Mantle Plumes, Hot Spots and Igneous Rocks

This laboratory supports the material covered in OCN 201 lectures on mantle plumes and hot spots but also provides much more information on igneous rocks. In today's laboratory, you will view a video of eruptions on the Big Island of Hawai`i. You will be given information about the formation and classification of igneous rocks and the hands on exercises will deal with identifying various types of volcanic rocks/formations.

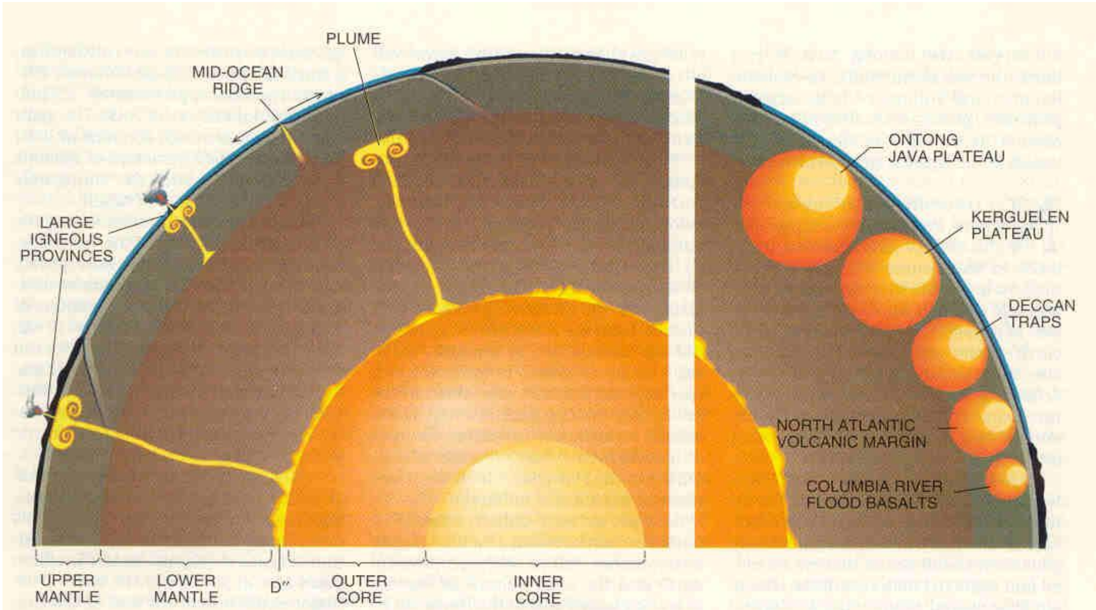
KEY WORDS: a`a, andesite, aseismic ridges, ash, atolls, Bowen's reaction series, cinder, clasts, columnar basalt, ejecta, flood basalts, fusiform bombs, glass, guyots, hot-spots, hyaloclastite, island chains, lapili, large igneous provinces, lava straws, mantle, magma, mantle plumes, (mantle) xenolith, oceanic plateaus, olivine, olivine basalt, pahoehoe, Pele's hair, Pele's tears, peridotite, pillow lava, phreatic, pumice, pyroxene, reticulite, scoria, ribbon lava, tuff, volcanism.

Introduction

The theory of plate tectonics accounts nicely for the slow and steady volcanic activity that occurs at mid-ocean ridges (MOR) and near subduction zones. It cannot, however, readily explain the outbursts of **magma** necessary to create mid-plate islands such as those in the Hawaiian Archipelago or some of the more expansive areas of volcanic activity known as **large igneous provinces**, such as **flood basalts** (e.g., the Columbia River Flood Basalts in the Northwest USA) and **oceanic plateaus** (e.g., Ontong Java Plateau). There is no diverging plate boundary at such locations, that allows upwelling of magma… Hence, some other mechanism is necessary to explain these features.

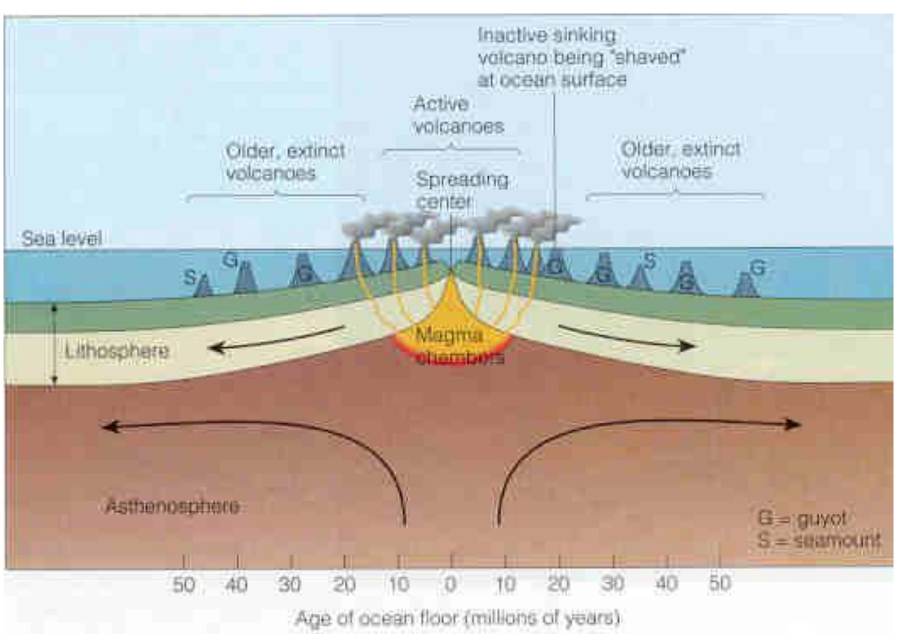
Mantle plumes or **hot spots** were first hypothesized in 1963 by J. Tuzo Wilson of the University of Toronto to explain linear **island chains** in the Pacific Ocean. The Hawaiian Island archipelago and the Emperor Seamount chain are probably the best known among these chains. Wilson proposed that hot spots represent the surface manifestation of point sources of magma, which have remained in a relatively fixed position in the mantle of the earth for extended periods of time. The hypothesis suggests that these sources of magma likely originate at the **core-mantle boundary** as well as at the boundary between the upper and lower mantle. This is shown in the figure below depicting mantle plumes and large igneous provinces (LIPs). Interestingly, the rocks that make up LIPs and hot spot islands have a very similar composition to those found at MOR, except there are some notable differences in their trace element composition. Explaining these differences is beyond the scope of this course so we will not discuss them any further. The lavas from mantle plumes/hot spots are basaltic and are therefore much more similar to oceanic crust than they are to continental crust.

