| EENS 3050 | Natural Disasters |
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# Volcanoes, Magma, and Volcanic Eruptions

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Since volcanic eruptions are caused by ***magma*** (a mixture of liquid rock, crystals, and dissolved gas) expelled onto the Earth's surface, we must first discuss the characteristics of magma and how magmas form in the Earth.

## Characteristics of Magma

### Types of Magma

Types of magma are determined by chemical composition of the magma. Three general types are recognized:

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 of the Earth. 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) & 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 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$^o$C
- Andesitic magma - 800 to 1000$^o$C
- Rhyolitic magma - 650 to 800$^o$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 very high, measured as trillions times 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 $^oC$ | Low | Low |
| Andesitic | Andesite | 55-65 $SiO_2$ %, intermediate in Fe, Mg, Ca, Na, K | 800 - 1000 $^oC$ | Intermediate | Intermediate |
| Rhyolitic | Rhyolite | 65-75 $SiO_2$ %, low in Fe, Mg, Ca, high in K, Na. | 650 - 800 $^oC$ | High | High |

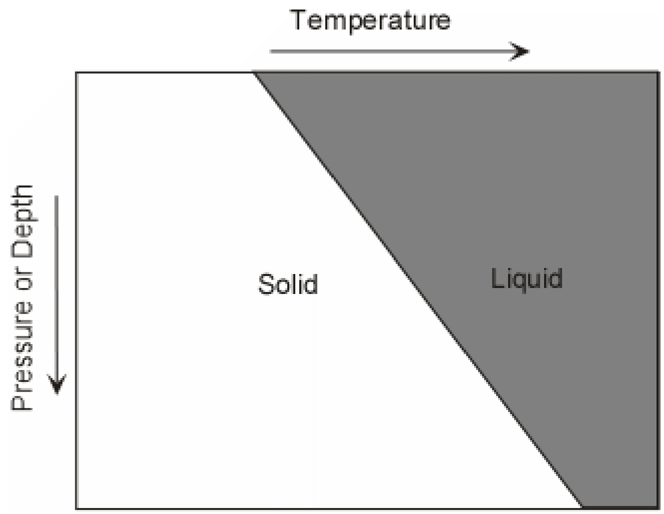
## How Magmas Form in the Earth

As we have seen the only part of the earth that is liquid is the outer core. But the core is not likely to be the source of magmas because it does not have the right chemical composition. The outer core is mostly Iron, but magmas are silicate liquids. Thus, magmas **DO NOT COME FROM THE MOLTEN OUTER CORE OF THE EARTH**. Since the rest of the earth is solid, in order for magmas to form, some part of the earth must get hot enough to melt the rocks present.

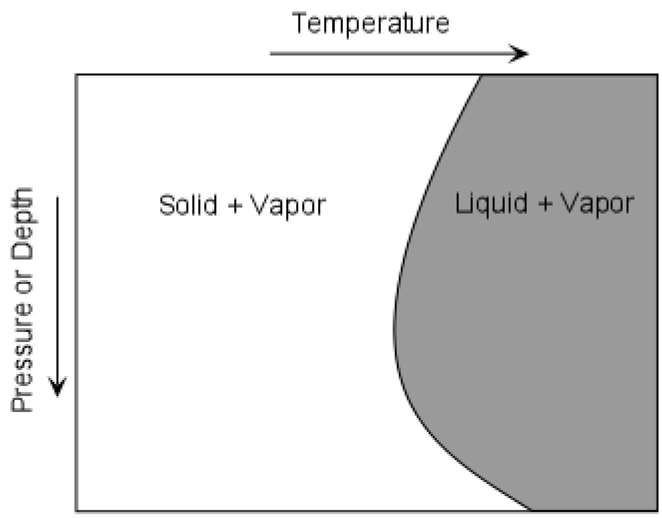
We know that temperature increases with depth in the earth along the geothermal gradient. The earth is hot inside due to heat left over from the original accretion process, due to heat released by sinking of materials to form the core, and due to heat released by the decay of radioactive elements in the earth. Under normal conditions, the geothermal gradient is not high enough to melt rocks, and thus with the exception of the outer core, most of the Earth is solid. Thus, magmas form only under special circumstances, and thus, volcanoes are only found on the Earth's surface in areas above where these special circumstances occur. (Volcanoes don't just occur anywhere, as we shall soon see). To understand this we must first look at how rocks and mineral melt. To understand this we must first look at how minerals and rocks melt.

