EENS-2120	Petrology	Prof. Stephen A. Nelson
Introduction & Textures & Structures of Igneous Rocks		

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Petrology & Petrography

Petrology - The branch of geology dealing with the origin, occurrence, structure, and history of rocks.

Petrography - The branch of geology dealing with the description and systematic classification of rocks, especially by microscopic examination of thin sections. Petrography is a subfield of Petrology.

In this course, most of the lecture material falls under the field of Petrology, while most of the laboratory material falls in the field of Petrography.

Introduction to Igneous Rocks

An ***igneous rock*** is any crystalline or glassy rock that forms from cooling of a magma.

A ***magma*** consists mostly of liquid rock matter, but may contain crystals of various minerals, and may contain a gas phase that may be dissolved in the liquid or may be present as a separate gas phase.

Magma can cool to form an igneous rock either on the surface of the Earth - in which case it produces a ***volcanic*** or ***extrusive igneous rock***, or beneath the surface of the Earth, - in which case it produces a ***plutonic*** or ***intrusive igneous rock***.

Characteristics of Magma

Types of Magma

Types of magma are determined by chemical composition of the magma. Three general types are recognized, but we will look at other types later in the course:

1. ***Basaltic magma*** -- SiO_2 45-55 wt%, high in Fe, Mg, Ca, low in K, Na
2. ***Andesitic magma*** -- SiO_2 55-65 wt%, intermediate. in Fe, Mg, Ca, Na, K
3. ***Rhyolitic magma*** -- SiO_2 65-75%, low in Fe, Mg, Ca, high in K, Na

Gases in Magmas

At depth in the Earth nearly all magmas contain gas dissolved in the liquid, but the gas forms a separate vapor phase when pressure is decreased as magma rises toward the surface. This is similar to carbonated beverages which are bottled at high pressure. The high pressure keeps the gas in solution in the liquid, but when pressure is decreased, like when you open the can or bottle, the gas comes out of solution and forms a separate gas phase that you see as bubbles. Gas gives magmas their explosive character, because volume of gas expands as pressure is reduced. The composition of the gases in magma are:

- Mostly H_2O (water vapor) with some CO_2 (carbon dioxide)
- Minor amounts of Sulfur, Chlorine, and Fluorine gases

The amount of gas in a magma is also related to the chemical composition of the magma. Rhyolitic magmas usually have higher dissolved gas contents than basaltic magmas.

Temperature of Magmas

Temperature of magmas is difficult to measure (due to the danger involved), but laboratory measurement and limited field observation indicate that the eruption temperature of various magmas is as follows:

- Basaltic magma - 1000 to 1200°C
- Andesitic magma - 800 to 1000°C
- Rhyolitic magma - 650 to 800°C.

Viscosity of Magmas

Viscosity is the resistance to flow (opposite of fluidity). Viscosity depends on primarily on the composition of the magma, and temperature.

- Higher SiO_2 (silica) content magmas have higher viscosity than lower SiO_2 content magmas (viscosity increases with increasing SiO_2 concentration in the magma).

- Lower temperature magmas have higher viscosity than higher temperature magmas (viscosity decreases with increasing temperature of the magma).

Thus, basaltic magmas tend to be fairly fluid (low viscosity), but their viscosity is still 10,000 to 100,0000 times more viscous than water. Rhyolitic magmas tend to have even higher viscosity, ranging between 1 million and 100 million times more viscous than water. (Note that solids, even though they appear solid have a viscosity, but it is very high, measured as trillions time the viscosity of water). Viscosity is an important property in determining the eruptive behavior of magmas.

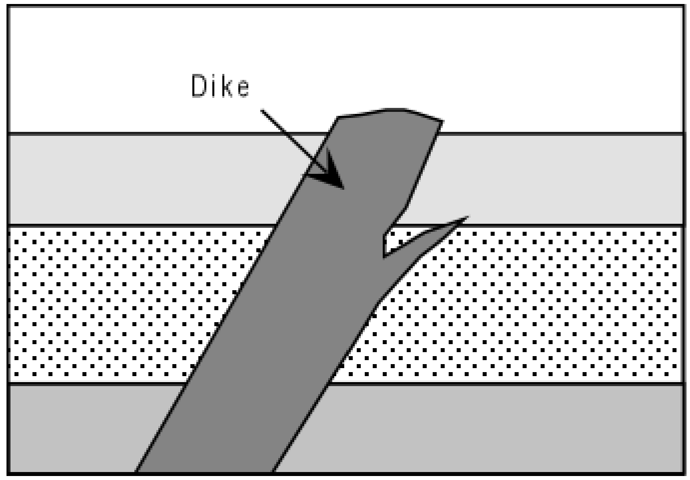
Summary Table					
Magma Type	Solidified Rock	Chemical Composition	Temperature	Viscosity	Gas Content
Basaltic	Basalt	45-55 SiO_2 %, high in Fe, Mg, Ca, low in K, Na	1000 - 1200 °C	10 - 10^3 PaS	Low
Andesitic	Andesite	55-65 SiO_2 %, intermediate in Fe, Mg, Ca, Na, K	800 - 1000 °C	10^3 - 10^5 PaS	Intermediate
Rhyolitic	Rhyolite	65-75 SiO_2 %, low in Fe, Mg, Ca, high in K, Na.	650 - 800 °C	10^5 - 10^9 PaS	High

