Chapter 1
Introduction – Review of Rocks and Plate Tectonics

Introduction

According to the Merriam-Webster online dictionary a **disaster** is a *sudden calamitous event bringing great damage, loss, or destruction* or more broadly *a sudden or great misfortune or failure.* If that event has a natural cause, then it is a natural disaster. For example, a volcanic eruption or a tsunami coming ashore both represent sudden events that can create great damage, loss, or destruction to some region of the Earth. Though some in academia argue that such events are not natural disasters unless they affect man or one of his structures or communities I do not accept that idea. My reasoning is simple. In both of the above cases, though man may not be present, the animals and plants living in both areas nevertheless *suffer a sudden or great misfortune or failure,* and the land surface is significantly modified.

In this course we will focus on the processes that produce natural disasters. Specific topics that we will discuss include volcanic eruptions, faults, earthquakes, tsunami, landslides, and cyclones. All of these events occur on time scales of minutes to days and can disrupt and modify substantial portions of the land surface. As you will learn in this class many of these events, as for example volcanic eruptions, faults, earthquakes, and cyclones evolve directly or indirectly from the movement of large lithospheric plates or the flow of air masses in the atmosphere. Significantly, both of these processes are in turn driven by the transfer of heat from one location to another. In the context of the former, plates are driven by the transfer of heat from the interior to the exterior of our planet, while in the context of the latter hot moist air at the equator flows toward the poles as it attempts to spread out radiant heat derived from the Sun across the surface of the planet.

The surface of the Earth is underlain by a wide variety of rocks that are constantly being modified by plate movement and changing weather patterns. So let's begin our study of the perilous earth by first reviewing the three major groups of rock that make up our planet as they form the context of much of the discussion to follow. After this review we will delve briefly into plate tectonics and then consider in subsequent chapters volcanoes, faults and earthquakes, landslides, and then end our study of natural disasters with cyclones.

Three Major Types of Rocks

Igneous, **sedimentary**, and **metamorphic** rocks represent the three major types or groups of rock on planet Earth. Igneous rocks make up the vast majority of our planet while sedimentary and metamorphic rocks making up a lesser volume. Classifying a rock into one of these three groups can be a difficult task often requiring an expert with many years of experience. However, we will not consider the nuisances, but will focus on the major differences and most essential characteristics of each major group.

Igneous Rocks

All igneous rocks begin in some form or another as a silicate liquid. When this liquid exists beneath the Earth's surface or seabed, then it is called **magma**. Igneous rocks derived from the slow cooling of magma are called **intrusive**. The term **pluton** refers to magma or its solidified equivalent. If magma reaches the Earth's surface or seabed and flows out along it, then it is referred to as **lava**. When lava cools it forms an **extrusive** rock.

Distinguishing between an intrusive and extrusive igneous rock is relatively straightforward as the former cools slowly beneath the Earth's surface while the latter cools quickly upon contact with the atmosphere, water, or ice. For example, magma may take hundreds of thousands to a few million years to crystallize to a solid while lava can be transformed into a solid in days to weeks. As a result of slow cooling the sizes of crystals in plutonic rocks are large enough that their outlines can be observed easily with the naked eye. In contrast, the sizes of crystals in an extrusive igneous rock are so small that a microscope is required to see them. Texture is a term that is used to describe the size and arrangement of the crystals in a rock. The texture of a plutonic rock is **phaneritic**, while that of an extrusive igneous rock is **aphanitic**.

Intrusive Igneous Rocks: The vast majority (over 80%) of planet Earth is composed of intrusive igneous rocks. Common intrusive igneous rocks include granite, granodiorite, tonalite, quartz diorite, diorite, and gabbro. All of these rocks are made up of various proportions of the light-colored minerals quartz, plagioclase, K-feldspar and muscovite along with various amounts of the dark-colored minerals olivine, pyroxene, amphibole, and biotite (Figure 1). Note that the former minerals, other than quartz, contain Ca, Na, or K in their formulae, while the latter minerals all include Fe and Mg.

Figure 1. The common silicate minerals found on planet Earth.

In order to classify an intrusive igneous rock you first determine the proportions or percentages of quartz, K-feldspar, and plagioclase. The sum of these values must equal 1 or 100%. Next you determine where that composition falls on the International Union of Geological Sciences (IUGS) ternary classification shown in Figure 2. In ternary diagrams like that in Figure 2, the apices represent 100% of the specified components. For intrusive igneous rocks, the apices represent 100% quartz, 100% alkali feldspar, and 100% plagioclase. The most

