Distribution of Rock Types in North America.

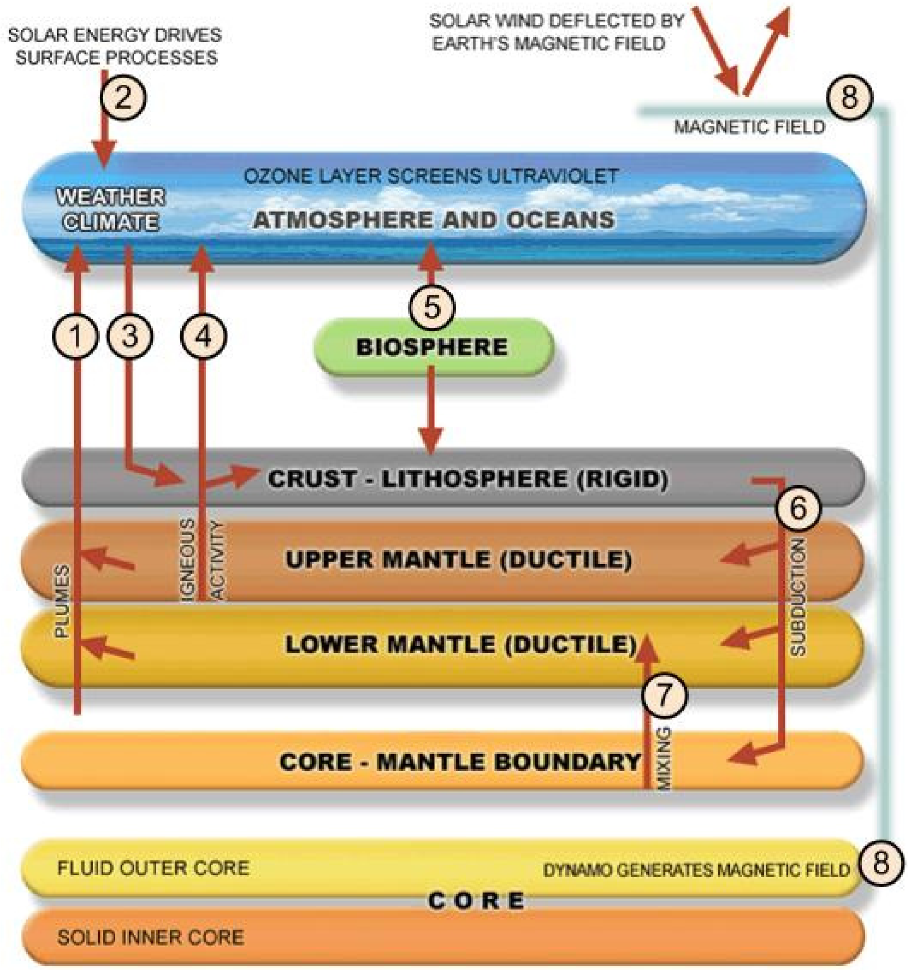
Maps showing the North American distribution of three principal types of rock: igneous: a) plutonic (blue areas) and b) volcanic (orange areas), c) sedimentary (yellow areas), and d) metamorphic (brown areas). Can you tell which type of rock dominates the area where you live? From the U.S. Geological Survey.

The Rock Cycle

The rock cycle describes how rocks can be transformed by various Earth processes into any other rock in the three-fold classification as illustrated in the figure below. Note that not every rock has to pass through each of the stages in the rock cycle.



The Rock Cycle. Starting from the bottom: partial melting of mantle material forms magma; magma crystallizes to form igneous rocks; weathering and erosion of igneous and metamorphic rock produces sediments which lithify to form sedimentary rocks; some igneous and sedimentary rock undergo tectonic burial and metamorphism to form metamorphic rock.



The Earth System, as seen in L5.3 but now annotated with some examples of the processes you just learned about. The arrows represent types of interconnectedness, however, the examples given next are not the only geological processes that can make the connections - just single examples. Annotation numbers are found below.

