Lab 2: Plate Tectonics and the Rock Cycle

Introduction

Plate tectonics is a fundamental concept that connects many aspects of modern geology. Outer portions of the Earth are broken into tectonic plates, which are continually moving, colliding, and being pushed on top of (or underneath) each other. Plates are composed of three kinds of rocks: igneous, sedimentary, and metamorphic. These types of rocks are commonly found in specific parts of the plates. During this lab you will become familiar with features related to tectonic plate activity, such as earthquakes, volcanoes, mountains, and oceans. You will examine the movement of some plates, and think about what kind of rocks are associated with specific types of tectonic settings.

A. Plate Tectonics

Earth's structure can be classified by chemical composition or by physical properties (Figure 2-1). The chemical layers of the Earth are the crust, mantle, and core. The **crust** is largely comprised of igneous rocks: **continental crust** is made of **felsic** (silica-rich) rocks like granite, and **oceanic crust** is made of **mafic** (silica-poor) rocks such as basalt. Below the crust is the **mantle**, which is made of minerals that are rich in iron and magnesium, and at Earth's center is the iron-nickel **core**. The physical layers that are most important for plate tectonics are the lithosphere and the asthenosphere. Tectonic plates are pieces of the **lithosphere**, which is a layer of brittle rock that corresponds to the crust and the upper mantle. The **asthenosphere** corresponds to the lower mantle, and it is hot enough to be ductile rather than rigid.

For the following discussion, refer to Figure 2-1. We will consider four distinct plate tectonic environments in which magmas (molten rock) may be present:
    (1) Divergent plate margin
    (2) Convergent plate margin
    (3) Oceanic intra-plate (interior) region
   (4) Continental intra-plate (interior) region
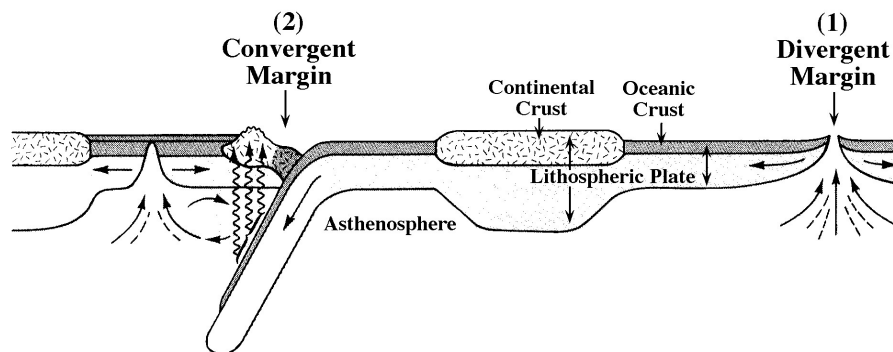
Figure 2-1: Cross-section of the outer solid Earth. The **lithospheric plates** are rigid, and consist of the crust and the upper mantle. The lithosphere is approximately 70 km thick under the oceans and perhaps 100-150 km thick under the continents. The lithosphere overlies the ductile (flexible) **asthenosphere**. Oceanic lithosphere forms at mid-ocean ridges (divergent margins) from rising molten rock; it descends back into the asthenosphere in subduction zones (convergent margins).

(1) Divergent Plate Margins

Oceanic crust underlies most of the Earth's oceans; therefore approximately 70% of the Earth's surface is oceanic crust. Basalt constitutes the bulk of this crust and is produced at places where two plates are moving apart. This plate margin is known as a **divergent margin**; the volcanic landform produced is called a **mid-ocean ridge**.