common alkali feldspar is K-feldspar, and thus in the following paragraphs I will often interchange these two terms.
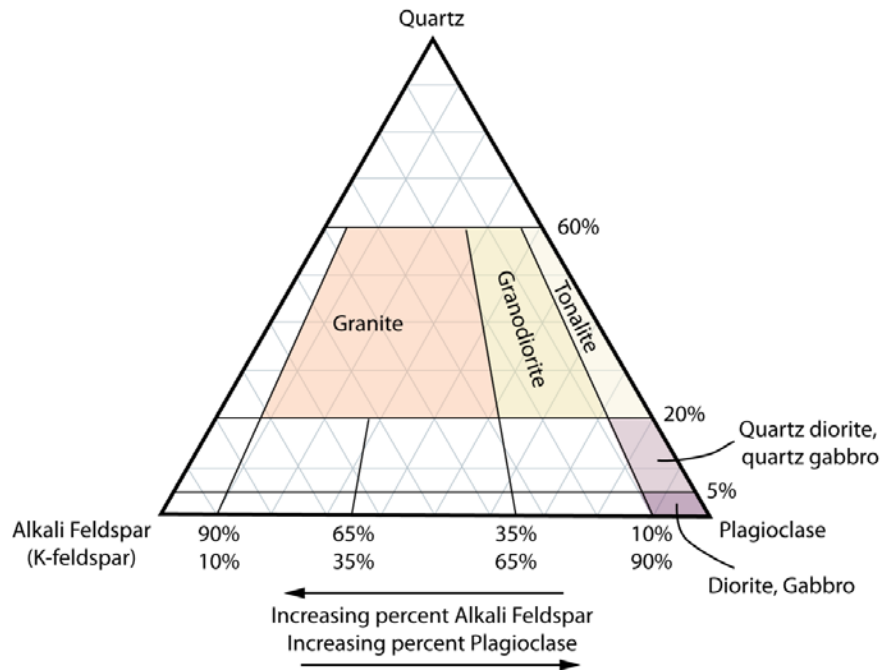

Figure 2. The International Union of Geological Sciences (IUCS) classification scheme for intrusive igneous rocks.

The horizontal grid lines shown in Figure 2 are the percentages of quartz shown varying in 10% increments from 0% at the alkali feldspar-plagioclase join to 100% at the top apex labeled Quartz. The grid lines running from upper left to lower right represent the percentages of K-feldspar again shown varying in 10% increments from 0% along the quartz-plagioclase join to 100% at the left apex labeled Alkali-feldspar. Finally, grid lines running from upper right to lower left are the percentage of plagioclase also shown varying in 10% increments from 0% along the quartz-K-feldspar join to 100% at the right apex labeled Plagioclase.

Let's plot a composition consisting of 30% quartz, 30% K-feldspar, and 40% plagioclase. To accomplish this task, in Figure 2 first count up along the quartz-plagioclase join from the base of the diagram to the 30% quartz grid line. Now count over (to the left) along the 30% quartz grid line to the 30% K-feldspar grid line. Note that the point where these two grid lines cross also lies on the 60% plagioclase grid line, and, as a result, it presents out composition in Quartz-Plagioclase-Alkali Feldspar space. Hence, an intrusive igneous rock with a composition of 30% quartz, 30% K-feldspar, and 40% plagioclase plots in the orange field and the sample is therefore granite. Make sure you understand how to read and use a ternary diagram as you will encounter additional ternary classification schemes in the following sections.

With the above as background, it should be clear from Figures 2 and 3 that granites, granodiorites, and tonalites all contain between 20% and 60% quartz, and that the proportion of K-feldspar to total feldspar (i.e., the sum of plagioclase and K-feldspar) varies from 90–35%

for a granite, from 35-10% for a granodiorite, and from 10-0% for a tonalite. Additionally, granites also contain varying but relatively small amounts of white mica, biotite, and amphibole, and as a result often display a light gray to white to pinkish color (Figure 3).
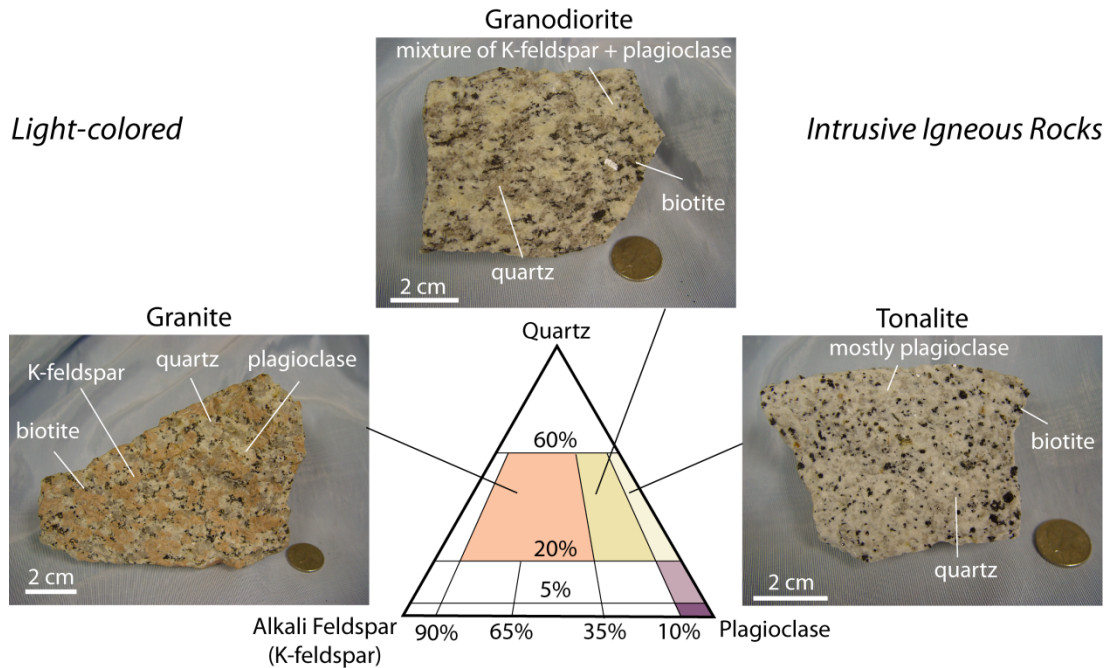

Figure 3. The common light-colored intrusive rocks and IUGS ternary classification scheme.