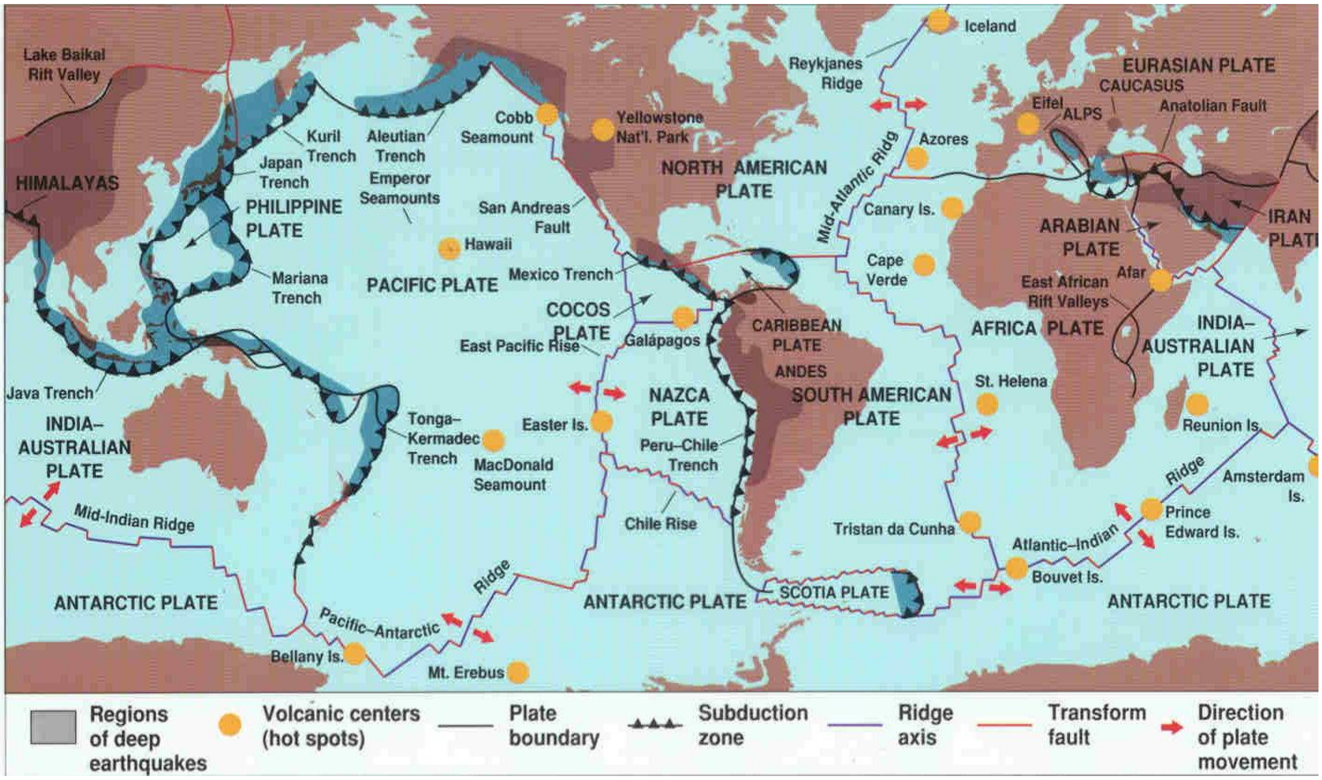
Hot spots commonly occur on or near spreading axes. Some examples of this type of hot spot include Iceland on the Mid Atlantic Ridge (MAR) and Easter Island on the East Pacific Rise (EPR). Because of their location on the MOR system, Morgan proposed in 1972 that hot spots may play an important role in driving plate motions. He suggested that hot spots represent major zones of focused upwelling in an overall pattern of mantle convection, whereas downwelling is instead, diffuse and not localized.



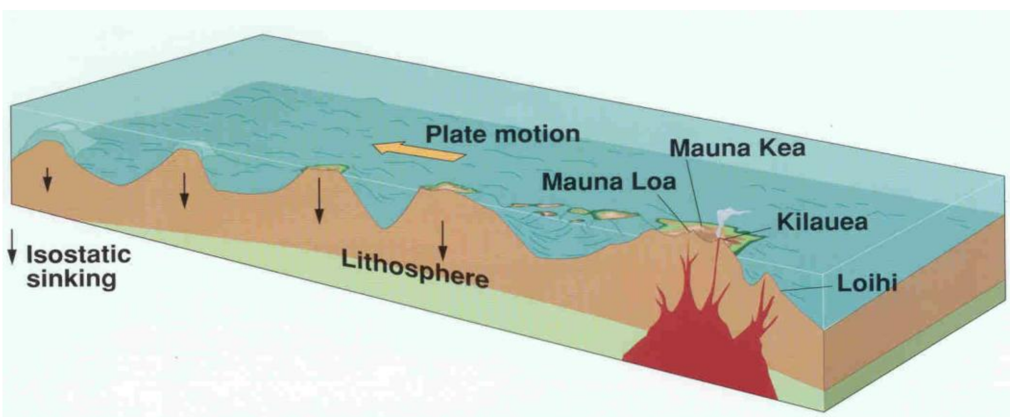
RISING PLUMES of hot material migrate through the earth's mantle; where the head of the plume reaches the surface, a large igneous province forms (*left*). Plumes probably originate at the boundary layers between the core and mantle (the D″) and between the upper and lower mantle. The parent plumes of the most voluminous igneous provinces were so huge that they must have originated at least in part in the lower mantle, most likely at the D″. The spheres on the right depict the minimum (*white*) and maximum (*dark orange*) inferred diameters of the plumes associated with five major igneous provinces.

The hot spots that occur on or near the MOR system lead to the formation, over time, of what are known as **aseismic ridges**. These extend outward from the spreading axis. The aseismic ridges result from the large output of magma that is associated with the hot spots. Examples include the Tristan da Cunha hot spot, which produced the Rio Grande Rise and the Walvis Ridge in the South Atlantic Ocean (see Figure of hot spot locations on next page). The mechanism of formation of such a ridge is analogous to that depicted in the figure immediately below, except the volcanoes are not necessarily separate and the locus of magma outpouring is not always necessarily along the ridge axis.