Magmas that form oceanic crust are produced by **decompressional melting**, which is melting due to a reduction in pressure as the convecting asthenosphere rises (Figure 2-2). The depth of melting in the rising asthenosphere is believed to be at 60-80 kilometers below the surface of the Earth. **Oceanic crust is almost entirely basalt**.
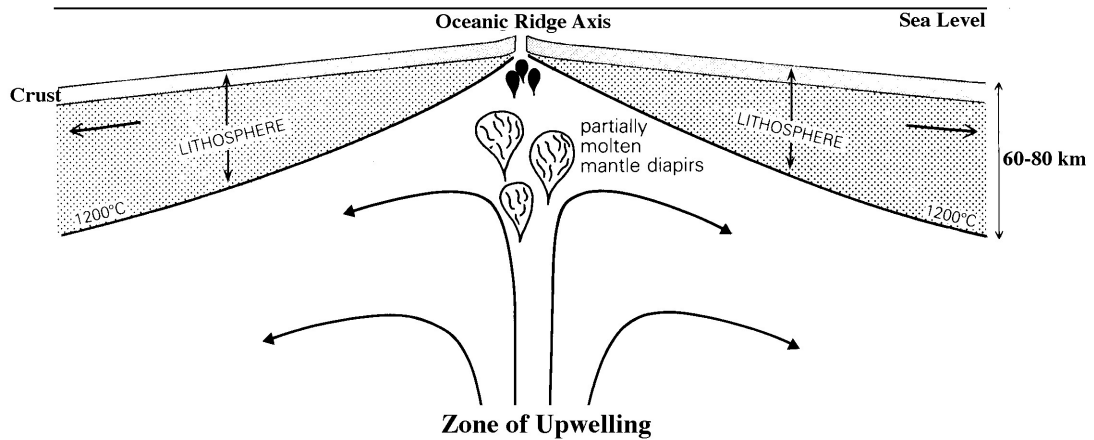

Figure 2-2: Schematic cross-section of a divergent plate margin and its relation to the zone of upwelling of magma. Oceanic lithosphere is generated at the ridge axis, cooling and increasing in thickness as it moves away from the plate margin. The base of the lithosphere is defined where geothermal temperatures reach 1200 °C. [From *Igneous Petrogenesis* by M. Wilson.]

(2) Convergent Plate Margins

Ultimately, nearly all oceanic lithosphere is returned to the asthenosphere along **convergent plate margins,** as evident from the observation that no oceanic lithosphere in the ocean basins is older than ~200 million years. In comparison, some continental lithosphere has been found that is as old as 3.8-4.0 billion years.

Along convergent plate margins, one plate **subducts** under the other plate (Figure 2-3). The subducting plate subducts because it is denser than the over-riding plate. Magmas are generated along convergent plate margins when the subducted lithosphere is heated (due to increasing temperature with depth in the Earth) and dewatered. The water "squeezed out" of the subducting plate lowers the melting point of the rocks in the overlying asthenosphere and initiates melting. Another potential mechanism for generating magma occurs when the subducted plate itself is metamorphosed and subsequently melted. However, this requires unusual conditions and occurs rather infrequently.

When the subducting and overlying plates along a convergent plate margin are both oceanic, the resulting magmatic activity forms an arcuate chain of volcanoes on the overlying plate, called an **island arc** (Figure 2-3). When an oceanic plate is subducted beneath a continental plate, deformation and volcanism occur along the continental margin, forming a mountain belt and **continental arc**. The Cascade volcanoes, here in Washington, and the Andes Mountains of South America are both continental arcs.
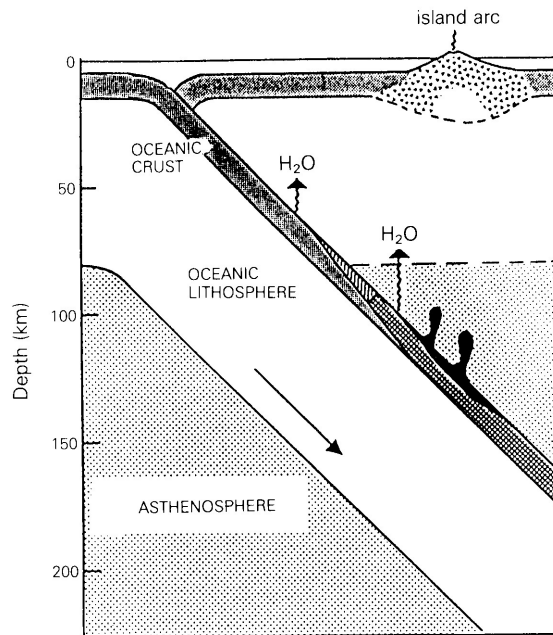
Figure 2-3: Potential source regions involved in island-arc magma genesis. The subducted oceanic slab is dehydrated at depth, releasing volatiles (e.g. CO2, H2O) into the overlying mantle, where melting is initiated. [From *Igneous Petrogenesis* by M. Wilson.]