In contrast to the light-colored intrusive igneous rocks, gabbros and diorites often exhibit a black to dark gray color (Figure 4). Of the sum of quartz, plagioclase, and K-feldspar, a gabbro or diorite would be composed of 90% - 100% plagioclase, 0% - 10% K-feldspar, and 0% - 5% quartz (Figures 2 and 4). In addition, the dark colored minerals olivine, amphibole, and/or
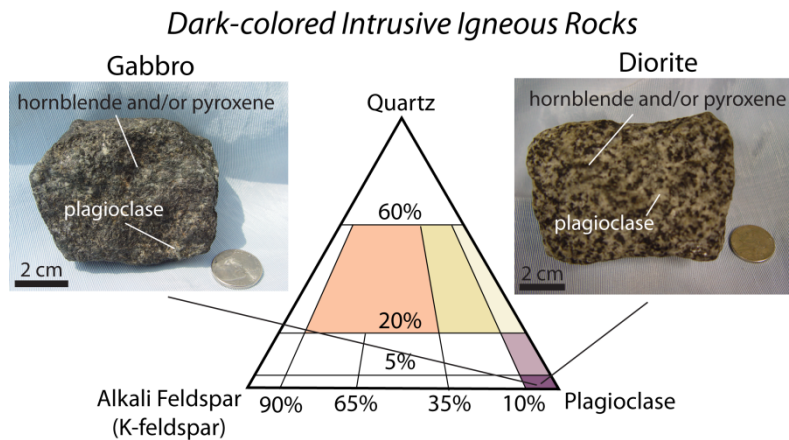

Figure 4. The common dark-colored igneous rocks and the IUGS ternary classification scheme.

pyroxene are typically present and can make up a significant proportion of the total rock volume. In fact, the proportion of dark colored minerals is called the **color index:** it is used to distinguish between a gabbro and a diorite. For example, a gabbro has a color index greater than 40%, while a diorite has a color index less than 40%.

Quartz diorites and quartz gabbros are like diorites and gabbros and exhibit many of their characteristics. However, they contain between 5% and 20% quartz, and thus are easily distinguished from the more quartz-poor gabbros or diorites.

Uplift and erosion has commonly exposed the above varieties of intrusive igneous rocks over large regions of the Earth's surface. However, though they are the most common intrusive igneous rock exposed at the surface, none are as volumetrically important as peridotite, an igneous rock that resides deep in the Earth's interior. Peridotites are composed of varying proportions of olivine and pyroxene with or without plagioclase.

Extrusive Igneous Rocks: Because extrusive igneous rocks cool quickly upon contacting the atmosphere, water, or ice they are difficult to work with. However, with the aid of a microscope one can determine the proportions of quartz, plagioclase, and alkali-feldspar, and then plot the resulting composition on the IUGS ternary classification scheme for extrusive volcanic rocks (Figure 5). Note that in this scheme, rhyolites and rhyodacites are mineralogically similar to granite, while dacites contain a mineralogy that is similar to granodiorites. Similarly, the mineralogy of quartz andesites is like that in tonalites, quartz diorites, and quartz gabbros, while basalts are mineralogically similar to gabbros and diorites.
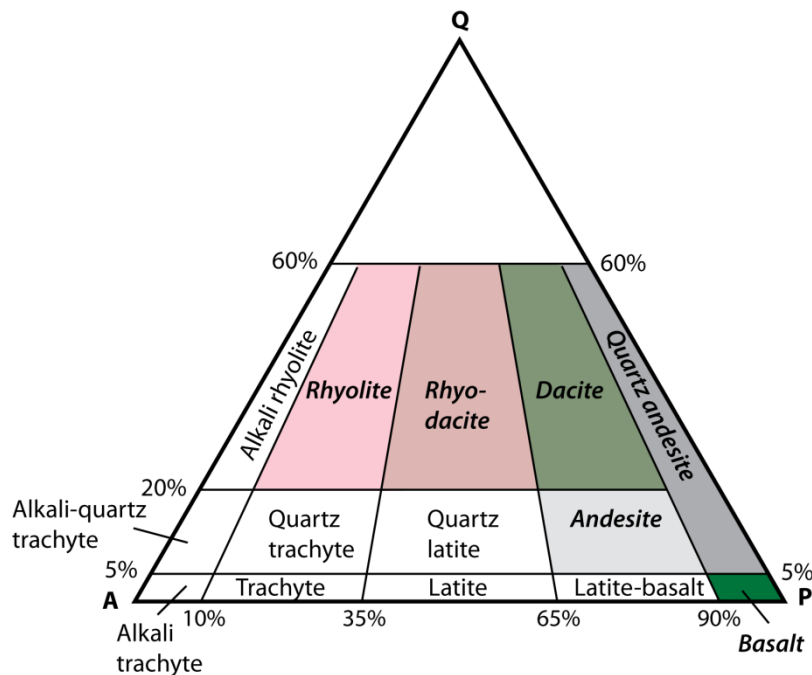

Figure 5. IUGS classification scheme for extrusive volcanic rocks.

These similarities should not come as a surprise to you, as the only difference between an intrusive and extrusive igneous rock is cooling rate. In other words, compositionally distinctive classes of rocks in both groups (e.g., gabbro and basalt) are derived from the same silicate liquid, but in one case the silicate liquid cooled slowly while in the other it cooled significantly more rapidly.

As shown in Figure 5, common extrusive rocks include rhyolite, rhyodacite, dacite, quartz andesite, andesite, and basalt. Make sure that you can read from the ternary diagram, the general mineralogical compositions of each of these rocks types. If you have difficulty, then please go back and read the material dealing with ternary classifications in the Intrusive Igneous Rocks section.