As pressure increases in the Earth, the melting temperature changes as well. For pure minerals, there are two general cases.

1. If the mineral contains no water ($H_2O$) or carbon dioxide ($CO_2$) and there is no water or carbon dioxide present in the surroundings, then melting occurs at a single temperature at any given pressure and increases with increasing pressure or depth in the Earth. This is called ***dry melting***.

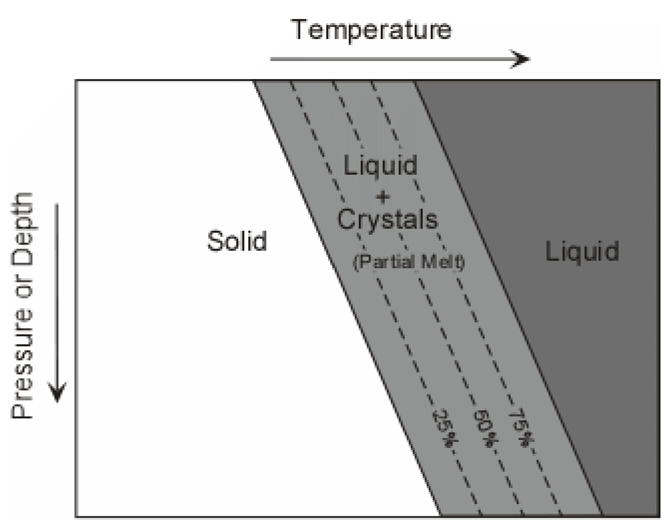



2. If water or carbon dioxide are present within or surrounding the mineral, then melting takes place at a single temperature at any given pressure, but first decreases with increasing pressure

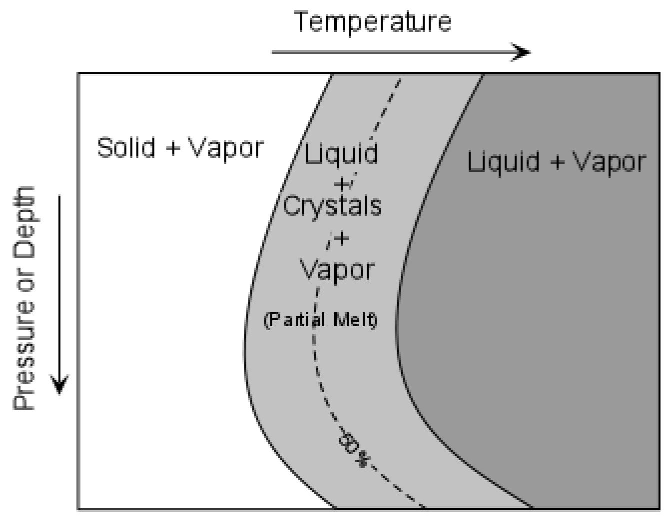



Since rocks are mixtures of minerals, they behave somewhat differently. Unlike minerals, rocks do not melt at a single temperature, but instead melt over a range of temperatures. Thus, it is possible to have partial melts, from which the liquid portion might be extracted to form magma. The two general cases are:

1. Melting of dry rocks is similar to melting of dry minerals, melting temperatures increase with increasing pressure, except there is a range of temperature over which there exists a partial melt. The degree of partial melting can range from 0 to 100%.