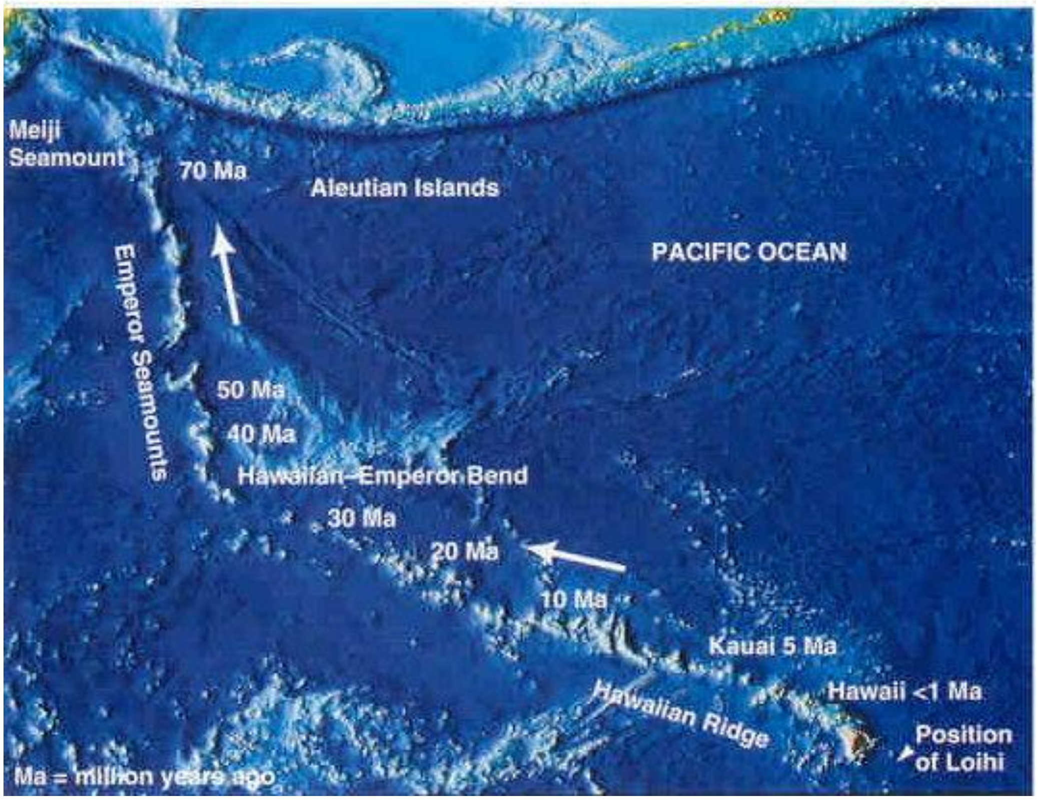




Hot spots can also occur in the middle of plates, either on oceanic crust (e.g., Hawaii, MacDonald Seamount, Reunion Island) or on continental crust (e.g., Yellowstone, Eiffel). Because the location of hot spots remains relatively fixed in the mantle for extended periods of time, the product of the hot spot volcanism is a linear track of volcanic activity. Thus, a chain of **seamounts** (or islands) is formed as the plate moves over the hot spot. Keep in mind that the chains of islands and seamounts are analogous to the aseismic ridges in their mode of formation, except they are not located at a ridge axis. The hot spot hypothesis also provides a means for determining the “absolute” motion of plates. That is, it allows determination of what the motion of the plate is relative to the underlying mantle. Remember that you used the orientation of the Hawaiian Island chain and the Emperor Seamounts in a previous laboratory to help determine where seafloor features had originally formed and to calculate their approximate ages based on spreading rates.



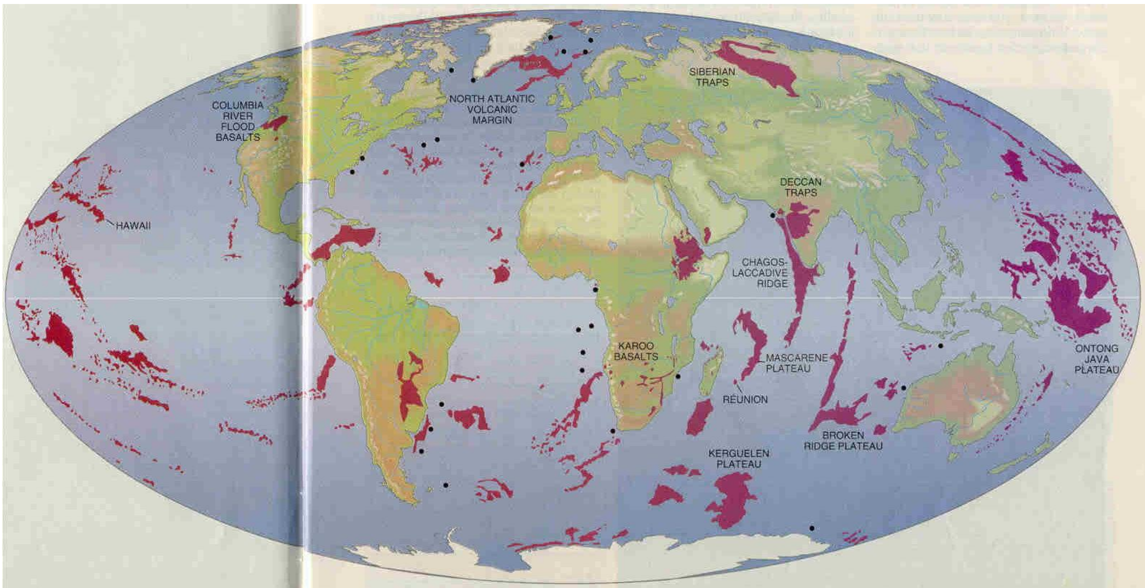
The very obvious bend in the Hawaiian-Emperor Seamount trend (see figure below) is thought to define a change in the direction of motion of the Pacific plate that took place around 43 Ma ago. The oldest of the Emperor Seamounts is 70 Ma old.