Another way to classify an extrusive, as well as an intrusive, igneous rock is on the basis of the amount of SiO_2 (i.e., silica or silicon dioxide) it contains. The amount of SiO_2 is expressed in weight per cent, i.e., the number of grams of SiO_2 in 100 grams of the rock. If the rock contains more than ~63 wt% SiO_2, then it is **felsic** or **silicic**. Rhyolites, rhyodacites, and dacites along with their intrusive compositional equivalents granite granodiorites, and tonalites are generally silicic. In contrast, if the rock contains between 55 wt% and 63 wt% SiO_2, then it is **intermediate** in composition. Andesites and their intrusive compositional equivalents quartz monzodiorites and quartz monzogabbros are generally intermediate in composition. Note that these latter rock types are not discussed in this course but are only included here for completeness. Quartz andesites have a wide range in SiO_2 concentration, and thus are both silicic and intermediate. Depending upon their composition, the intrusive compositional equivalent for a quartz andesite might be a tonalite, quartz diorite, quartz gabbro, or diorite. Finally, if the rock contains between 45 wt% and 55 wt% SiO_2, then it is **basic**. Basalts and their intrusive equivalents gabbros are basic in composition.

Pyroclastic Rocks: In contrast to the rapid cooling of lava, pyroclastic rocks are composed of material blown out of a volcano. Such material is called **tephra** or **pyroclasts**, and depending upon its size is classified as bombs, blocks, lapilli, or ash.

Bombs and **blocks** are both larger than 64 mm but differ in form or shape (Figure 6). Bombs are partially congealed globs of magma blown out of the volcano and then aerodynamically streamlined as they are hurled through the atmosphere. In contrast, blocks are angular and blocky hard pieces commonly broken from the walls of the volcano during an explosive eruption.

If an accumulation of pyroclastic material is transformed into a rock, then depending upon the proportions of ash, lapilli, blocks, or bombs in the rock, it will be classified as tuff, lapilli tuff, lapillistone, tuff breccia, volcanic breccia or agglomerate (Figure 6). For example, if the rock is composed of more than 75% ash then it is a tuff. On the other hand, if it is composed of more than 75% lapilli, then it is lapillistone. However, if the rock is composed of a mixture of ash and lapilli but neither component makes up more than 75% of the total volume of the rock, then it is a lapilli tuff (Figure 6). On the coarse end of the scale, if the pyroclastic rock is composed of more than 75% bombs or blocks, then it is classified as an agglomerate or volcanic breccia respectively. However, if it is composed of 25% to 75% blocks, then it is a tuff breccia.
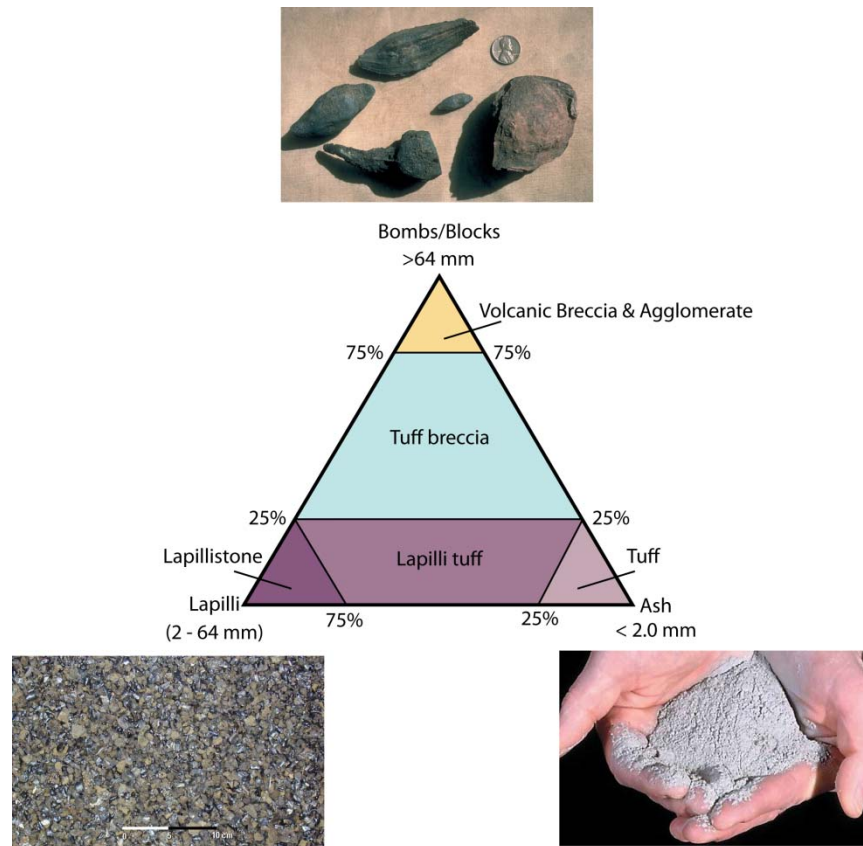
Figure 6. General classification scheme for pyroclastic volcanic rocks. Photographs are from United States Geological Survey.

When tephra, regardless of its size, is derived from the congealing of frothy magma (i.e., a mixture of magma and gases), then it is called **pumice**. Such material is riddled with holes or voids called vesicles that are surrounded by glass that formed from the quick chilling of magma. Pumice commonly floats in water and is a characteristic product of violent eruptions of felsic magma.