Plutonic (Intrusive) Igneous Rocks

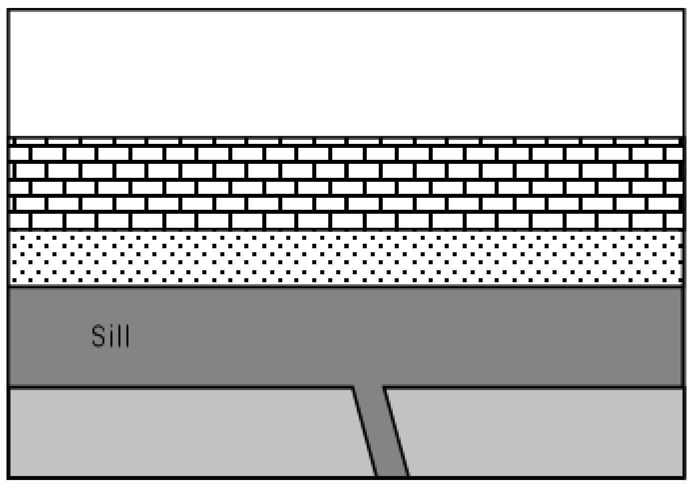
Hypabyssal Intrusions

Intrusions that intrude rocks at shallow levels of the crust are termed hypabyssal intrusions. Shallow generally refers to depths less than about 1 km. Hypabyssal intrusions always show sharp contact relations with the rocks that they intrude. Several types are found:

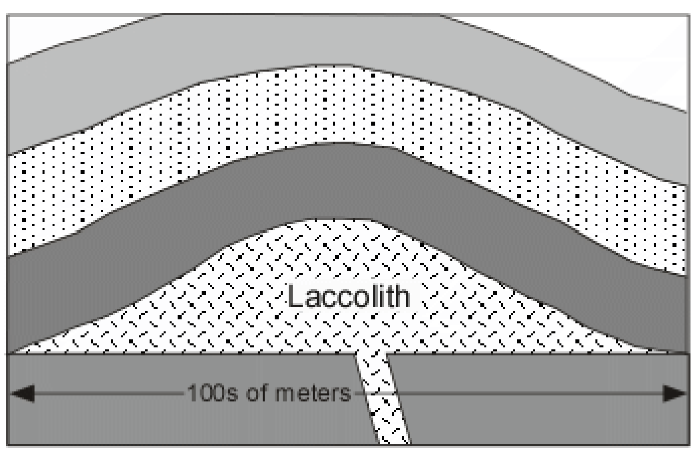
- **Dikes** are small (<20 m wide) shallow intrusions that show a discordant relationship to the rocks in which they intrude. Discordant means that they cut across preexisting structures. They may occur as isolated bodies or may occur as swarms of dikes emanating from a large intrusive body at depth.



- **Sills** are also small (<50 m thick) shallow intrusions that show a concordant relationship with the rocks that they intrude. Sills usually are fed by dikes, but these may not be exposed in the field.



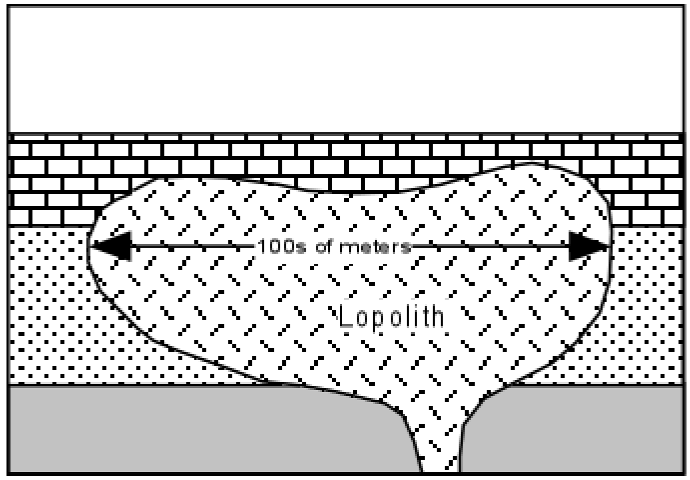
- **Laccoliths** are somewhat large intrusions that result in uplift and folding of the preexisting rocks above the intrusion. They are also concordant types of intrusions.



Plutons

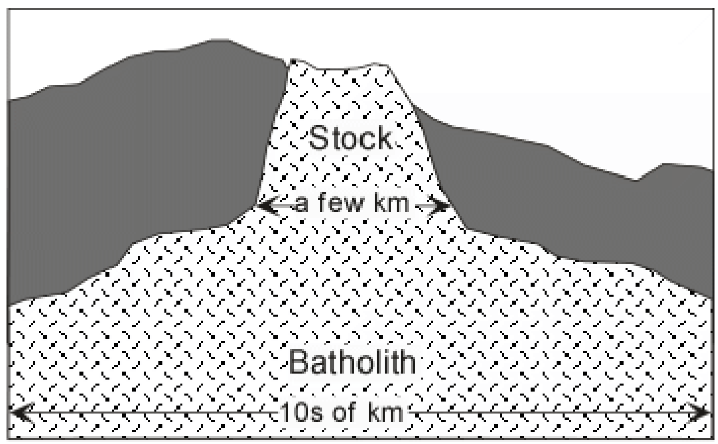
Plutons are generally much larger intrusive bodies that have intruded much deeper in the crust. Although they may show sharp contacts with the surrounding rocks into which they intruded, at deeper levels in the crust the contacts are often gradational.