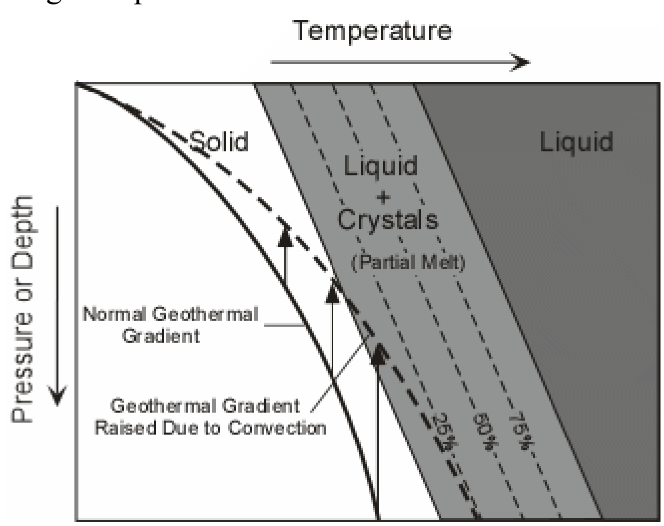
2. Melting of wet rocks is similar to melting of wet minerals, except there is range of temperature range over which partial melting occurs. Again, the temperature of beginning of melting first decreases with increasing pressure or depth, then at high pressure or depth the melting temperatures again begin to rise.




**Three ways to Generate Magmas**
From the above we can conclude that in order to generate a magma in the solid part of the earth either the geothermal gradient must be raised in some way or the melting temperature of the rocks must be lowered in some way.
The geothermal gradient can be raised by upwelling of hot material from below either by uprise solid material (decompression melting) or by intrusion of magma (heat transfer). Lowering the melting temperature can be achieved by adding water or Carbon Dioxide (flux melting).

The Mantle is made of garnet peridotite (a rock made up of olivine, pyroxene, and garnet) -- evidence comes from pieces brought up by erupting volcanoes. In the laboratory we can determine the melting behavior of garnet peridotite.

**Decompression Melting** - Under normal conditions the temperature in the Earth, shown by the geothermal gradient, is lower than the beginning of melting of the mantle. Thus in order for the mantle to melt there has to be a mechanism to raise the geothermal gradient. Once such mechanism is convection, wherein hot mantle material rises to lower pressure or depth, carrying its heat with it.

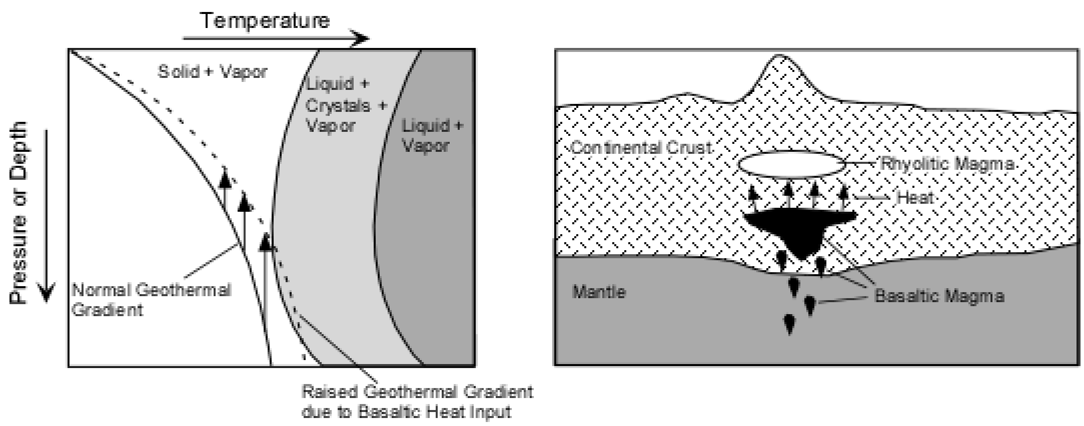



If the raised geothermal gradient becomes higher than the initial melting temperature at any pressure, then a partial melt will form. Liquid from this partial melt can be separated from the remaining crystals because, in general, liquids have a lower density than solids. Basaltic magmas appear to originate in this way.