Sedimentary Rocks

Sedimentary rocks are composed of (1) particles derived from older geologic material through the processes of weathering and erosion, or from (2) particles precipitated from sea or lake water, or from (3) particles derived from a once living organism or plant. Accumulations of the first material in this list make up the clastic sedimentary rocks, while accumulations of the second and third sets of materials make up limestones, dolomites, evaporates, and coals. In this class we will focus on the clastic sedimentary rocks, i.e., those sedimentary rocks composed of weathered and eroded particles derived from older geological materials.

The weathered and eroded particles making up the various clastic sedimentary rocks are sometimes referred to as **detritus**. Depending upon their size they may be either fragments of

a single type of mineral, as for example quartz or feldspar, or fragments of preexisting rock, as for example granodiorite, rhyolite, or older sedimentary rock. **Gravel** represents large pieces of weathered and eroded rock that is larger than 2 mm in size (Figure 7). For reference, the thickness of a penny is close to this size. Gravel is then further subdivided into **pebbles**, **cobbles**, and **boulders**. The easiest way to remember these sizes is to recall that a baseball has a diameter of about 64 mm while a basketball has a diameter of about 256 mm. Hence, pebbles range in size from about the thickness of a penny to about the diameter of a baseball, while cobbles range from the size of a baseball to the size of a basketball. Boulders, the coarsest sedimentary particles, are larger than a basketball.

If you have been to the beach, then you know that sand is composed of particles smaller than gravel. In fact, **sand** by definition lies between 0.06 to 2.0 mm in size (Figure 7). Though 0.06 mm is small, both silt and clay are particles that are still yet smaller. **Silt** ranges from 0.004 to 0.06 mm in size, while **clay** is smaller than 0.004 mm. Because silt and clay particles are very difficult to distinguish from each other, they are sometimes lumped together as **mud** (Figure 7).

When an accumulation of gravel, sand, or mud is transformed into a rock, then they are given different names. For example, a rock composed of rounded gravel is called **conglomerate**. If the gravel is angular rather than rounded, then the same rock would be called a **breccia** (Figure 7).   A sedimentary rock composed of sand-sized particles is **sandstone** while a sedimentary rock composed of mud-sized particles is **mudstone** (Figure 7).
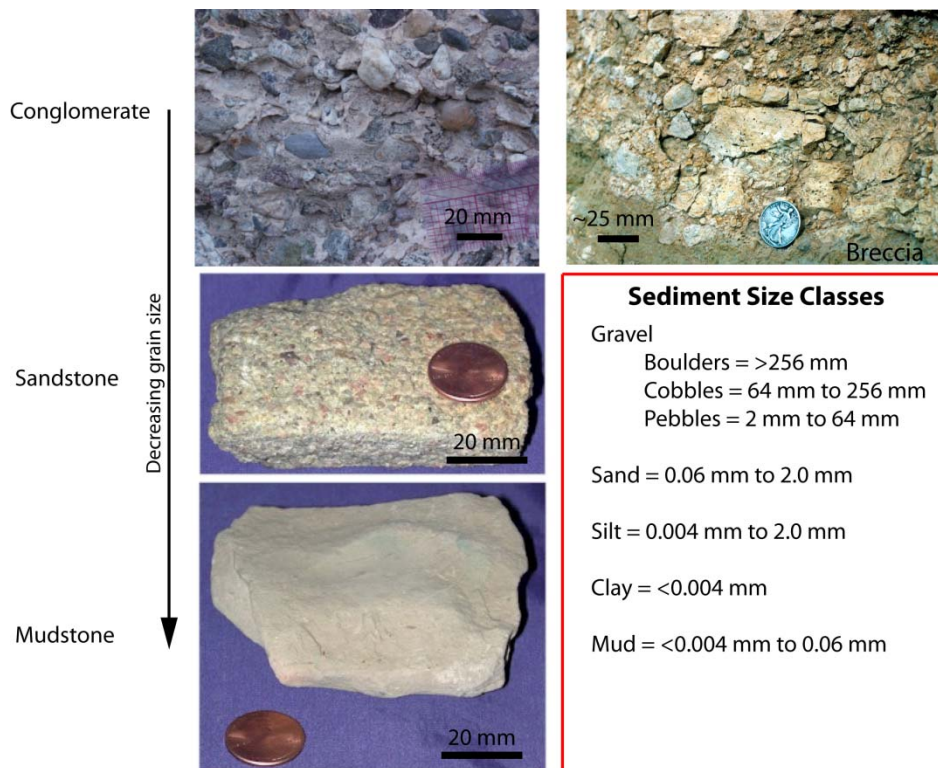

Sediment Size Classes

Gravel
  Boulders = >256 mm
  Cobbles = 64 mm to 256 mm
  Pebbles = 2 mm to 64 mm

Sand = 0.06 mm to 2.0 mm

Silt = 0.004 mm to 2.0 mm

Clay = <0.004 mm

Mud = <0.004 mm to 0.06 mm

Figure 7. Sediment size classes and common clastic sedimentary rocks. Photograph of breccia courtesy United States Geological Survey.

Metamorphic Rocks

Metamorphic rocks are derived from older rocks (i.e., igneous, sedimentary, or metamorphic rocks) through solid-state recrystallization at varying pressures and temperatures. Generally, for a metamorphic rock to form the pressures and temperatures must be significantly greater than they are at or near the Earth's surface. Both temperature and pressure increase with depth within the Earth's interior. The **geothermal gradient** is the change in temperature with depth, while the **geobarometric gradient** is the change in pressure with depth. The geotherm in continental areas is about 20°-30^oC/kilometer. In contrast, in volcanic arcs the geotherm can reach ~50^oC/kilometer. A common geobarometric gradient is ~0.33 kilobars/kilometer.