Because the mechanisms for generation of magmas at convergent plate boundaries are different from those at divergent plate boundaries, the resulting magma is significantly different in composition. Initially, **the magmas formed along convergent plate margins are predominantly basalti**c. Because these magmas have a high melting temperature (~1200°C), they have a tendency to melt and assimilate rocks that have a lower melting temperature (e.g. felsic rocks) during their passage through the lithosphere.

- Island-arc magmas pass only through oceanic lithosphere (which is predominantly basaltic) on their way to the surface, so their **composition tends to be more mafic, ranging from basalt to andesite, with felsic compositions (e.g. rhyolites) being rare**.
- Continental-arc magmas must pass through and assimilate continental lithosphere, which is more felsic. **As a result, continental-arc magmas are on average andesitic, and range in composition from basaltic to rhyolitic**.

Convergent plate-margin magmas in general are also much richer in **volatiles** (e.g. gases such as water and carbon dioxide) than are the magmas formed at divergent plate margins, due to the contribution of water from the subducted plate. **Explosive volcanism** occurs mostly where the magmas are enriched with volatiles, especially water.
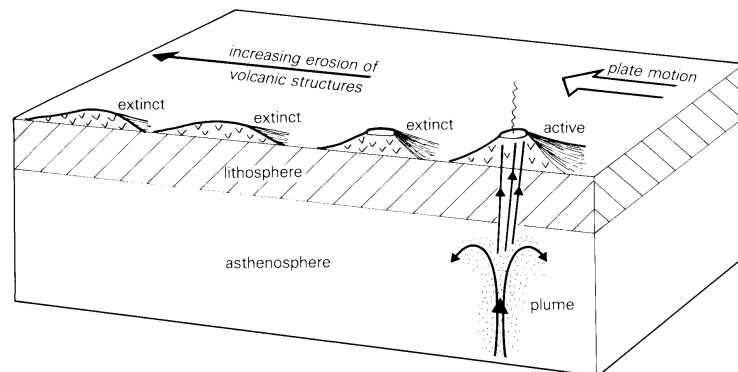
(3) Oceanic Intra-Plate Hotspot Volcanism

Some volcanism occurs within the ocean basins and is not related to the processes operating at plate margins. Because the deep ocean floor can be at depths on the order of 5000 meters or more, the volcanoes that emerge as islands are by far the largest on Earth.

For example, Mauna Kea on the island of Hawaii rises some 4170 meters (~13,500 feet) above sea level, but its base is on the ocean floor at a depth of more than 5000 meters (>16,000 feet) below sea level. Therefore, this mountain has the largest relief of any landform on Earth. The magmas that produce oceanic island volcanism, such as in Hawaii, are believed to be generated by a **hotspot** beneath the oceanic lithosphere, in the asthenosphere. A hotspot is caused by enhanced upwelling in the deep mantle (Figure 24). Over time, the upwelling magma migrates through the lithosphere to the surface. Because most asthenosphere hotspots are stationary relative to each other, the overlying oceanic lithosphere moves with respect to the hotspot (average plate velocities are on the order of 1-4 cm/yr). This volcanism often produces a line of volcanic islands such as the Hawaii-Emperor Seamount Chain (Figure 2-5). Oceanic island volcanism, like divergent plate margin volcanism, is predominantly basaltic.
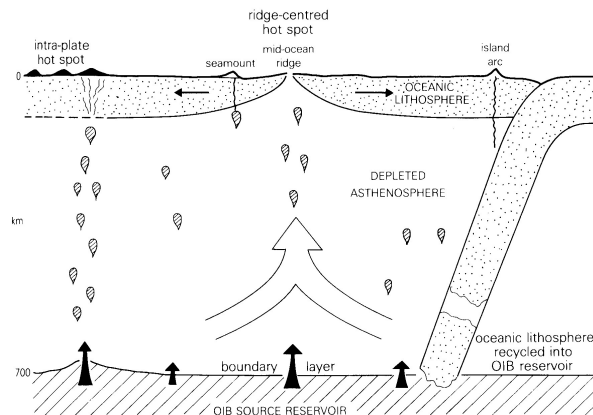
Figure 2-4: Sketch showing the lithosphere environment for an oceanic intra-plate (ocean island) hotspot volcano. [From *Igneous Petrogenesis* by M. Wilson]