- **Lopoliths** are relatively small plutons that usually show a concave downward upper surface. This shape may have resulted from the reduction in volume that occurs when magmas crystallize, with the weight of the overlying rocks causing collapse of into the space once occupied by the magma when it had a larger volume as a liquid.



- **Batholiths** are very large intrusive bodies, usually so large that there bottoms are rarely exposed. Sometimes they are composed of several smaller intrusions.

- **Stocks** are smaller bodies that are likely fed from deeper level batholiths. Stocks may have been feeders for volcanic eruptions, but because large amounts of erosion are required to expose a stock or batholith, the associated volcanic rocks are rarely exposed.



Volcanic (Extrusive) Igneous Rocks

Volcanic Eruptions

- In general, magmas that are generated deep within the Earth begin to rise because they are less dense than the surrounding solid rocks.

- As they rise they may encounter a depth or pressure where the dissolved gas no longer can be held in solution in the magma, and the gas begins to form a separate phase (i.e. it makes bubbles just like in a bottle of carbonated beverage when the pressure is reduced).

- When a gas bubble forms, it will also continue to grow in size as pressure is reduced and more of the gas comes out of solution. In other words, the gas bubbles begin to expand.

- If the liquid part of the magma has a low viscosity, then the gas can expand relatively easily. When the magma reaches the surface, the gas bubble will simply burst, the gas will easily expand to atmospheric pressure, and a non-explosive eruption will occur, usually as a lava flow (***Lava*** is the name we give to a magma on the surface of the Earth).

- If the liquid part of the magma has a high viscosity, then the gas will not be able to expand easily. Thus, pressure will build inside the gas bubble(s). When the magma reaches the surface, the gas bubbles will have a high pressure inside, which will cause them to burst explosively on reaching atmospheric pressure. This will cause an explosive volcanic eruption.

Explosive Eruptions
Explosive eruptions are favored by high gas content and high viscosity (andesitic to rhyolitic magmas).

- Explosive bursting of bubbles will fragment the magma into clots of liquid that will cool as they fall through the air. These solid particles become ***pyroclasts*** (meaning - hot fragments) and ***tephra*** or ***volcanic ash,*** which refer to sand- sized or smaller fragments.

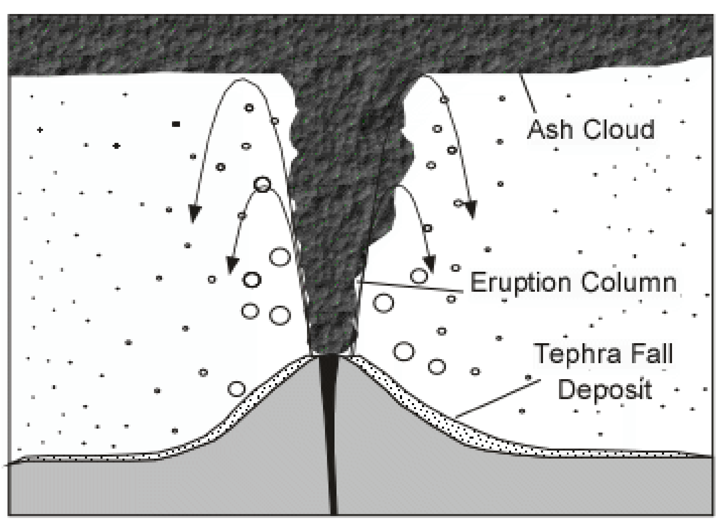
Tephra and Pyroclastic Rocks		
Average Particle Size (mm)	Unconsolidated Material (Tephra)	Pyroclastic Rock
>64	Bombs or Blocks	Agglomerate
2 - 64	Lapilli	Lapilli Tuff
<2	Ash	Ash Tuff

- ***Blocks*** are angular fragments that were solid when ejected.

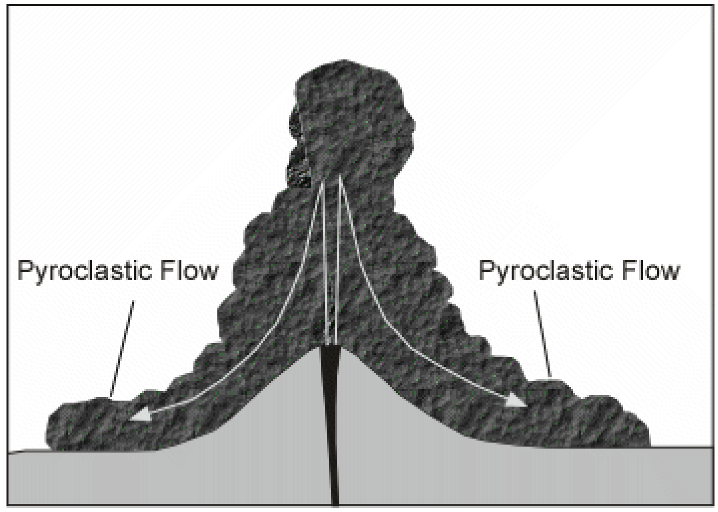
- ***Bombs*** have an aerodynamic shape indicating they were liquid when ejected.