Along a particular geothermal gradient, the term **grade** refers to the general temperature conditions of metamorphism with low grade representing low temperatures at relatively shallow depth while high grade represents higher temperatures at deeper crustal levels (Figure 8). Examples of metamorphic rocks reflecting progressively higher metamorphic grades include **slates**, **schists**, and **gneisses** (Figure 8). With this as a necessary background, let's now turn our attention to plate tectonics.
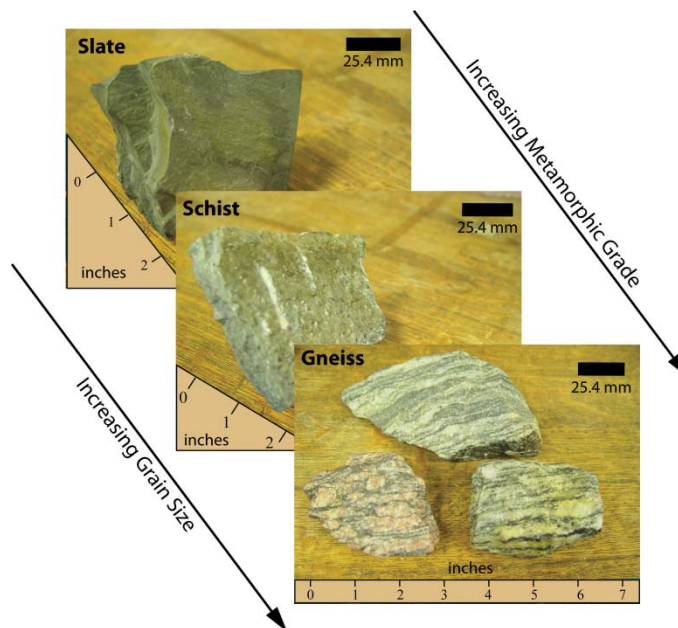

Figure 8. Common metamorphic rocks.

Plate Tectonics

Today planet Earth consists of from its interior to its surface, the solid Fe-Ni **inner core**, liquid **outer core**, **mantle**, and **crust** (Figure 9). The inner core is very hot reaching temperatures as great as $9,000^o$ F (4982^oC) while the temperature at or near the outer core/mantle boundary was recently estimated to be $6,650^oF$ ($3,277^oC$). By comparison the temperature of the surface of the Sun is about 9932^oF (5500^oC).
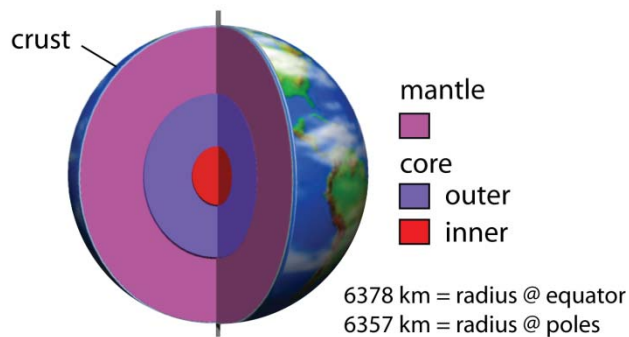
Figure 9. Earth's interior compositional shells. Note that the Earth is not a perfect sphere but is instead an oblate ellipsoid. This form is indicated by its different pole and equatorial diameters.

The outer core is an electrically conducting Fe-Ni liquid. Thermal convection and the rotation of the Earth cause it to be in a constant state of motion which in turn induces the Earth's magnetic field. Without the magnetic field as a shield, the Earth would be unprotected from the solar winds, and would not be able to sustain an atmosphere or oceans.

The mantle is composed of peridotite and makes up about 82% of the volume of Earth. It is overlain by the crust which varies from ~7 kilometers thick in ocean basins to between ~35 to ~75 kilometers in continental areas. The interface separating the mantle from the crust is called the **Mohorovicic discontinuity** or more simple, the **Moho**.

Superimposed on the compositionally defined shells shown in Figure 9 are a series of layers that vary in terms of their strength and rigidity. The outermost ~100-125 kilometer thick layer is relatively strong and rigid and is called the **lithosphere** (Figure 10). It consists of the upper mantle and the crust. Lying beneath it is an ~200 kilometer thick layer that is weak and plastic and probably contains as much as 3-5% melt. This weak plastic layer is contained
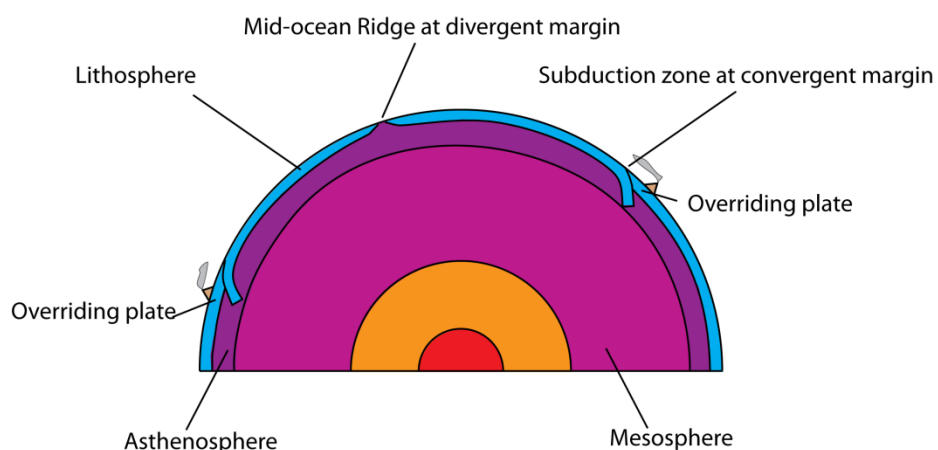