What causes plate motions to change remains speculative. It is possible that they are related to changes in plate boundaries caused by the inability of subduction zones to subsume continental crust. For example the collision between India and Asia occurred about 43 Ma ago, and the subduction zone in existence before India ran into Asia was unable to absorb the subcontinent of India. Note that the bend in the Hawaiian-Emperor trend also dates back to 43 Ma. Coincidence? Perhaps, but maybe not!

The initiation of a new mantle plume is thought to lead to the formation of a LIP, because of the large dimension of the plume within the mantle. If you examine the first diagram in this handout you will see how large some of the plumes are that formed various LIPs (on land and at sea).

When a LIP surfaces on land the provinces are called **flood basalts**. The Deccan Traps in India date back to 67 Ma ago and are the largest expression of a LIP on land. The dimensions are several hundred kilometers across and several kilometers thick. The Deccan Traps formed during a period of less than one million years, which indicates an eruption rate of about 2 to 8 km^3/yr. These basalts also produced the Chagos-Laccadive Ridge and the Mascarene Plateau. The current location of this hot spot is Reunion Island, near Madagascar in the Indian Ocean (see figure below).



LARGE IGNEOUS PROVINCES (*red regions*) appear in widely varied geologic settings around the globe. Dots indicate locations where seismic reflection studies seem to reveal ancient volcanism along continental margins. The largest igneous province—the Ontong Java Plateau—covers nearly two million square kilometers. Studies of these huge magmatic formations are providing new insight into the internal workings of the earth and how they may affect conditions at the surface.

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Other examples of land based LIPs, which were covered during OCN 201 lectures include:

1. The Siberian flood basalts, which formed about 248 Ma ago and coincided with one of the largest biological extinctions in the Phanerozoic Era. About 95% of all marine species disappeared at this time.

2. The Columbia River Plateau flood basalts, which date back to about 17 Ma ago and covered an area larger than New York State. The eruptions lasted for about 1.5 million years.

When a LIP erupts on the seafloor, rather than on land, it is called an **oceanic plateau**. In reality oceanic plateaus are no different than flood basalts. Notable examples that were discussed in lecture include:

1. The Ontong-Java Plateau is located in the central western Pacific Ocean and is the largest oceanic plateau. It formed about 122 Ma ago and a volume of 36 million km^3 of basalt erupted in less than three million years. This translates to an eruption rate of about 12 km^3/yr. This plateau is approximately 25 times larger than the Deccan traps, or about 2/3 the size of Australia. The plume head (assuming a melt fraction of 5-30%) associated with the Ontong-Java Plateau would have had a diameter of about 600-1400 km, which is up to about half the thickness of the mantle (see figure at the top of page 2 of this handout). The large volumes of lava produced during the eruption would have raised sea level by about 10 m and could have increased the temperature of the atmosphere by 7-13^{o}C.

2. The Kerguelen Plateau is located in the southern Indian Ocean and is the second largest oceanic plateau. It formed about 112 Ma ago over a period of about 4.5 million years.

Eruption rates during the formation of LIPs are very large, and the heat flux to the surface of the earth (ocean and atmosphere) would be substantial. The formation of LIPs would likely have changed climate substantially and the impact on biological activity must have been severe! In fact, LIP formation has been suggested as a major cause of mass biological extinctions.

In summary, Hot Spots or Mantle Plumes are important because they represent the third type of volcanic activity on earth. The other two are formation of new oceanic crust at MOR and formation of volcanic arcs associated with subduction zones. Mantle plumes also represent major points of focused upwelling of magma, and are helpful in measuring absolute plate motion relative to fixed points in the mantle.

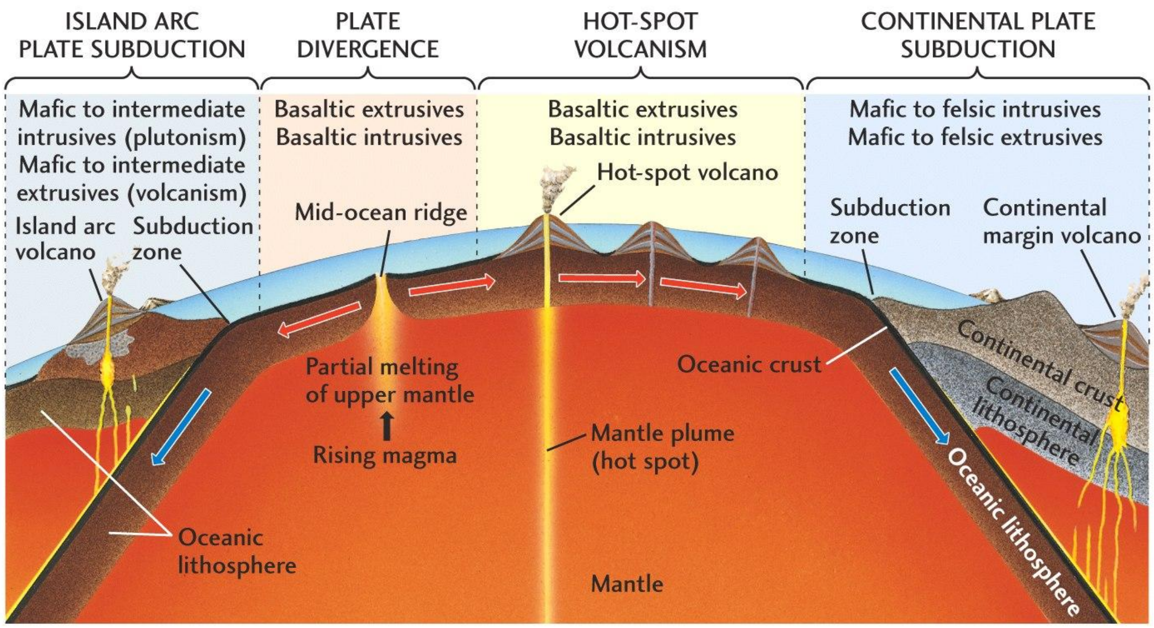
Igneous Rocks

Rocks are natural aggregates of **minerals**, **mineraloids**, glass, or organic particles. For example, **granite** is a continental rock composed of several rock-forming minerals (quartz, feldspar and mica); **obsidian** is a rock composed of volcanic glass, and amber is a rock composed of solidified pine resin. A **mineral** is a naturally occurring, inorganic substance that has a **crystalline structure** defined by its chemical composition. Substances having crystalline structure are called **crystals**. Minerals also have specific and distinct physical properties (such as hardness, solubility, color, refractive index, etc.). A **mineraloid** is much like a mineral, except it lacks a crystalline structure, i.e., mineraloids are **amorphous** (no shape).