- Bombs and lapilli that consist mostly of gas bubbles (***vesicles***) result in a low density highly vesicular rock fragment called ***pumice***.

- Clouds of gas and tephra that rise above a volcano produce an ***eruption column*** that can rise up to 45 km into the atmosphere. Eventually the tephra in the eruption column will be picked up by the wind, carried for some distance, and then fall back to the surface as a ***tephra fall*** or ***ash fall***.



- If the eruption column collapses a ***pyroclastic flow*** will occur, wherein gas and tephra rush down the flanks of the volcano at high speed. This is the most dangerous type of volcanic eruption. The deposits that are produced are called ***ignimbrites*** if they contain pumice or ***pyroclastic flow deposits*** if they contain non-vesicular blocks.



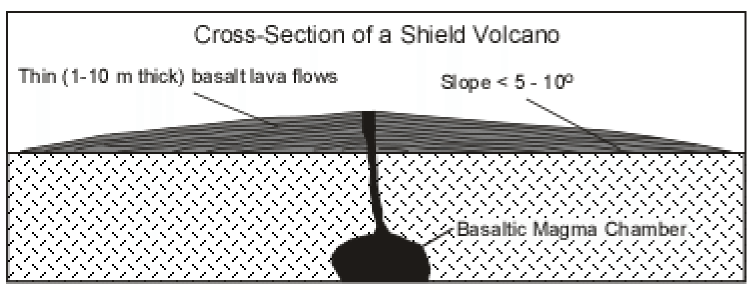
Nonexplosive Eruptions
Non explosive eruptions are favored by low gas content and low viscosity magmas (basaltic to andesitic magmas).

- If the viscosity is low, nonexplosive eruptions usually begin with fire fountains due to release of dissolved gases.
- Lava flows are produced on the surface, and these run like liquids down slope, along the lowest areas they can find.
- Lava flows produced by eruptions under water are called ***pillow lavas***.
- If the viscosity is high, but the gas content is low, then the lava will pile up over the vent to produce a ***lava dome*** or ***volcanic dome.***

Volcanic Landforms

Shield Volcanoes

- A shield volcano is characterized by gentle upper slopes (about 5^{o}) and somewhat steeper lower slopes (about 10^{o}).



- Shield volcanoes are composed almost entirely of thin lava flows built up over a central vent.

- Most shields are formed by low viscosity basaltic magma that flows easily down slope away form a summit vent.

- The low viscosity of the magma allows the lava to travel down slope on a gentle slope, but as it cools and its viscosity increases, its thickness builds up on the lower slopes giving a somewhat steeper lower slope.

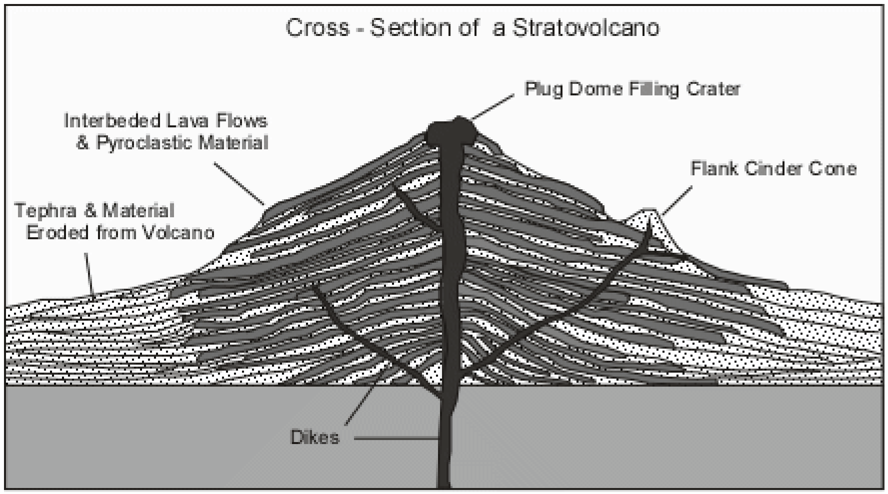
- Most shield volcanoes have a roughly circular or oval shape in map view.

- Very little pyroclastic material is found within a shield volcano, except near the eruptive vents, where small amounts of pyroclastic material accumulate as a result of fire fountaining events.

Stratovolcanoes (also called **Composite Volcanoes**)

- Have steeper slopes than shields, with slopes of 6 - 10^{o} low on the flanks to 30^{o} near the summit.

- Steep slope near the summit result from thick, short viscous lava flows that don't travel far from the vent.



- The gentler slopes near the base are due to accumulations of material eroded from the volcano and to the accumulation of pyroclastic material.

- Stratovolcanoes show inter-layering of lava flows and pyroclastic material, which is why they are sometimes called composite volcanoes. Pyroclastic material can make up over 50% of the volume of a stratovolcano.