Figure 2-5: Hotspot model for the generation of ocean island (and seamount) chains. [From *Igneous Petrogenesis* by M. Wilson]

(4) Continental Intra-Plate Volcanism

Intra-plate volcanism occurs in two tectonic settings within the continental lithosphere: **continental hotspot volcanism** (e.g. the Columbia River Plateau and the Yellowstone Caldera) and **continental rift-zone volcanism** (e.g. the East Africa Rift). Although volcanism in these two settings is relatively minor at the present time, there have been sites of extremely voluminous intra-plate eruptions in the geologic past, such as in the Deccan Plateau region of India.

Volcanism within the continents is complex and not well understood. Two origins have been suggested for continental flood basalts, which are voluminous basaltic eruptions that cover large areas and make up most continental intra-plate volcanism (Figure 2-6). One model suggests that some of the continental flood basalts are the result of magmas generated by a hotspot underneath the continental lithosphere (e.g. the Columbia River basalts). The remainder of the continental flood basalts, as well as the continental rift basalts, are believed to be related to the rifting apart of the continental lithosphere. The East Africa Rift is one such setting in which this is actively occurring today, and it may be considered to be a young divergent plate margin.
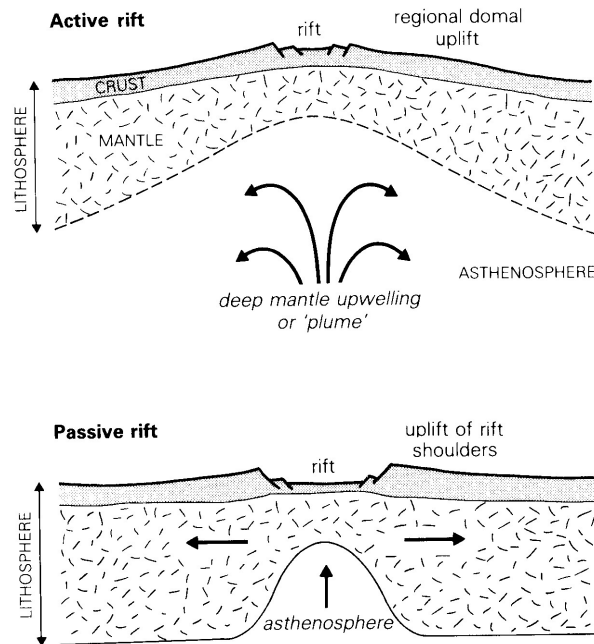
Figure 2-6: Diagrammatic sketch of a continental rift zone, showing two different models for rifting. [From *Igneous Petrogenesis* by M. Wilson]

Both of these types of continental intra-plate volcanism produce predominantly basalts. This is somewhat surprising if one considers the continental crust through which these magmas must pass. However, the large volume of these magmatic events apparently has minimized the effect of melting and mixing of the continental crust.

B. The Rock Cycle

Rocks are divided into three major categories on the basis of their origin:

(1) **Igneous rocks** (from the Latin word *ignis*, fire) are composed of minerals that crystallized from a high-temperature melted rock called a **magma**. This category includes rocks that formed as a result of volcanic activity and those that crystallized from magmas that cool below the Earth's surface.

(2) **Sedimentary rocks** (from the Latin word *sedimentum*, settling) form by the accumulation and consolidation of material derived from existing rocks through the processes of **weathering** and **erosion**.