Igneous rocks are aggregates of minerals that crystallize from molten material (**magma**) that is generated within the earth's mantle. It is the material that, upon eruption, leads to the formation of the various forms of lava and volcanic rocks. Note that lava is defined as magma that flows onto the surface of the land or seafloor. Hence, the same “stuff” is magma while underground and becomes lava when it exits the crust of the earth. Magma degasses, as it is extruded/erupted on Earth’s surface.

The type of igneous rock formed depends on a number of factors, including the original composition of the magma, the rate of cooling, and the reactions that occurred within the magma as cooling took place. Igneous rocks are widely studied for many reasons. First, many people live close enough to volcanoes to be killed by explosive eruptions or huge landslides triggered by eruptions. Geologists study the ancient deposits of volcanoes to understand their likely (future) eruptive style. Second, the bulk of the Earth's crust, both continental and oceanic, is made of igneous rocks. Third, igneous rocks commonly form at tectonic plate boundaries; hence, the study of ancient igneous rocks tells us a great deal about the history of the Earth. Finally, hot magmas drive circulation of a lot of hot water. These hot fluids pick up a number of important metals and can deposit them to create ore deposits. Igneous rocks form in continental as well as in oceanic settings.

Magma forms under conditions that are strongly connected to movements of lithospheric plates. These movements control where rocks of the crust and upper mantle melt and whether they will be intruded or extruded.

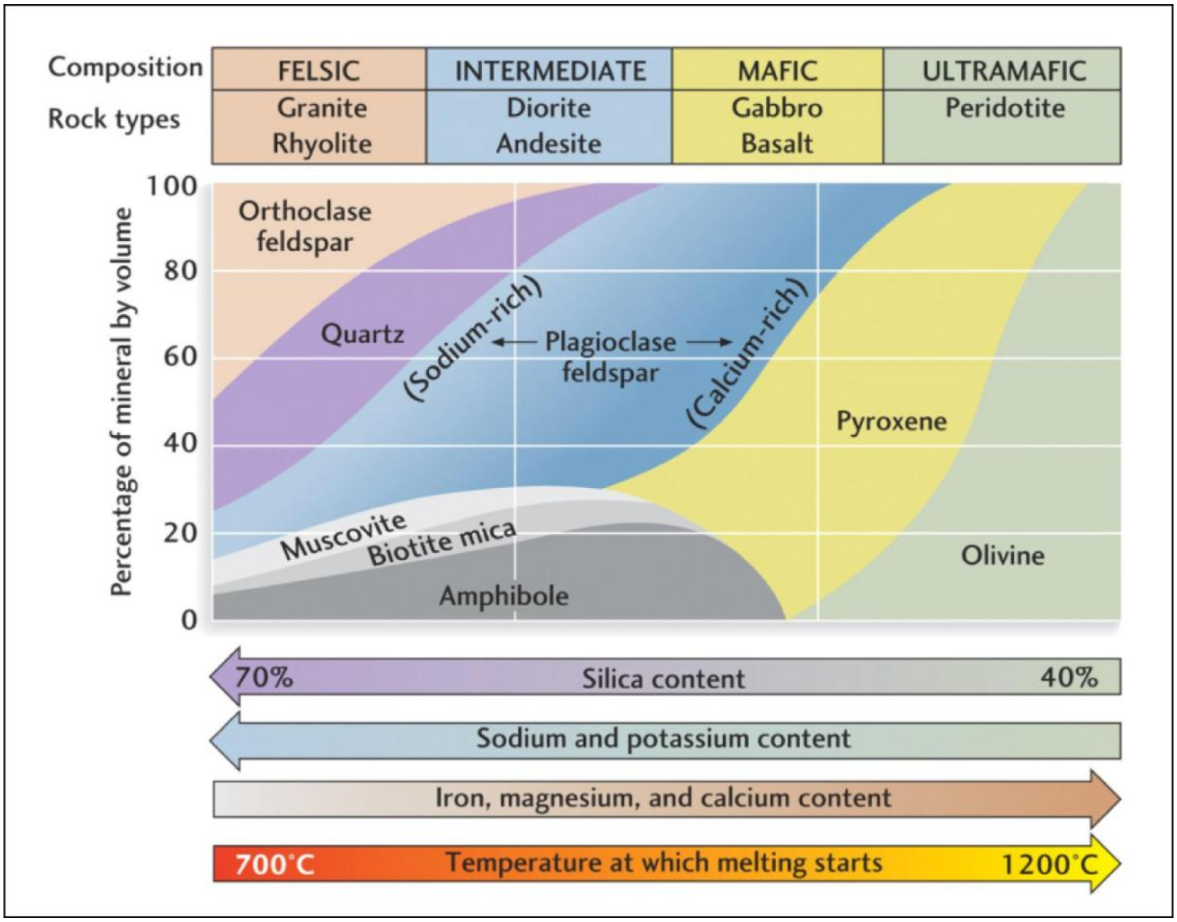


Igneous rocks formed from magma are called **intrusive** rocks, whereas those formed from lava are called **extrusive** rocks. The sizes of mineral crystals that form in igneous rocks indicate the rate at which the magma or lava cooled. The slower the cooling rate, the bigger the individual crystals will grow. The opposite also holds true, if magma or lava cools quickly, the crystals will be small. For example, **obsidian** is an extreme example of rapid cooling. In this case, the lava cooled so fast (it was "quenched") that crystals did not have enough time to form, and the resulting glass (obsidian) is **amorphous.** Igneous rocks composed of crystals that can be seen with the naked eye are known to be **phaneritic,** while those with crystals that are too small to see with the naked eye are called **aphanitic**. If the crystals in a rock are larger than about 1 cm on edge, the rock is said to have a **pegmatitic** structure.

Three characteristics are used to classify igneous rocks:

- Their composition (i.e., the minerals they contain)
- Their **color index**
- Their texture

Modern classifications group igneous rocks according to their relative proportions of silicate minerals - quartz, feldspar, muscovite, biotite, amphibole, pyroxene and olivine. **Felsic** (= Feldspar-Silica) minerals are high in silica; **mafic** (=Magnesium-Ferric) minerals are low in silica. The adjectives felsic and mafic are applied to both minerals and rocks that have high contents of these minerals. Mafic minerals crystallize at higher temperatures-that is, earlier in the cooling of magma than do felsic minerals. The figure below shows the classification model of igneous rocks. The vertical axis measures the mineral composition of a given rock as a percentage of its volume. The horizontal axis is a scale of silica content by weight.