- Lavas and pyroclastics are usually andesitic to rhyolitic in composition.

- Due to the higher viscosity of magmas erupted from these volcanoes, they are usually more explosive than shield volcanoes.

- Stratovolcanoes sometimes have a crater at the summit, that is formed by explosive ejection of material from a central vent. Sometimes the craters have been filled in by lava flows or lava domes, sometimes they are filled with glacial ice, and less commonly they are filled with water.

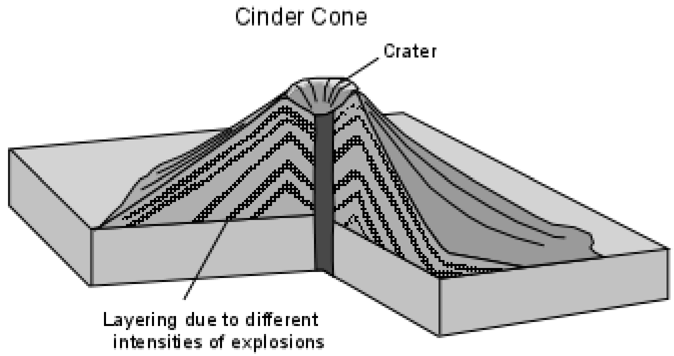
- Long periods of repose (times of inactivity) lasting for hundreds to thousands of years, make this type of volcano particularly dangerous, since many times they have shown no historic activity, and people are reluctant to heed warnings about possible eruptions.

Tephra Cones (also called **Cinder Cones**)

- Tephra cones are small volume cones consisting predominantly of tephra that result from strombolian eruptions. They usually consist of basaltic to andesitic material.

- They are actually fall deposits that are built surrounding the eruptive vent.

- Slopes of the cones are controlled by the angle of repose (angle of stable slope for loose unconsolidated material) and are usually between about 25 and 35^{o}.



- They show an internal layered structure due to varying intensities of the explosions that deposit different sizes of pyroclastics.
- On young cones, a depression at the top of the cone, called a crater, is evident, and represents the area above the vent from which material was explosively ejected. Craters are usually eroded away on older cones.

- If lava flows are emitted from tephra cones, they are usually emitted from vents on the flank or near the base of the cone during the later stages of eruption.

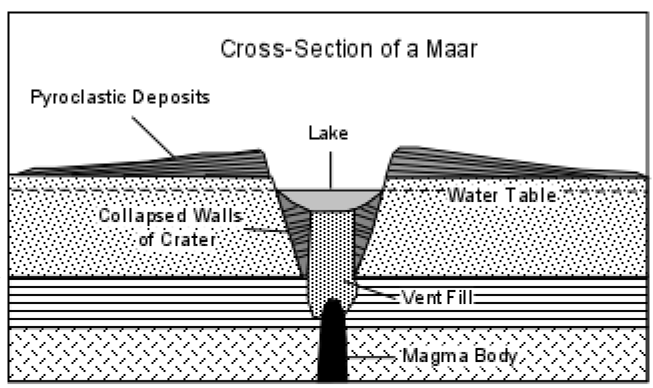
- Cinder and tephra cones usually occur around summit vents and flank vents of stratovolcanoes.

- An excellent example of cinder cone is Parícutin Volcano in Mexico. This volcano was born in a farmers corn field in 1943 and erupted for the next 9 years. Lava flows erupted from the base of the cone eventually covered two towns.

- Cinder cones often occur in groups, where tens to hundreds of cones are found in one area

Maars

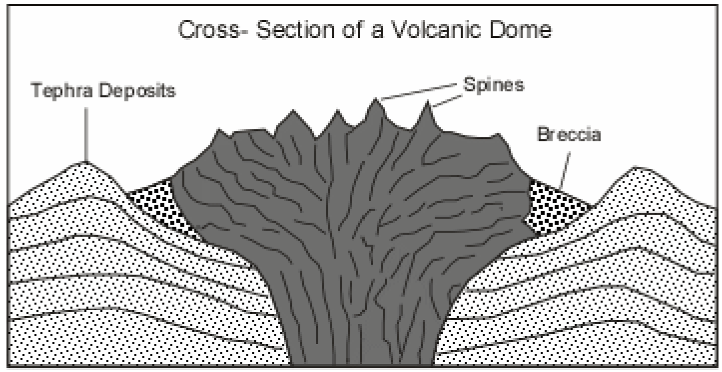
- Maars result from phreatic or phreatomagmatic activity, wherein magma heats up water in the groundwater system, pressure builds as the water to turns to steam, and then the water and preexisting rock (and some new magma if the eruption is phreatomagmatic) are blasted out of the ground to form a tephra cone with gentle slopes.