(3) **Metamorphic rocks** (from the Greek word *metamorphose*, to transform) are derived from existing rocks that have been texturally and mineralogically altered. Metamorphic rocks develop from igneous, sedimentary, and/or other metamorphic rocks when they are exposed to increasing temperatures and/or pressures.

Rocks do not remain the same throughout geologic time. They are constantly being changed by external forces. Given enough time, these forces can change any one rock type into any other rock type. These relationships constitute the **rock cycle** (Figure 2-7).
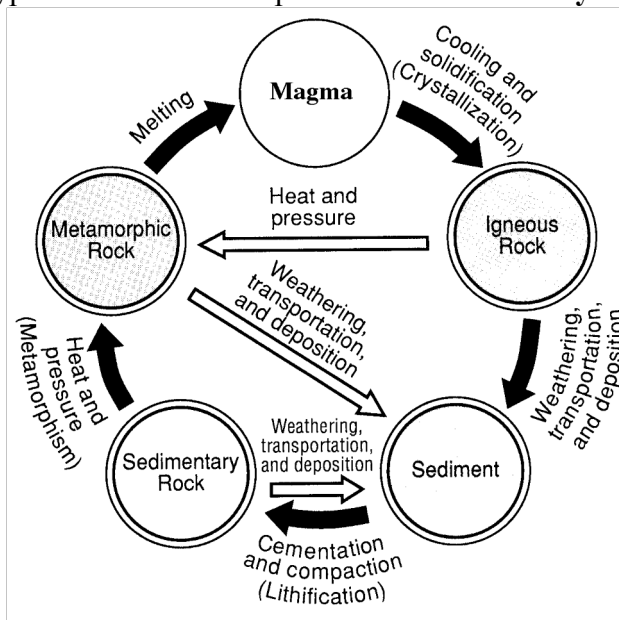
Figure 2-7: The Rock Cycle.

You will spend time looking specifically at each of these types of rock during the quarter. The texture and mineralogic composition of a rock frequently reflect its geologic history and help us to determine whether it has an igneous, sedimentary, or metamorphic origin. Distinguishing the different types of rocks is sometimes difficult, but below are a few things you can use to categorize rocks into their respective rock type.

Texture refers to the size, shape, and interrelationship of minerals in a rock. In general, igneous rocks have a **crystalline texture**, where the crystals have grown together and are interlocking. Sedimentary rocks usually have a **clastic texture**, because they are made up of fragments of other rocks (**clasts**) and fossils. Metamorphic rocks often have a **foliated**, or layered, **texture**. We will discuss rock texture in more detail over the next few weeks.

Exercises

Group Members: _____
One answer sheet per group should be turned into your T.A.

1. Find the East Pacific Rise on the plate tectonic map of the circum-Pacific region *(southeast quadrant)*.
(a) What type of plate boundary is this, and which plates are at this boundary?

(b) What type of igneous rock (formed from magma) is produced here?

(c) Is the topography higher or lower at this plate margin compared to the surrounding ocean basin?

(d) Observe the nearly symmetrical 'stripes' oriented parallel to the mid-ocean ridge. Do the presence of these stripes reinforce the idea that the plates are moving apart? How do these 'stripes' form? *(Hint: think about the discussion of paleomagnetism in lecture.)*

(e) What could be a possible explanation for the asymmetry (i.e., stripes do not have the same spacing on each side of the spreading ridge) in these stripes?

2. Find the west coast of South America on the plate tectonic map of the circum-Pacific region *(southeast quadrant)*.
(a) What type of plate boundary is this, and which plates are at this boundary?

(b) What topographic feature is produced on the continent by this plate motion?

(c) What type of igneous rock (formed from magma) is produced here?

3. Find the Juan de Fuca plate off the coast of Washington State on the plate tectonic map of the circum-Pacific region *(northeast quadrant)*.
(a) How fast is the Juan de Fuca plate moving, and in what direction?

(b) How fast is the North American plate moving, and in what direction?
(c) What is the relative (combined) speed of the two plates?

(d) What will ultimately happen to the Juan de Fuca plate?