As you know, the interior of the Earth is molten to semi-molten, and upwelling of magma in the plate tectonic system leads to formation of the crust which contains various types of igneous rocks. The property that determines what types of minerals form under given conditions and a given composition of a magma, is principally the temperature of crystallization. This is really the same thing as the freezing point; it is the transition between liquid and solid state.

The different materials that make up the Earth have different melting points. For example, we know that ice melts at a much lower temperature than wax. When non-homogenous rocks are heated, the different minerals melt at temperatures characteristic of each mineral. Therefore, it is possible to have rocks that are partly molten and partly solid at a given temperature. This is known as partial melting. When rocks are heated and undergo partial melting, the magma formed by the low temperature melting minerals may rise (for example in a convection cell) and separate from the remaining solid parts of the rocks to produce felsic magma. At higher temperatures, the other minerals begin to melt and form intermediate magma. **Peridotite,** a rock type commonly found deep in hot spot volcanic environment, is an intrusive, phaneritic rock having a very high color index (>95% dark ferro-magnesian minerals). It is composed primarily of green **olivine**. If the rock has large abundance of (black) **pyroxene**, rather than olivine, it is called a **pyroxenite**. Pyroxene generally crystallizes from magma at lower temperatures than olivine (see Figure-7, Bowen's Reaction Series), but because of an overlap in the melting range, it is possible to have both olivine and pyroxene in a single rock. Some of the xenoliths from Hualalai volcano on the Big Island (Hawai`i) contain both olivine and pyroxene.

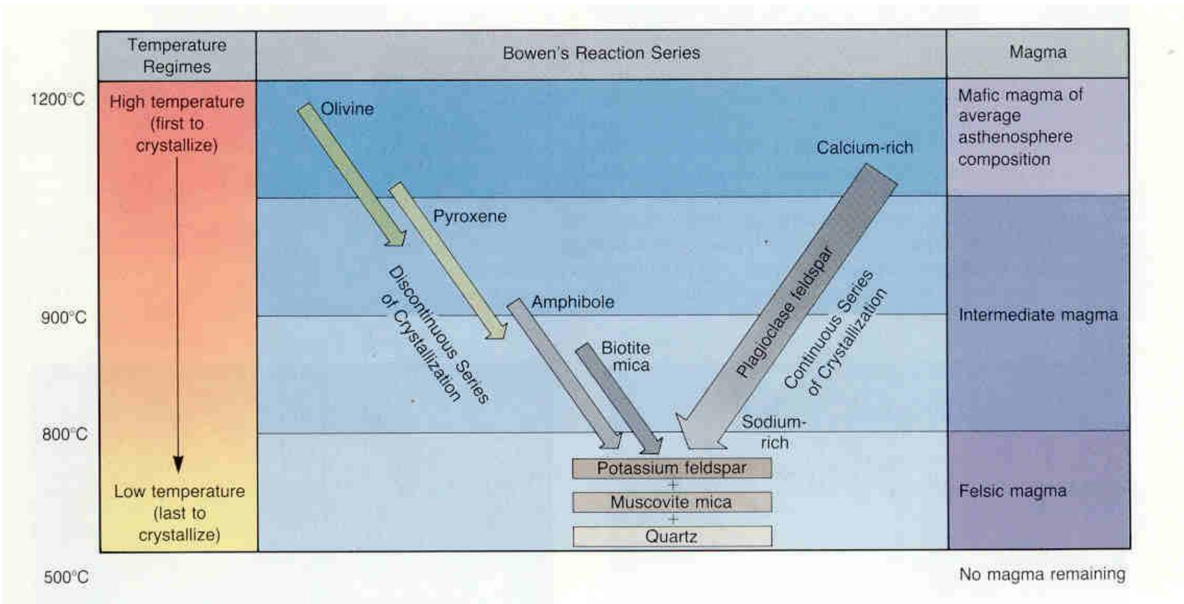
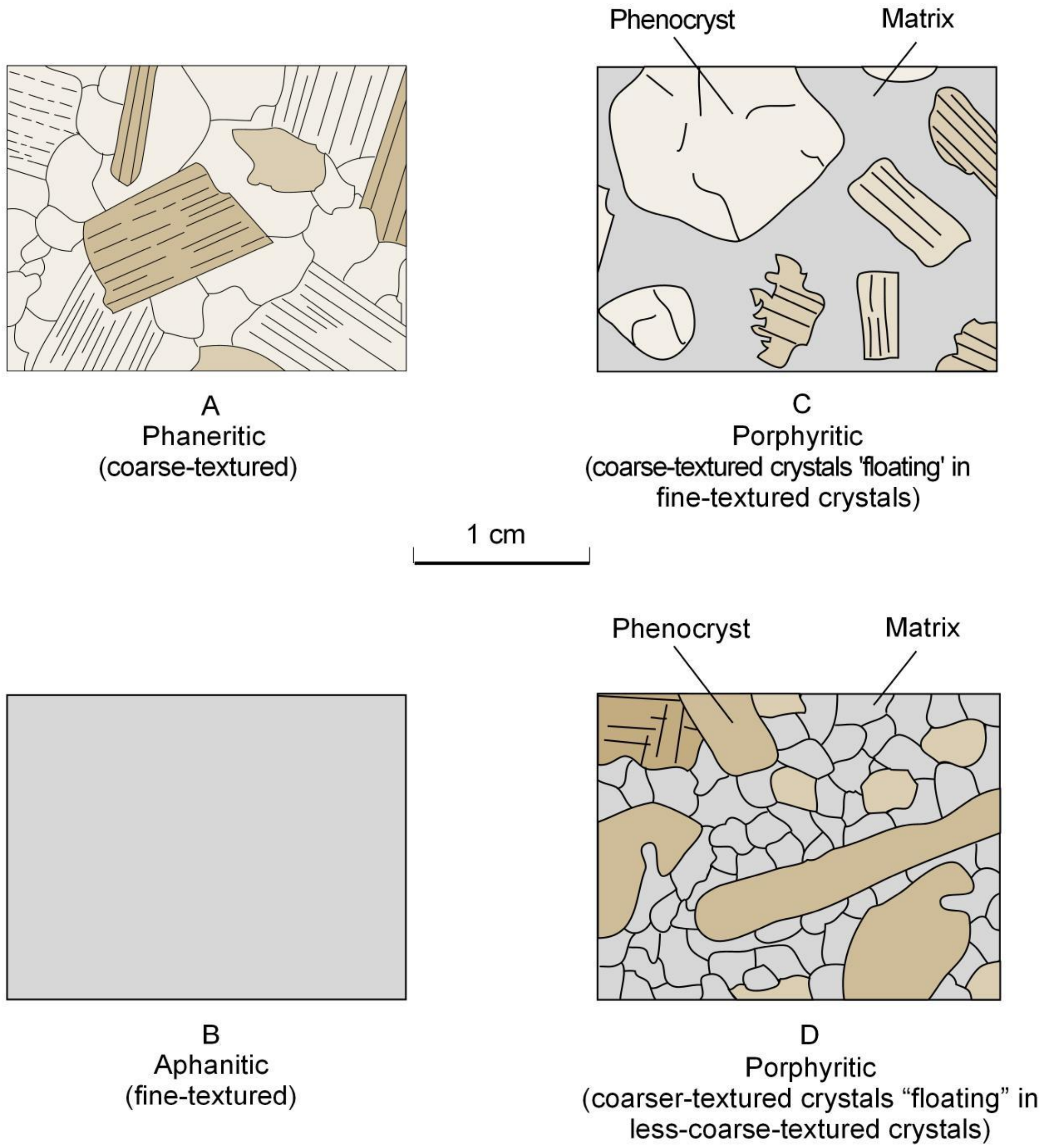