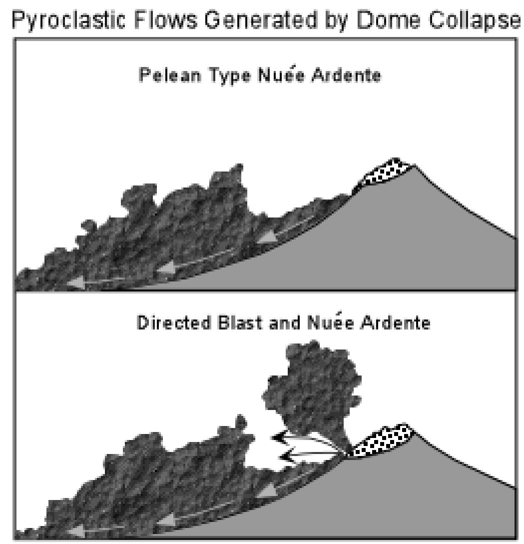
Parts of the crater walls eventually collapse back into the crater, the vent is filled with loose material, and, if the crater still is deeper than the water table, the crater fills with water to form a lake, the lake level coinciding with the water table.

Lava Domes (also called **Volcanic Domes**)

- Volcanic Domes result from the extrusion of highly viscous, gas poor andesitic and rhyolitic lava. Since the viscosity is so high, the lava does not flow away from the vent, but instead piles up over the vent.



- Blocks of nearly solid lava break off the outer surface of the dome and roll done its flanks to form a breccia around the margins of domes.
- The surface of volcanic domes are generally very rough, with numerous spines that have been pushed up by the magma from below.



- Most dome eruptions are preceded by explosive eruptions of more gas rich magma, producing a tephra cone into which the dome is extruded.
- Volcanic domes can be extremely dangerous. because they form unstable slopes that may collapse to expose gas-rich viscous magma to atmospheric pressure. This can result in lateral blasts or Pelean type pyroclastic flow (nuee ardent) eruptions.

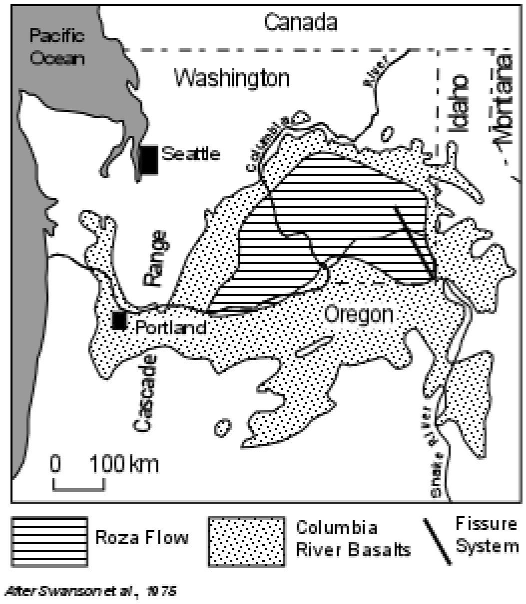
Craters and Calderas

- Craters are circular depressions, usually less than 1 km in diameter, that form as a result of explosions that emit gases and tephra.
- Calderas are much larger depressions, circular to elliptical in shape, with diameters ranging from 1 km to 50 km. Calderas form as a result of collapse of a volcanic structure. The collapse results from evacuation of the underlying magma chamber.
- In shield volcanoes, like in Hawaii, the evacuation of the magma chamber is a slow drawn out processes, wherein magma is withdrawn to erupt on from the rift zones on the flanks.
- In stratovolcanoes the collapse and formation of a caldera results from rapid evacuation of the underlying magma chamber by voluminous explosive eruptions that form extensive fall deposits and pyroclastic flows.
- Calderas are often enclosed depressions that collect rain water and snow melt, and thus lakes often form within a caldera.

Plateau Basalts or **Flood Basalts**

- Plateau or Flood basalts are extremely large volume outpourings of low viscosity basaltic magma from fissure vents. The basalts spread huge areas of relatively low slope and build up plateaus.

- The only historic example occurred in Iceland in 1783, where the Laki basalt erupted from a 32 km long fissure and covered an area of 588 km^2 with 12 km^3 of lava. As a result of this eruption, homes were destroyed, livestock were killed, and crops were destroyed, resulting in a famine that killed 9336 people.
- In Oregon and Washington of the northwestern U.S., the Columbia River Basalts represent a series of lava flows all erupted within about 1 million years 12 million years ago. One of the basalt flows, the Roza flow, was erupted over a period of a few weeks traveled about 300 km and has a volume of about 1500 km^3.



Textures of Igneous Rocks

The main factor that determines the texture of an igneous rock is the ***cooling rate*** (dT/dt)

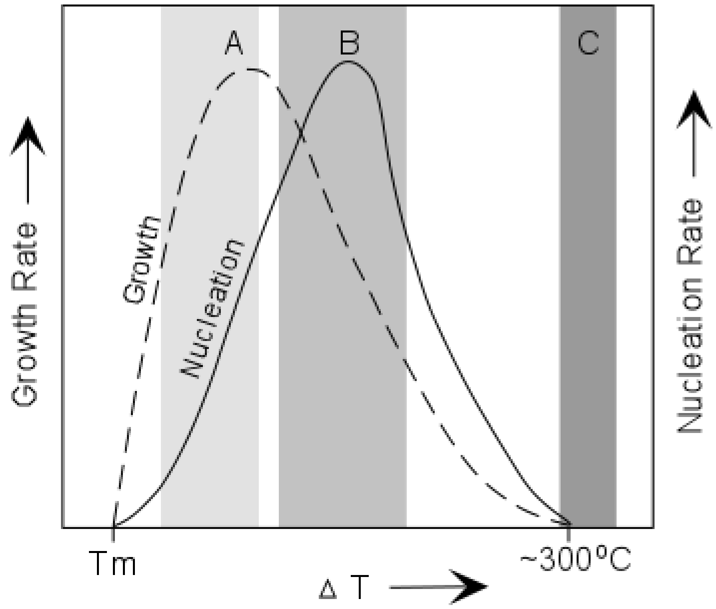
Other factors involved are:

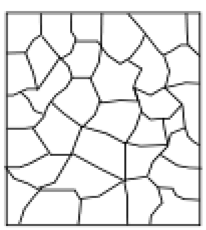
- The diffusion rate - the rate at which atoms or molecules can move (diffuse) through the liquid.
- The rate of nucleation of new crystals - the rate at which enough of the chemical constituents of a crystal can come together in one place without dissolving.
- The rate of growth of crystals - the rate at which new constituents can arrive at the surface of the growing crystal. This depends largely on the diffusion rate of the molecules of concern.

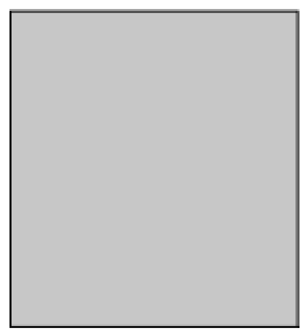
In order for a crystal to form in a magma enough of the chemical constituents that will make up the crystal must be at the same place at the same time to form a ***nucleus*** of the crystal. Once a nucleus forms, the chemical constituents must diffuse through the liquid to arrive at the surface of the growing crystal. The crystal can then grow until it runs into other crystals or the supply of chemical constituents is cut off.

All of these rates are strongly dependent on the temperature of the system. First, nucleation and growth cannot occur until temperatures are below the temperature at which equilibrium crystallization begins. Shown below are hypothetical nucleation and growth rate curves based on experiments in simple systems. Note that the rate of crystal growth and nucleation depends on how long the magma resides at a specified degree of undercooling ($\Delta T = T_m - T$), and thus the rate at which temperature is lowered below the the crystallization temperature. Three cases are shown.

1. For small degrees of undercooling (region A in the figure to the right) the nucleation rate will be low and the growth rate moderate. A few crystals will form and grow at a moderate rate until they run into each other. Because there are few nuclei, the crystals will be able to grow to relatively large size, and a coarse grained texture will result. This would be called a ***phaneritic texture***.



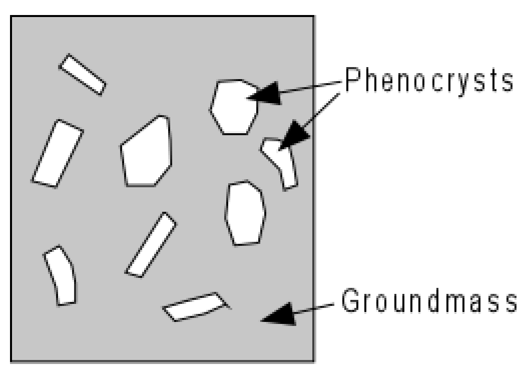




2. At larger degrees of undercooling, the nucleation rate will be high and the growth rate also high. This will result in many crystals all growing rapidly, but because there are so many crystals, they will run into each other before they have time to grow and the resulting texture will be a fine grained texture. If the size of the grains are so small that crystals cannot be distinguished with a handlens, the texture is said to be ***aphanitic***.

3. At high degrees of undercooling, both the growth rate and nucleation rate will be low. Thus few crystals will form and they will not grow to any large size. The resulting texture will be glassy, with a few tiny crystals called microlites. A completely glassy texture is called ***holohyaline texture***.

Two stages of cooling, i.e. slow cooling to grow a few large crystals, followed by rapid cooling to grow many smaller crystals could result in a ***porphyritic texture***, a texture with two or more distinct sizes of grains. Single stage cooling can also produce a porphyritic texture. In a porphyritic texture, the larger grains are called ***phenocrysts*** and the material surrounding the the phenocrysts is called ***groundmass*** or ***matrix***



In a rock with a phaneritic texture, where all grains are about the same size, we use the grain size ranges shown to the right to describe the texture:

<1 mm	fine grained
1 - 5 mm	medium grained
5 - 3 cm	coarse grained
> 3 cm	very coarse grained

In a rock with a porphyritic texture, we use the above table to define the grain size of the groundmass or matrix, and this table to describe the phenocrysts:

0.03 - 0.3 mm	microphenocrysts
0.3 - 5 mm	phenocrysts
> 5 mm	megaphenocrysts

Another aspect of texture, particularly in medium to coarse grained rocks is referred to as fabric. ***Fabric*** refers to the mutual relationship between the grains. Three types of fabric are commonly referred to:

1. If most of the grains are ***euhedral*** - that is they are bounded by well-formed crystal faces. The fabric is said to be ***idomorphic granular***.

2. If most of the grains are ***subhedral*** - that is they bounded by only a few well-formed crystal faces, the fabric is said to be ***hypidiomorphic granular***.

