Some notes on igneous rock

Revised April 17, 2020, by Vince Cronin

Principle of ***uniformitarianism***: The physical and chemical laws that govern the physical/chemical world are the same now as in the past. (That is, during virtually all of the 13.8 billion year history of the universe.)

Rocks are naturally occurring aggregates of mineral grains.
- ***Igneous*** rock crystallizes from magma – a hot silicate melt.
- ***Sedimentary*** rock develops as a result of sedimentation or precipitation at the ground surface
- ***Metamorphic*** rock occurs when pre-existing rock (igneous, sedimentary or metamorphic) is changed by stress, pressure, or temperature changes.

Extrusive igneous rock crystallizes ***rapidly*** under relatively low pressure at or near Earth's surface. The texture of extrusive igneous rock features small crystals (<∼1 mm), although in porphyritic rocks there might also be some larger crystals embedded in a groundmass of small crystals.

Intrusive igneous rock crystallizes ***slowly*** at relatively high pressure below Earth's surface. The texture of intrusive igneous rock features large visible crystals (>∼1 mm).

A ***phaneritic*** igneous rock contains visible crystals that are typically >∼1 mm in diameter, and are frequently ∼1 cm in diameter.

An ***aphanitic*** igneous rock contains very small crystals that are typically <∼1 mm in diameter.

Volcanic glass like *obsidian* is not a rock because it is not made (primarily) of mineral grains. It solidifies very rapidly over a few seconds to a few minutes – too fast for crystals to form.

A ***porphyritic*** texture in an igneous rock involves two distinctly different sizes of grains in the same rock. The general interpretation is that the larger grains formed over a relatively longer time in the magma chamber, and then a change in temperature/pressure caused the more rapid crystallization of the rest of the magma. That change is most easily understood in porphyritic extrusive rock, in which the larger ***phenocrysts*** probably grew while the magma was still in the magma chamber, and the smaller ***groundmass*** crystallized after eruption.

Different minerals crystallize at different temperatures and pressures. For example, the minerals *olivine* and *calcium-rich plagioclase feldspar* crystallize at higher (hotter) temperatures in the vicinity of 1200°C, while minerals like *potassium feldspar* and *quartz* crystallize at lower (cooler) temperatures in the vicinity of ∼750°C. This relationship is illustrated in the classic Bowen's Reaction Series, although the BRS does not reflect the initial composition of all magmas.

Earth's crust is NOT floating on a sea of molten magma. Earth's lithospheric plates are NOT floating on a sea of molten magma. The only layer of Earth's interior that is in the liquid state is the outer core. Otherwise, magma exists in specific limited areas in the crust or uppermost mantle.

Magma can be found...

...above a subducting slab, approximately where the top of the slab reaches a depth of ~100 km,

...along a mid-ocean ridge or continental rift,

...above a hotspot, as occurs beneath the main island of Hawaii, under Yellowstone, and under Iceland,

...and associated with minor gaps in the crust caused by faulting, or in areas of unusually thick crust like the Himalaya.

Igneous rocks can be grouped into compositional twins: rocks that have different textures because they are intrusive or extrusive, but that have identical minerals.

- *granite* (phaneritic, intrusive) and *rhyolite* (aphanitic, extrusive) are felsic rocks
- *diorite* (phaneritic, intrusive) and *andesite* (aphanitic, extrusive) are intermediate rocks
- *gabbro* (phaneritic, intrusive) and *basalt* (aphanitic, extrusive) are mafic rocks

Magmas have different compositions because different processes can affect them. All magmas are produced by partial melting of pre-existing rock. Partial melting of the upper mantle produces a mafic magma that crystallizes to form *basalt* (aphanitic, extrusive) or *gabbro* (phaneritic, intrusive). Partial melting of the continental curst produces a more diverse array of magmas that tend to be more felsic. Some of the processes that further affect the composition of a given magma include:

- assimilation, in which bits of the rock that surrounds the magma chamber is melted or incorporated as chunks into the magma, which might result in development of xenoliths in the crystallized rock;
- mixing, in which magmas from two sources meet in a conduit or magma chamber and share some of their content;
- fractional crystallization, in which the minerals that crystallize at higher (hotter) temperatures form early in the crystallization process, stick to the walls or floor of the magma chamber, and deplete the remaining liquid magma of the elements that are now bonded into their crystal structures. So the magma becomes progressively enriched in elements that are not incorporated in the high-T minerals.
- different source areas, in which diverse source rocks are converted to magmas that have a diversity of compositions.