Figure-7: Bowen's reaction series, showing the sequence in which minerals crystallize from magma when an "average" magma from the asthenosphere is cooled slowly. Note the relationship between temperature and mineral composition and stability. The process of rock melting to form magma is the reverse of what is indicated in this diagram.

When magma intrudes country rock (often sedimentary rocks) in continental settings but does not break the surface it has the opportunity to cool very slowly (up to millions of years) and form very large crystals. This type of rock is known as **granite pegmatite**, which has large crystals of quartz, feldspar, and mica. Quartz is the most common mineral in the crust of the earth; but feldspars and mica are also very common. Depending on the abundance of minerals other than quartz and feldspar (and the type of feldspar) the color of the granite can vary. Pink granites are rich in potassium feldspar, but those rich in sodium feldspar ($NaSi_3O_8$) are either gray or white.

The following diagrams show how to classify igneous rocks based on their texture.



The flow chart below show how to classify igneous rocks based on composition, color and texture.

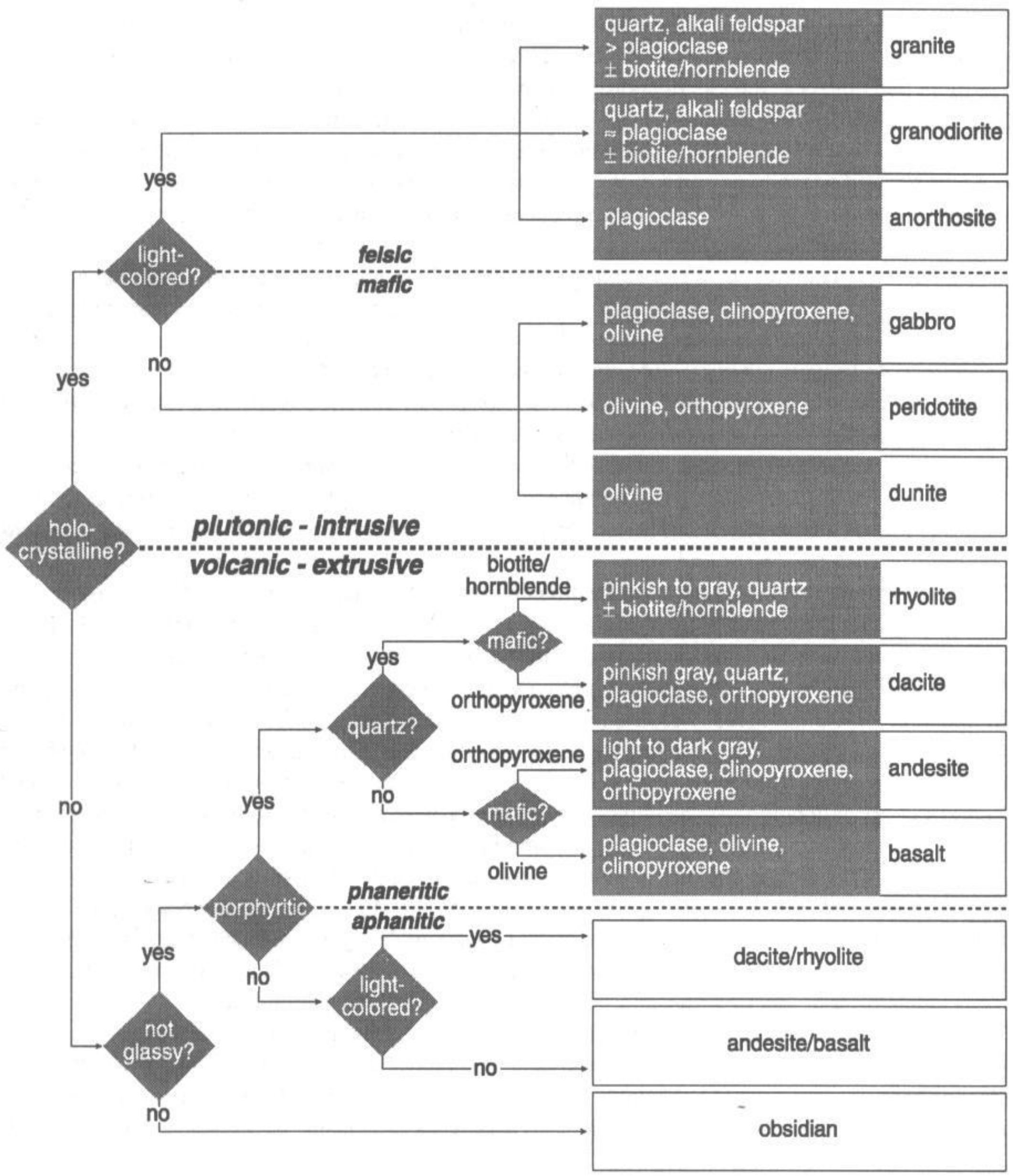


Fig. 3-1: Flowchart for identifying igneous rocks.