Figure 10. The key mechanically defined shells of planet Earth are the lithosphere, asthenosphere, and mesosphere.

entirely within the mantle and is called the **asthenosphere** (Figure 10). Near the boundary with the lithosphere, the asthenosphere reaches temperatures of about $1300^{\circ}C$. Below the asthenosphere and continuing to the boundary with the outer core is the **mesosphere** (Figure 10).

Based on the composition and thickness of the crustal component, the lithosphere consists of two end-member varieties referred to as oceanic and continental. **Oceanic lithosphere** underlies the world's oceans while **continental lithosphere** underlies continental regions.

Continental lithosphere differs from oceanic lithosphere by having a thicker and compositionally different crustal component (Figure 11). For example, **oceanic crust** is basaltic in composition, and is, on average, about 7 km thick. In contrast, **continental crust** is, on average, granodioritic in composition, and varies between about 35 and 45 km in thickness (Figure 11), but, in some cases, as for example along the western edge of the South American plate, can reach in excess of 75 km thickness.
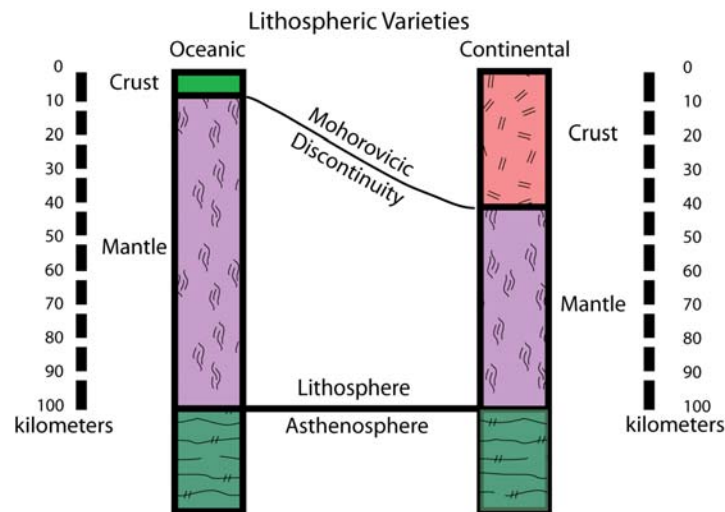

Figure 11. The two main types of lithosphere.

The lithosphere is broken into a number of very large plates and smaller microplates. Regardless of their size, these plates interact in a variety of ways including convergence, divergence, and transform motion. Along convergent margins, two plates move toward each other and along their juncture one plate descends beneath the other (i.e., the overriding plate) (Figure 12). The process of one plate descending beneath another is called **subduction**. As a result of subduction along the margin of the overriding plate a chain of volcanoes, i.e., a volcanic arc develops (Figure 12).

If the volcanic arc is embedded in oceanic lithosphere, then it is called an **intraoceanic island arc** (Figure 12). On the other hand if it is embedded in continental lithosphere, then it is called a **continental-margin island arc**.

In contrast to convergent margins, along a **divergent margin** two plates move directly away from each other (Figure 12). **Mid-ocean ridges** mark the locations of divergent margins, and are sites where new oceanic crust and lithosphere are forming.

Transform margins are sites where two plates are sliding past each other (Figure 12). Ideally, along such margins there is neither convergence nor divergence.
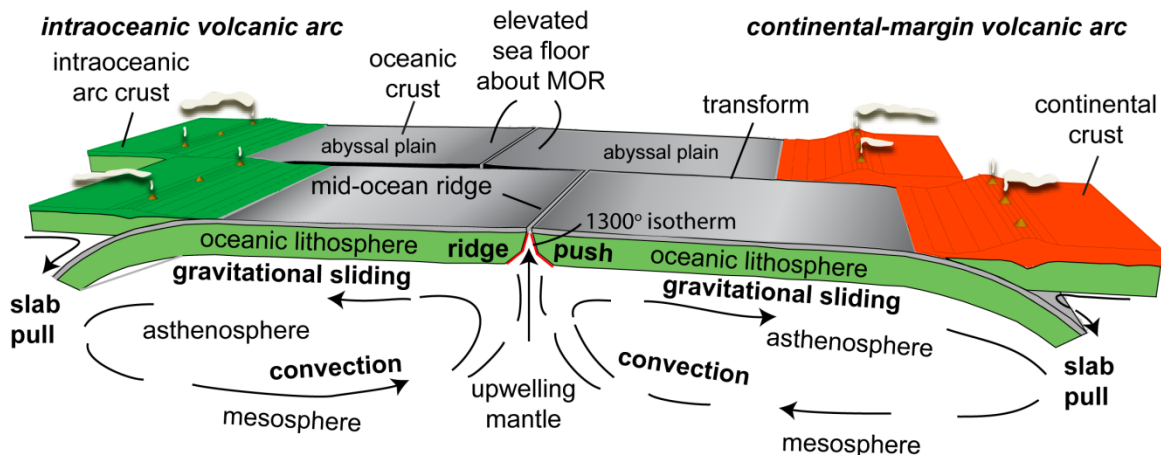

Figure 12. The dominant forces driving top-down convection driven plate tectonics.