Upwelling mantle appears to occur beneath oceanic ridges, at hot spots, and beneath continental rift valleys. Thus, generation of magma in these three environments is likely caused by decompression melting.

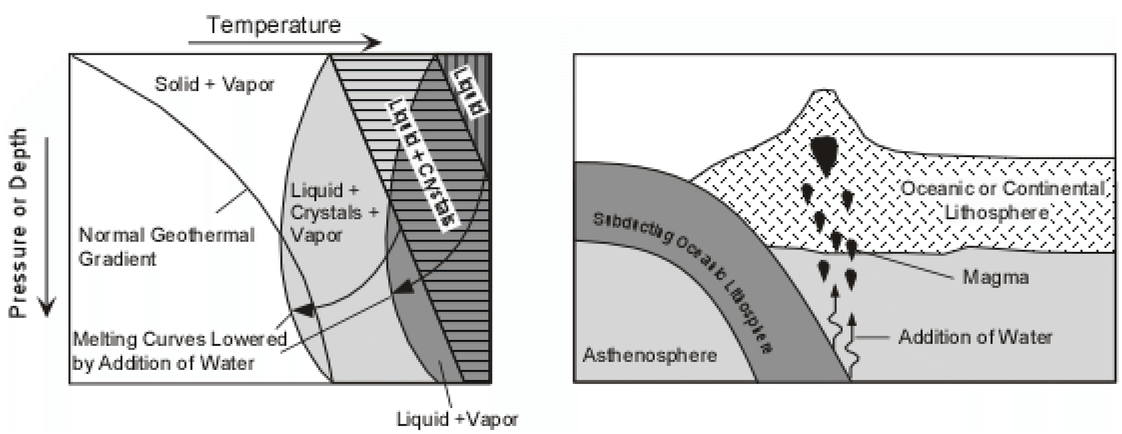
**Transfer of Heat**- When magmas that were generated by some other mechanism intrude into cold crust, they bring with them heat. Upon solidification they lose this heat and transfer it to the surrounding crust. Repeated intrusions can transfer enough heat to increase the local geothermal gradient and cause melting of the surrounding rock to generate new magmas.

Rhyolitic magma can also be produced by changing the chemical composition of basaltic magma as discussed later.




Transfer of heat by this mechanism may be responsible for generating some magmas in continental rift valleys, hot spots, and subduction related environments.

**Flux Melting -** As we saw above, if water or carbon dioxide are added to rock, the melting temperature is lowered. If the addition of water or carbon dioxide takes place deep in the earth where the temperature is already high, the lowering of melting temperature could cause the rock to partially melt to generate magma. One place where water could be introduced is at subduction zones. Here, water present in the pore spaces of the subducting sea floor or water present in minerals like hornblende, biotite, or clay minerals would be released by the rising temperature and then move in to the overlying mantle. Introduction of this water in the mantle would then lower the melting temperature of the mantle to generate partial melts, which could then separate from the solid mantle and rise toward the surface.




## Chemical Composition of Magmas

The chemical composition of magma can vary depending on the rock that initially melts (the source rock), and process that occur during partial melting and transport.

### Initial Composition of Magma

The initial composition of the magma is dictated by the composition of the source rock and the degree of partial melting. In general, melting of a mantle source (garnet peridotite) results in mafic/basaltic magmas. Melting of crustal sources yields more siliceous magmas.

In general more siliceous magmas form by low degrees of partial melting. As the degree of partial melting increases, less siliceous compositions can be generated. So, melting a mafic source thus yields a felsic or intermediate magma. Melting of ultramafic (peridotite source) yields a basaltic magma.

### Magmatic Differentiation

But, processes that operate during transportation toward the surface or during storage in the crust can alter the chemical composition of the magma. These processes are referred to as magmatic differentiation and include assimilation, mixing, and fractional crystallization.

- **Assimilation** - As magma passes through cooler rock on its way to the surface it may partially melt the surrounding rock and incorporate this melt into the magma. Because small amounts of partial melting result in siliceous liquid compositions, addition of this melt to the magma will make it more siliceous.