Laboratory Exercise

In this part of the laboratory you will be asked to identify a variety of volcanic rocks based on their color and texture and, to a lesser extent, on their composition. The following is a description of the materials you will be asked to identify. Volcanic rocks (whether intrusive or extrusive rocks) can take on many different forms. Which form occurs depends largely on the composition of the magma and on the conditions under which their formation or the eruption takes place.

From the reading above you already know about peridotite. This material is composed primarily of the green mineral olivine, and minor amounts of other minerals such as pyroxene and formed in the early stageof cooling of a rising magma. When olivine is optically clear (well-crystallized and fracture free) it is known as peridot and is a semi-precious gem often used in jewelry. Pyroxenes are the second class of minerals to crystallize from a melt. In Hawaii (and other areas), when magma rises through a conduit that passes through a layer peridotite, it can rip out solid fragments of the crystallized peridotite and bring them up to the surface of the earth along with the liquid lava. Occasionally, the magma rises through layers of mixed peridotite and pyroxenes and carries some of that material upwards. The material is ejected from the throat of the volcanic pipe, lands on the ground, and the lava surrounding the previously crystallized peridotite cools and hardens. This forms a rock type known as a **xenotlith**. This type of rock has “normal” lava on the outside and the inside is full of crystallized green olivine and/or dark pyroxene. Xenolith, however, is really a term which applies to any rock that contains crystals torn from deep within the earth and carried up by magma. In the case of peridotite or pyroxene xenoliths, they are easily recognized even when you cannot see the crystals within, because they tend to be very dense.

Olivine basalt is another type of rock commonly found in Hawaii. Olivine crystals are disseminated throughout the dark basalt, rather than concentrated in the middle of the rock. There are many examples of olivine basalt throughout the Hawaiian Islands. A short walk onto the large boulders that make up the jetty at Magic Island or at Ala Moana harbor leads to fine examples of this material.

Another olivine rich material is “green sand”. This is simply finely ground olivine crystals derived from erosion of peridotite or very olivine-rich basalt. There are green sand beaches on most of the main Hawaiian Islands. Green sand can be found at the base of Mount Leahi (Diamond Head) in Honolulu. Here this material is found in pockets or small coves between rocks just below the Diamond Head lighthouse. There is also green sand at the Blow Hole end of Sandy Beach in East Oahu.

When volcanic activity occurs through water saturated rock, the eruptions are explosive, or **phreatic**. Under such conditions, **volcanic ash** or **tuff**, results if the eruption occurs above sealevel. Tuff is defined as consolidated volcanic ash, composed largely of fragments smaller than 4 mm, produced directly by volcanic eruption. Much of the fragmented material represents finely divided crystals and rocks. If the eruption occurs under water or ice, however, as in the case of eruptions near the summit of Mauna Kea when covered by a glacier several thousand years ago, the product is called **hyaloclastite**.

Hyaloclastite also forms when lava flows into the ocean (or any other body of water) and the (glassy) material fragments. Thus, hyaloclastite is a rock composed of a mixture of glassy **clasts** (small fragments caused by mechanical breakdown of larger rocks) which, with age, can become altered and weathered. It then looks like a conglomerate of different angular volcanic rock fragments, which is also known as **breccia**. The latter is held together in a compacted matrix (often composed of clay minerals).

Volcanic **glass** looks, as its name implies, glassy, and forms when lava cools too rapidly to allow the minerals to crystallize. Often, volcanic rocks have an outer rind of glass, that cooled rapidly, whereas the interior, which cooled more slowly is not glassy, and may even appear to be crystallized. Volcanic glass can also be called obsidian, particularly when it is of rhyolitic composition (rhyolite occurs in volcanoes associated with subduction zones, rather than hot spots or mid-ocean ridge volcanoes).

The large variety of volcanic rock products also includes **a`a**, **pahoehoe**, **Pele's tears**, **Pele's hair**, **fusiform volcanic bombs**, etc. There are many forms of volcanic rocks but we will only discuss a few of these here. When material similar to that which forms Pele's hair ends up in small clumps with lots of void space in between the fragments of rock, rather than as long fine filaments, it is known as **reticulite**. This type of rock has a very low density. Lava can also drip down the edge of a flow, and as the outside of the drip cools and solidifies, material inside can continue to flow. These miniature lava tubes are known as **lava straws**. **Cinder** is another term used to describe small pieces of ejecta that often resemble a`a, but are only up to a couple centimeters in diameter. If ejecta is more like pahoehoe, but is also spewed out of the volcano and lands on the ground, it can form what is known as **volcanic splatter**. Today you will see volcanic splatter from Mauna Ulu, a vent area on the East Rift Zone of Kilauea volcano, that has also been steam altered on the exterior; it is reddish brown in appearance and looks more like pahoehoe than a`a. Occasionally, sheet-like fragments of molten ejecta does not spin into the shape of a bomb. Instead it lands on its edge and folds upon itself to forms what is called **ribbon lava, or ribbon bombs**. Another form of volcanic rock, which many people have seen, but whose origin is often unknown to them, is **pumice**. It is also known as volcanic foam. This material is "rock froth," sort of the "smoothie" of volcanic fluids. It forms by extreme puffing up of liquid lava by expanding gases that are liberated from solution in the lava prior to and during solidification. Pumice has such a low density it can float on water. In most cases it is light gray in color. Its composition is variable depending on its origin. The specimen available today came from the Rabaul Caldera, in New Britain, an island in the South West Pacific Ocean.

In today's exercise, you will also sort volcanic rocks by vesicularity. This term expresses how abundant vesicles (holes) are in the rock; it is a measure of the porosity of the rock. Obviously, retucilite and pumice are at one end of the spectrum and **columnar basalt,** which has no evident vesicles, and is very dense, is at the other end of the spectrum. Vesicles in volcanic rocks result from expanding gases present in the erupting magma and its escape during the subsequent cooling (solidifying) of the lava. Highly vesiculated rocks have a low density, whereas those with few or no vesicles are much denser. Why is density inversely proportional to vesicularity?