Intrusive igneous rock bodies

- dikes: cracks created by the injection of magma that cut across the pre-existing layering or fabric of a rock
- sills: cracks created by the injection of magma that are parallel to the pre-existing layering of a rock

- plutons: large round blobs of magma that rise through the crust, like the blobs in a lava lamp.
- stocks: an exposure of igneous rock at the ground surface that has an area less than 100 km^2
- batholiths: an exposure of igneous rock at the ground surface that has an area greater than 100 km^2; examples include the Sierra Nevada, Idaho, and Southern California batholiths
- laccoliths: a mushroom-shaped intrusive body with a generally planar-horizontal base and an arched top, developed because the magma pressure in a sill was sufficient to lift the rock above it.
- necks: the hard, erosionally-resistant interior conduit of an extinct volcano that is left behind as a high-point in the landscape after the rest of the volcano has eroded away.

Some Notes on Volcanoes and Extrusive Igneous Rock

Volcanoes occur above subduction zones, above mantle hotspots, along rift zones and the mid-ocean ridge system, and in localized areas in continental crust where block rotations and translations result in deep gaps that (perhaps) generate decompression melting(?)

Volcanoes, viscosity and magma. Mafic magma begins to crystallize at a higher (hotter) temperature than felsic magma. Mafic magma also has less silica (minerals with silicon + oxygen) than felsic magmas. The result is that mafic magmas are less viscous than felsic magmas, meaning that they flow more easily – they are more like water than like silly putty.

Magma viscosity is affected by several things. The viscosity of a magma tends to be ***greater*** if it has…

…less thermal energy (lower temperature)

…more silica

…less water

…more gas bubbles

Low-viscosity (mafic) magmas tend to produce volcanoes with ***gently sloping sides*** and ***broad bases***, like the volcanoes of the Hawaiian Islands. The main island of Hawaii is the tallest mountain on Earth if measured from its base (below sea level) to its top, and it is broad enough to cover the state of Wisconsin. These ***shield volcanoes*** do *not* produce explosive eruptions, although they can appear to be very energetic on the human scale for anyone standing close to an active vent during an eruption.

High-viscosity (felsic) magmas produce volcanoes with more ***steeply sloping sides*** and ***narrower bases***, like the volcanoes of the Cascade Range of northern California through British Columbia, or the Andes Mountains of South America. These ***stratavolcanoes*** (or ***composite volcanoes***) can produce violent explosive eruptions, such as the eruptions of Mt. Vesuvius in Italy (79 AD), Mt. St. Helens in Washington (1980), and Mt. Pinatubo in the Philippines (1991).

Extrusive igneous rock types (simplified for the purposes of this course)

- **rhyolite**
  - same composition as intrusive rock "granite"
  - pink potassium feldspar, sodium feldspar, quartz, amphibole
  - silica rich
  - crystallizes at cooler temperatures (~750°C) than basalt
  - higher viscosity magma than basalt
  - rhyolitic volcanoes are composite/stratavolcanoes that tend to erupt explosively
  - rhyolitic volcanoes are located on continental crust
- **andesite**
  - same composition as intrusive rock "diorite"
  - feldspar, little or no quartz, amphibole ± pyroxene
  - intermediate silica content
  - crystallizes at intermediate temperatures relative to rhyolite or basalt
  - higher viscosity magma than basalt
  - andesitic volcanoes are composite/stratavolcanoes that tend to erupt explosively
  - andesitic volcanoes are located on continental crust
- **basalt**
  - same composition as intrusive rock "gabbro"
  - darker/translucent calcium feldspar, pyroxene, olivine
  - silica poor
  - crystallizes at high/hot temperatures (starting at ~1250°C)
  - lower viscosity magma than rhyolite or andesite
  - shield volcanoes are basaltic, and erupt without explosion
  - basaltic volcanism is characteristic of oceanic crust, and occurs locally on continental crust: rift zones, above hot spots, etc.

Tuff is a volcanic rock composed largely or entirely of solidified ash

Pyroclastic breccia is composed of gravel-sized particles ejected from a volcano, usually in a matrix of ash.

Pumice is a frothy material composed largely of glass and air. Blocks of pumice float on water, at least until water fills enough of the pore space in it.

Obsidian is volcanic glass, formed from the rapid quenching of magma -- fast enough so that mineral crystals could not form. Obsidian is said to be a supercooled liquid.

The material blown out of a volcano is collectively called **pyroclastic** material, from the words "pyro" meaning *fire* and "klastos" meaning *broken*

- **dust** is less than 1/16 mm in diameter (silt-clay sized particles)
- **ash** is 1/16 to 2 mm in diameter (sand sized particles)
- **cinders** or **lapilli** are 2-64 mm in diameter (pebbles-cobbles)

- **bombs** and **blocks** are more than 64 mm in diameter (boulders)

Magma **viscosity** is a function of...