3. If most of the grains are ***anhedral*** - that is they are generally not bounded by crystal faces, the fabric is said to be ***allotriomorphic granular***.

If the grains have particularly descriptive shapes, then it is essential to describe the individual grains. Some common grain shapes are:

- *Tabular* - a term used to describe grains with rectangular tablet shapes.

- *Equant* - a term used to describe grains that have all of their boundaries of approximately equal length.

- *Fibrous* - a term used to describe grains that occur as long fibers.

- *Acicular* - a term used to describe grains that occur as long, slender crystals.

- *Prismatic* - a term used to describe grains that show an abundance of prism faces.

Other terms may apply to certain situations and should be noted if found in a rock.

- *Vesicular* - if the rock contains numerous holes that were once occupied by a gas phase, then this term is added to the textural description of the rock.

- *Glomeroporphyritic* - if phenocrysts are found to occur as clusters of crystals, then the rock should be described as glomeroporphyritic instead of porphyritic.

- *Amygdular* - if vesicles have been filled with material (usually calcite, chalcedonay, or quartz, then the term amygdular should be added to the textural description of the rock. An amygdule is defined as a refilled vesicle.

- *Pumiceous* - if vesicles are so abundant that they make up over 50% of the rock and the rock has a density less than 1 (i.e. it would float in water), then the rock is pumiceous.
- *Scoraceous*- if vesicles are so abundant that they make up over 50% of the rock and the rock has a density greater than 1, then the rock is said to be scoraceous.
- *Graphic* - a texture consisting of intergrowths of quartz and alkali feldspar wherein the orientation of the quartz grains resembles cuneiform writing. This texture is most commonly observed in pegmatites.
- *Spherulitic* - a texture commonly found in glassy rhyolites wherein spherical intergrowths of radiating quartz and feldspar replace glass as a result of devitrification.
- *Obicular* - a texture usually restricted to coarser grained rocks that consists of concentrically banded spheres wherein the bands consist of alternating light colored and dark colored minerals.

Other textures that may be evident on microscopic examination of igneous rocks are as follows:

- *Myrmekitic texture* - an intergrowth of quartz and plagioclase that shows small wormlike bodies of quartz enclosed in plagioclase. This texture is found in granites.
- *Ophitic texture* - laths of plagioclase in a coarse grained matrix of pyroxene crystals, wherein the plagioclase is totally surrounded by pyroxene grains. This texture is common in diabases and gabbros.
- *Subophitic texture* - similar to ophitic texture wherein the plagioclase grains are not completely enclosed in a matrix of pyroxene grains.
- *Poikilitic texture* - smaller grains of one mineral are completely enclosed in large, optically continuous grains of another mineral.
- *Intergranular texture* - a texture in which the angular interstices between plagioclase grains are occupied by grains of ferromagnesium minerals such as olivine, pyroxene, or iron titanium oxides.
- *Intersertal texture* - a texture similar to intergranular texture except that the interstices between plagioclase grains are occupied by glass or cryptocrystalline material.
- *Hyaloophitic texture* - a texture similar to ophitic texture except that glass completely surrounds the plagioclase laths.
- *Hyalopilitic texture* - a texture wherein microlites of plagioclase are more abundant than groundmass, and the groundmass consists of glass which occupies the tiny interstices between plagioclase grains.
- *Trachytic texture* - a texture wherein plagioclase grains show a preferred orientation due to flowage, and the interstices between plagioclase grains are occupied by glass or cryptocrystalline material.

- *Coronas or reaction rims* - often times reaction rims or coronas surround individual crystals as a result of the crystal becoming unstable and reacting with its surrounding crystals or melt. If such rims are present on crystals they should be noted in the textural description.

- *Patchy zoning* - This sometimes occurs in plagioclase crystals where irregularly shaped patches of the crystal show different compositions as evidenced by going extinct at angles different from other zones in the crystal.

- *Oscillatory zoning* - This sometimes occurs in plagioclase grains wherein concentric zones around the grain show thin zones of different composition as evidenced by extinction phenomena.

- *Moth eaten texture* (also called *sieve texture*)- This sometimes occurs in plagioclase wherein individual plagioclase grains show an abundance of glassy inclusions.

- *Perthitic texture* - Exsolution lamellae of albite occurring in orthoclase or microcline.

Examples of questions on this material that could be on an exam

1. Define the following terms (a) porphyritic texture, (b) viscosity (c) magma, (d) perthitic texture, (e) volcanic dome, (f) crystal nucleation rate, (g) crystal growth rate

2. What properties of magma favor an explosive volcanic eruption?

3. Explain the role of temperature, viscosity, and gas content of the magma in producing each of the following features (a) lava flow, (b) volcanic dome, (c) pyroclastic material, (d) shield volcano, (e) stratovolcano.

4. Be able to explain and illustrate each of the following landforms or bodies (a) dike, (b) sill, (c) laccolith, (d) cinder cone, (e) caldera, (f) batholith (g) stock

5. Describe and explain the origin of each of the following textures (a) phaneritic texture, (b) aphanitic texture, (c) pophytritic texture, (d) Poikilitic te xture, (e) vesicular texture

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