(e) Calculate when (d) will happen (remember that velocity equals distance divided by time). Show your calculations.

(f) What will happen to the Cascade volcanoes when the answer to (d) happens?

4. The color photocopy of the Pacific Ocean and the plate-tectonic map of the circumPacific region *(NE and NW quadrants)* show the Hawaiian Islands and the other islands and **seamounts** (submarine volcanoes) that form the Hawaiian-Emperor chain. All of the features along the chain have a volcanic origin, and are younger than the oceanic lithosphere upon which they sit. In 1963, J. Tuzo Wilson proposed that all of the volcanoes in the Hawaiian chain had formed above the same hotspot. If this hypothesis is correct, then (1) the volcanos should be older farther away from the hotspot, and (2) the distance-age relationship of the volcanos can be used to measure the rate of plate motion.

(a) Plot the data in Table 2.1 on the graph paper provided. Use the whole sheet of paper and be sure to label your axes. Myrs = millions of years.

Volcano Name	Distance from Kilauea (km)	Age (Myrs)
Mauna Kea	54	0.375
West Maui	221	1.32
Kauai	519	5.1
Nihoa	780	7.2
Necker	1058	10.3
La Perouse Pinnacle	1209	12.0
Laysan	1818	19.9
Midway	2432	27.7
Abbott	3280	38.7
Daikakuji	3493	42.4
Koko	3758	48.1
Jingu	4175	55.4
Nintoku	4452	56.2
Suiko (southern)	4794	59.6
Suiko (central)	4860	64.7

Table 2.1: Islands in the Hawaiian Islands and the Emperor Seamounts with their respective distance from Kilauea in kilometers and their age in millions of years.

(b) Use a ruler to draw a best-fit straight line through the data. What does the graph indicate about the general relationship between age and distance from Kilauea?

(c) Calculate the average rate of plate movement in centimeters per year (divide the distance by the time interval over which the travel took place). Show your calculations. (1 km = 100,000 cm)

(d) The chain of seamounts bends where the Hawaiian and Emperor chains meet. When did the bend in the chain occur? Explain how you arrived at your answer.

(e) Assuming the hotspot has remained stationary, explain why the volcanic island chain has a bend.

5. At the back of the room are three rock samples labeled A, B, and C. Look at the rock texture and try to determine if the rocks are igneous, sedimentary, or metamorphic. (We'll cover rock identification in much more detail in the coming weeks.)

Rock Specimen	Igneous, Sedimentary, or Metamorphic	Reason for classification
A		
B		
C		

6. Each type of rock has particular tectonic settings with which it is commonly associated. For each of the tectonic settings indicate which type of rock is likely to be formed. Use an I for igneous, S for sedimentary, and M for metamorphic. Remember that the crust of the earth is complicated, and *some settings may contain more than one type of rock*.

   a. Mountain chain above where an oceanic plate is being subducted under a continental plate: _____
   b. A 'passive' margin, such as the east coast of North America: _____
   c. A convergent margin where two continental plates are colliding: _____
   d. A divergent margin, below sea level: _____
   e. An island chain above where one ocean plate is subducting under another ocean plate: _____
   f. Mid-continent, maybe like Wyoming: _____

Discussion

An important component of any science is to be able to separate data (that is, the observations and measurements) from interpretations of those data. In lab and lecture we have given you information about plate tectonics and the rocks that are related to specific plate settings.

7. Which are the data: rocks or plate tectonics? Why?

8. In your opinion, do the data (from your answer to question 7) support the interpretation? Why?

9. Tectonic activity is responsible for many features on Earth's surface, such as mountain ranges. What might be some other reasons, in addition to plate tectonics, for why the Earth's surface is not perfectly flat?

10. Metamorphic rocks tend to form in conditions of extreme heat and pressure, such as deep below the earth's surface. How can you explain the presence of metamorphic rocks at the surface?

11. Sediment tends to collect in low spots and basins, carried by water, ice, wind, and gravity. Why are there sedimentary rocks on top of the Rocky Mountains?

12. Why might it be difficult to convince people that the continents actually *are* moving, especially if you were a geologist in the early 1900's?