- **temperature**: hotter magma has lower viscosity
- **silica content**: less silica results in lower viscosity
- **dissolved water**: more dissolved water results in lower viscosity
- **gas bubbles**: more gas bubbles results in ***higher*** viscosity

Volcano types

- **shield volcanoes** have gently sloping sides and a broad base. The tallest mountains in the solar system are shield volcanoes: Hawaii (Earth) and Olympus Mons (Mars). All of the Hawaiian Islands are shield volcanoes.
  - **composite volcanoes** or **stratavolcanoes** have steeply sloping sides and a relatively narrow base. Arc volcanoes (above subduction zones) like those in the Cascade Range of Washington, Oregon and northern California, are shield volcanoes. Formed by successive layers of lava flows and pyroclastic debris.
  - **cinder cones** are (essentially) small volcanoes composed largely or entirely of scoriaceous basalt (a.k.a. scoria or cinder), like the stuff at the bottom of many barbeques.
  - **rhyolite domes** or **obsidian domes** form from very viscous felsic magma. The crater of Mt. St. Helens contains a rhyolite dome formed since the catastrophic eruption of May 1980. Collapse of rhyolite domes can generate devastating pyroclastic flows.
  - **flood basalts** or **plateau basalts**: massive eruptons covering thousands of km^2

Some geomorphic elements of volcanoes

- a **vent** is the orifice at the top of a volcano through which gas and magma erupt
  - a **crater** is the bowl-shaped feature at the top of a volcano where the vent is located.
  - a **fissure** is a crack in the side of a volcano through which magma can flow. These might be circular and concentric with the crater, or (more commonly) radial, extending like spokes away from the crater.
  - a **caldera** is a broad depression at the top of some volcanoes, formed when the magma chamber collapses after eruption.
  - a volcanic **neck** is the eroded remnants of the main conduit in the center of a volcano through which magma flowed when the volcano was active.

Some terms associated with volcanic flow forms

- **aa** (pronounced AH-ah) is the Hawaiian word for blocky lava
  - **pahoehoe** (pronounced pah-HOY-hoy) is the Hawaiian word for ropey lava
  - **pillow lava** is formed when magma flows onto the seafloor. When the >1000°C lava meets the cold sea water, the outer surface urns to a glass film and the magma is extruded in big glass bubbles, a bit like filling water balloons. Pouring molten wax into water yields the same sort of forms. The pillows can vary from less than a meter to a couple of meters in length.

- **columnar jointing** occurs during cooling of thick magma flows, and in some near-surface sills. As the magma cools and solidifies, it shrinks. One mechanism to allow shrinkage is the generation of fracture systems that isolate ~6-sided columns of cooling rock from one another, in a process that is quite similar to the development of shrinkage cracks in drying mud.

Some effects of volcanoes

- Volcanic activity can lead to the creation of new land area
  - source of geothermal energy
  - concentration of economic minerals such as gold, silver, et cetera
  - might have played a role in providing the environment for development of life on Earth, perhaps along mid-ocean ridges or in other niches like the geyser pools at Yellowstone
  - source of much of Earth's atmosphere and (perhaps) water
  - natural contributor to acid rain
  - natural contributor of the "greenhouse gas" carbon dioxide to the atmosphere
  - Large explosive eruptions can insert fine particles into the upper atmosphere that have the effect of changing Earth's albedo, making it look whiter from space and reflecting some of the Sun's radiation away from Earth's surface

Volcanic hazards

- being blown to pieces, if you have the bad luck of standing in the crater of an explosive volcano when it erupts (*e.g.,* Galeras Volcano, 1993)
- burial by volcanic flows (*e.g.,* Kalapana, Hawaii)
- burial by ejected volcanic material ± flows (*e.g.,* Heimaey, Iceland)
- burial by ash (*e.g.,* area around Mt. Pinatubo, Philippines) leading to collapse of buildings and destruction of crops, transportation, communication facilities, water supplies, famine and starvation
- burial/incineration by pyroclastic flows (*e.g.,* Pompeii and Herculaneum destroyed in 79 AD by pyroclastic flows from Vesuvius, and St. Pierre (30,000 dead) on the island of Martinique destroyed by pyroclastic flows from Mt. Pelee in 1902)
- burial by volcanic debris flows called **lahars** (*e.g.,* Columbian town of Armero, buried along with ~23,000 residents by a lahar from Nevada del Ruiz Volcano)
- suffocation or poisoning from volcanic gas or ash (*e.g.,* Lake Nyos, Cameroon; 1700 dead)
- Floods related to melting snow or ice (jökulhlaup)
- damage to motors and other mechanical devices by ash
- earthquakes
- tsunamis (*e.g.,* Krakatau eruption in Indonesia (1883), which killed at least 36,417 people)