Annotations

1. Mantle plumes can add volatiles to the atmosphere during volcanism and degassing.
2. Solar energy drives surface processes.
3. Meteoric water (water originating from the surface) infiltrates the crust and alters rocks. These fluids may participate in igneous activity or metamorphism of rocks. On the surface, meteoric water may chemically or physically weather rocks.
4. Igneous activity includes both intrusive events and extrusive events. During these processes fluids are released into surrounding rocks and gases are released into the atmosphere if they reach the surface.
5. The biosphere hosts critters in the ocean and lakes that can precipitate biominerals as sediments, which can eventually become rocks.
6. Subduction occurs with the forceful downward motion of super positioned material to deeper depths as the result of tectonic forces.
7. Mantle mixing is thought to occur at the core-mantle boundary and is a possible source for higher reaching plumes.

8. The magnetic field generated from the outer core deflects solar winds and also imparts a geological signature on newly formed rocks, such as volcanic rocks.

Check Your Understanding

Consider the Following Quick Questions about Rock Classification and the Rock Cycle

- Is it possible for beach sediments to become a metamorphic rock?
- Is it possible for beach sediments to become molten magma?

Similarly, and considering what we learned about the "Earth System", answer the following questions:

- How many different systems (from the Earth System figure) would be involved in the formation of a fossil-bearing sedimentary rock?
- Describe how these systems were involved in the formation of this rock.
- Could this rock have formed without interaction between different systems?

Geological Deep Time

In a human lifetime, apart from the occasional volcano or landslide, not very much appears to change our planet Earth. However, an understanding of the vast depths of geological time helps us understand how continents can drift, mountain ranges form, only to be eroded back to a flat plain; or how creatures such as dinosaurs can evolve, inhabit the planet, and ultimately suffer decline and extinction. In order to appreciate the scale of geological time it is often useful to use the analogy of compressing all of Earth's 4.5 billion year history into one calendar year. Under this analogy...

Earth in One Year: An Analogy of Geological Time Based on a Calendar Year

January 1, Earth forms

February... March... April... May... June... July... August... September... October...

November... November 18, first creatures with shells evolve

December... Dec 25, dinosaurs suffer extinction... Dec 31, 11:59:57 PM, modern humans evolve

As you can see, we humans are a **very** recent feature of our planet Earth's history.

CHECK YOUR UNDERSTANDING

Module A. Rocks, Minerals and Gems

Lesson 5 - Key Geoscience Concepts

Learning Objectives

- Using the concept of Earth System Science, describe why the Earth should be considered a interconnected system.
- Familiarize yourself with the steps involved in the scientific method.
- List the layers and basic characteristics of the Earth's Interior and their correct sequence.
- Summarize the basic concept of plate tectonics and describe processes that occur along the three types of tectonic plate boundaries
- Compare the thicknesses of continental and oceanic crust and their variability across the globe
- Define the terms rock, mineral, and gemstone.
- Describe the relationship between rocks and minerals.
- Describe the relationship between gems and minerals.
- Define the three main rock types (igneous, metamorphic, and sedimentary), how each are formed and their relative positions in the Rock Cycle.
- Appreciate the scale of geological time.

Check Your Understanding

- Can you identify the following as a mineral, gemstone, or rock?
  a) emerald
  b) beryl
  c) ruby
  d) corundum
  e) diamond
  f) ice
  g) granite

h) concrete
i) cubic zirconia
j) sugar crystal

- Regarding plate tectonics, consider:
  a) what happens when two continental plates converge?
  b) what happens when two oceanic plates converge?
  c) which plate is subducted when a continental and oceanic plate converge? Why?
  d) what kind of plate interaction that results in the formation of island arc chains?

L05 CYU Form

What does this definition apply to:
A ________ is a (i) naturally occurring (ii) homogeneous solid with a (iii) definite (but generally not fixed) chemical composition and a (iv) crystalline structure. It is usually formed by (v) inorganic processes

What does this definition apply to:
A __________ is a naturally occurring aggregate of minerals.

Can a rock be a gemstone?
- Yes
- No

Are all gemstones minerals?
- Yes
- No

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