The forces driving plate motion are complex and are dominated by ridge push, gravitational sliding, slab pull, and by a density inversion. Let's delve deeper into this complex and intriguing issue (Figure 12).

As new zero-aged oceanic lithospheric crust is created at mid-ocean ridges it is less dense then the underlying asthenosphere and as a result it floats above it (Figure 12). However, as new oceanic crust moves away from the axis of the ridge, it and the underlying asthenospheric mantle cool. Once the upper part of the asthenospheric mantle cools below ~1300°C, it becomes part of the lithospheric mantle; hence, the lithospheric mantle thickens away from the ridge axis (Figure 12). After about 20 to 40 million years have elapsed, the oceanic lithosphere has reached about 100-125 km thick, and *its density has increased to a value greater than that in the underlying asthenosphere*. At this point in its development, oceanic lithosphere is negatively buoyant, and, as a result, it begins to sink and **gravitationally slide** toward the adjacent trench along the lithosphere-asthenosphere boundary.

As the leading edge of the descending plate encounters greater and greater depths beneath the overriding plate, atoms are forced to occupy smaller and smaller volumes. As a result, the density of the leading edge of the descending plate increases significantly. This increase in density is likely marked by the transformation of basaltic crust to eclogite, a metamorphic rock composed of the high pressure minerals garnet, pyroxene, and olivine. The result of this process is that the dense leading edge of the subducting plate now tends to pull it downward much like the weight on a fishing line pulls it to the bottom of a stream bed or lake; hence, the term **slab pull** (Figure 12).

Ridge push occurs at mid-ocean ridges where hot buoyant asthenosphere rises beneath the ridge elevating it relative to adjacent areas (e.g., the abyssal plains) (Figure 12). In other

words, the rising asthenosphere creates a force that "pushes" or "shoulders aside" the two plates (Figure 12).

In summary, as the subducting plate moves laterally and downward into the asthenosphere it displaces material, and, thus induces the asthenospheric convective flow patterns depicted in Figure 12. This overall process is self organizing and is referred to by Professor D.L. Anderson of the California Institute of Technology as **top-down convection**.

The seven major plates of planet Earth are the **North American**, **South American**, **Pacific**, **African**, **Euroasian**, **Indian- Australian**, and **Antarctica** plates (Figure 13). The Juan de Fuca, Riveria, Cocos, Nazca, Caribbean, Burma, Arabia, Philippine, and Scotia are examples of microplates. Each of the seven major plates is composed of both continental and oceanic lithosphere. However, the Pacific plate differs from the other six major plates by being composed mostly of oceanic lithosphere (Figure 13). It, in fact, only contains continental lithosphere along its eastern edge where the San Andreas fault has displaced a small sliver of the North American plate northwestward. This small sliver underlies Baja California, Mexico, and extends northward along the coast of California to about San Francisco.
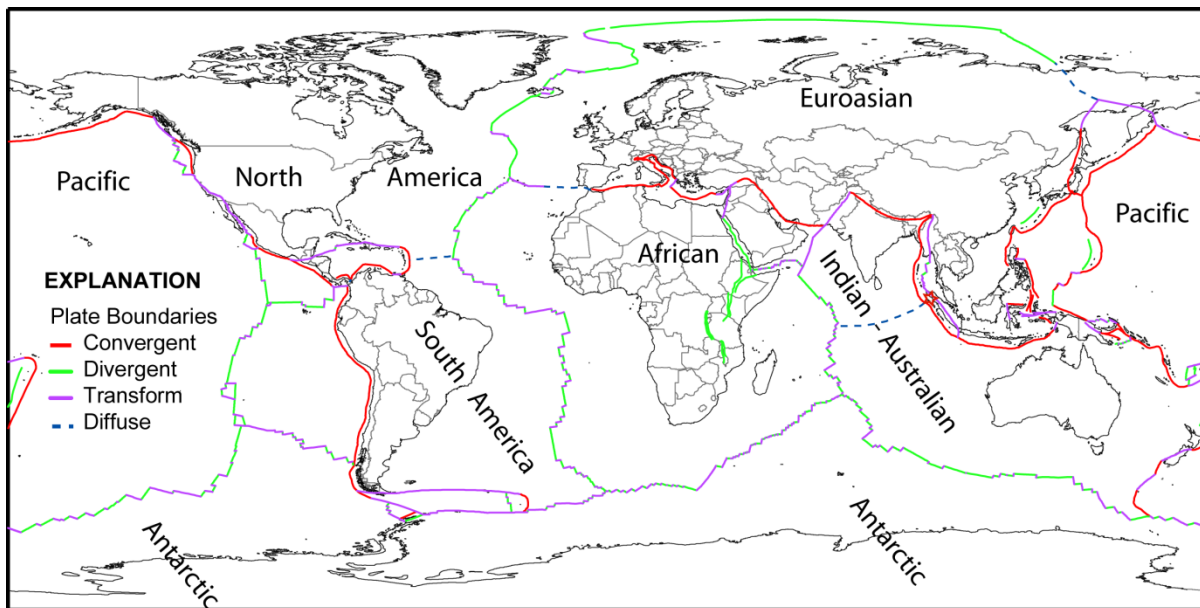
SOURCE: http://wwwneic.cr.usgs.gov/neis/plate_tectonics/plates.html

Figure 13. The seven major lithospheric plates of planet Earth.

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