- **Mixing** - If two magmas with different compositions happen to come in contact with one another, they could mix together. The mixed magma will have a composition somewhere between that of the original two magma compositions. Evidence for mixing is often preserved in the resulting rocks.

- **Crystal Fractionation** - When magma solidifies to form a rock it does so over a range of temperature. Each mineral begins to crystallize at a different temperature, and if these minerals are somehow removed from the liquid, the liquid composition will change. Depending on how many minerals are lost in this fashion, a wide range of compositions can be made. The processes is called magmatic differentiation by crystal fractionation.

  Crystals can be removed by a variety of processes. If the crystals are more dense than the liquid, they may sink. If they are less dense than the liquid they will float. If liquid is squeezed out by pressure, then crystals will be left behind. Removal of crystals can thus change the composition of the liquid portion of the magma. Let me illustrate this using a very simple case.

  Imagine a liquid containing 5 molecules of MgO and 5 molecules of $SiO_2$. Initially the composition of this magma is expressed as 50% $SiO_2$ and 50% MgO

  .

| | | |
|---|---|---|
| ● ● ● ● ● | 5 MgO | %MgO = 5/10*100 = 50% |
| ○ ○ ○ ○ ○ | +5 $SiO_2$ | %$SiO_2$ = 5/10*100 = 50% |
| | 10 Total | |

Now let's imagine I remove 1 MgO molecule by putting it into a crystal and removing the crystal from the magma. Now what are the percentages of each molecule in the liquid?

| | | | |
|---|---|---|---|
| ● ● ● ● | 4 | MgO | %MgO = 4/9*100 = 44.44% |
| ○ ○ ○ ○ ○ | +5 | $SiO_2$ | %$SiO_2$ = 5/9*100 = 55.56% |
| | 9 | Total | |

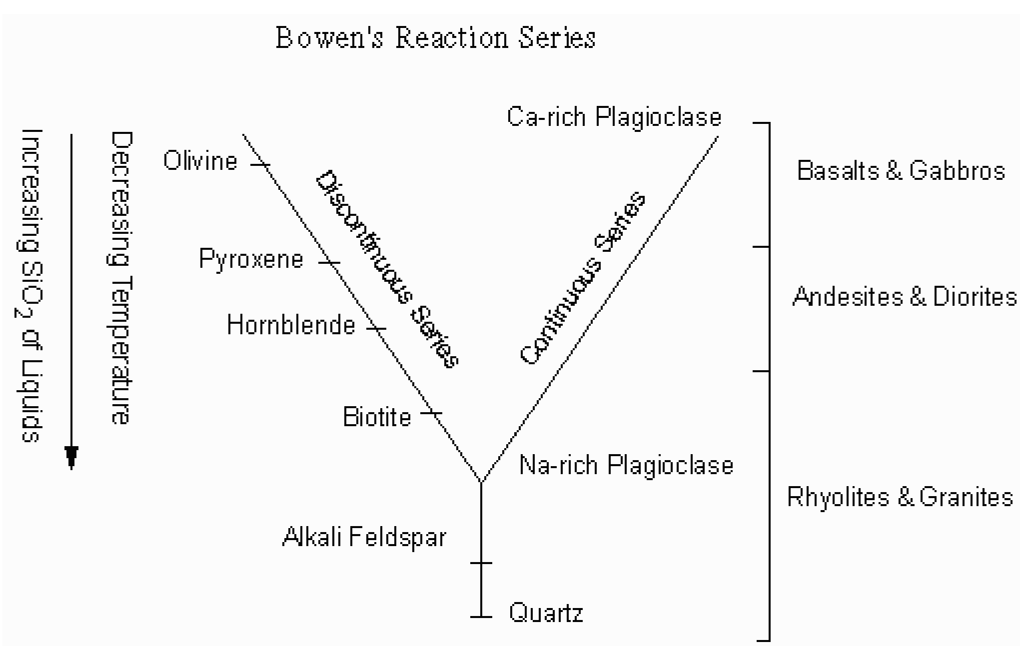
If we continue the process one more time by removing one more MgO molecule.

| | | | |
|---|---|---|---|
| ● ● ● | 3 | MgO | %MgO = 3/8*100 = 37.50% |
| ○ ○ ○ ○ ○ | +5 | $SiO_2$ | %$SiO_2$ = 5/9*100 = 62.50% |
| | 8 | Total | |

Thus, composition of liquid can be changed. This process is called **crystal fractionation**. A mechanism by which a basaltic magma beneath a volcano could change to andesitic magma and eventually to rhyolitic magma through crystal fractionation, is provided by Bowen's reaction series, discussed next.

**Bowen's Reaction Series**

Bowen found by experiment that the order in which minerals crystallize from a basaltic magma depends on temperature. As a basaltic magma is cooled Olivine and Ca-rich plagioclase crystallize first. Upon further cooling, Olivine reacts with the liquid to produce pyroxene and Ca-rich plagioclase react with the liquid to produce less Ca-rich plagioclase. But, if the olivine and Ca-rich plagioclase are removed from the liquid by crystal fractionation, then the remaining liquid will be more $SiO_2$ rich. If the process continues, an original basaltic magma can change to first an andesite magma then a rhyolite magma with falling temperature.



## 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 Earth's 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 when it 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 very easily, and thus, pressure will build up inside of the gas bubble(s). When this 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.

## Effusive (Non-explosive) Eruptions

Non explosive eruptions are favored by low gas content and low viscosity magmas (basaltic to andesitic magmas). If the viscosity is low, non-explosive eruptions usually begin with fire fountains due to release of dissolved gases.

When magma reaches the surface of the earth, it is called lava. Since it its a liquid, it flows downhill in response to gravity as a lava flows. Different magma types behave differently as lava flows, depending on their temperature, viscosity, and gas content.

### Lava Flows

***Pahoehoe Flows*** - Basaltic lava flows with low viscosity start to cool when exposed to the low temperature of the atmosphere. This causes a surface skin to form, although it is still very hot and behaves in a plastic fashion, capable of deformation. Such lava flows that initially have a smooth surface are called pahoehoe flows. Initially the surface skin is smooth, but often inflates with molten lava and expands to form pahoehoe toes or rolls to form ropey pahoehoe. (See figure 6.17 in your text). Pahoehoe flows tend to be thin and, because of their low viscosity travel long distances from the vent.

***A'A' Flows*** - Higher viscosity basaltic and andesitic lavas also initially develop a smooth surface skin, but this is quickly broken up by flow of the molten lava within and by gases that continue to escape from the lava. This creates a rough, clinkery surface that is characteristic of an A'A' flow (see figure 6.18 in your text).

***Pillow Lavas*** - When lava erupts on the sea floor or other body of water, the surface skin forms rapidly, and, like with pahoehoe toes inflates with molten lava. Eventually these inflated balloons of magma drop off and stack up like a pile of pillows and are called pillow lavas.

Ancient pillow lavas are readily recognizable because of their shape, their glassy margins and radial fractures that formed during cooling.

***Siliceous Lava Flow***s - High viscosity andesitic and rhyolitic lava flows, because they can't flow very easily, form thick stubby flows that don't move far from the vent.

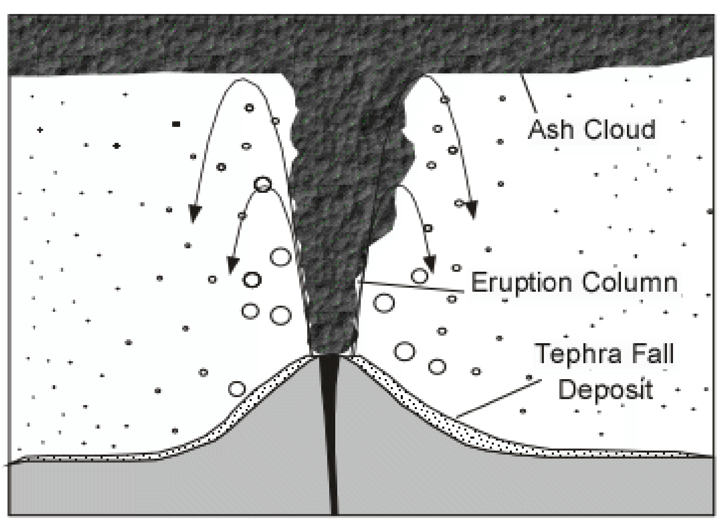
***Lava Domes*** or ***Volcanic Domes*** - result from the extrusion of highly viscous, gas poor andesitic and rhyolitic lava. Since the viscosity is so high, the lava does not flow away from the vent, but instead piles up over the vent. Blocks of nearly solid lava break off the outer surface of the dome and roll down 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.

**Explosive Eruptions**

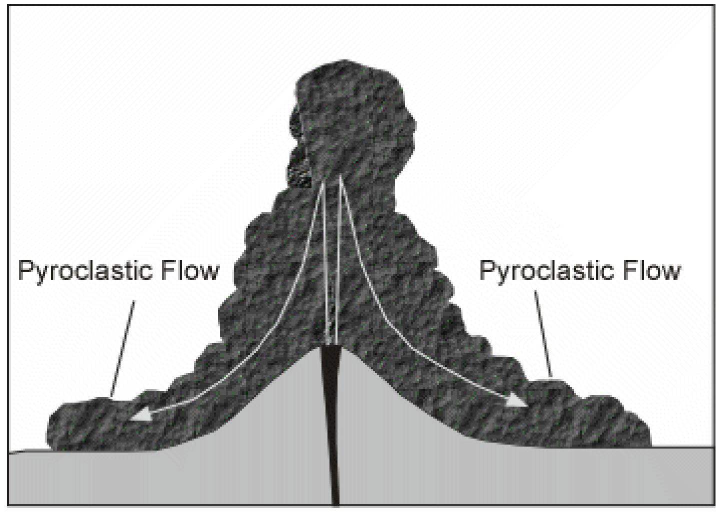
Explosive eruptions are favored by high gas content and high viscosity (andesitic to rhyolitic magmas). Explosive bursting of bubbles will fragment the magma into clots of liquid that will cool as they fall through the air. These solid particles become ***pyroclasts*** (meaning - hot fragments) and ***tephra*** 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 |

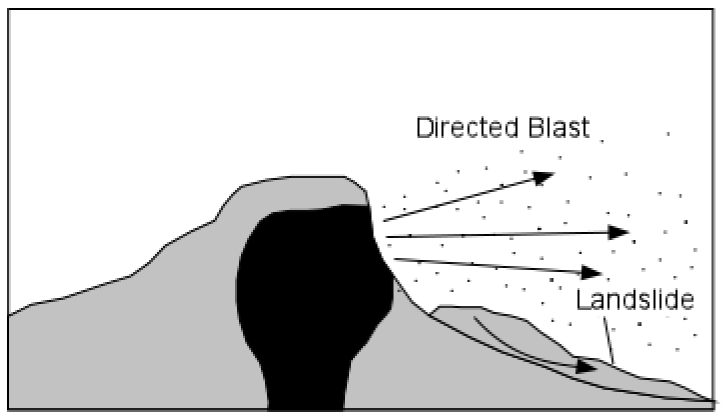
- ***Blocks*** are angular fragments that were solid when ejected.
- ***Bombs*** have an aerodynamic shape indicating they were liquid when ejected.
- Bombs and lapilli that consist mostly of gas bubbles (***vesicles***) result in a low density highly vesicular rock fragment called ***pumice***.
- Clouds 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.




- If the gas pressure inside the magma is directed outward instead of upward, a ***lateral blast*** can occur. When this occurs on the flanks of a lava dome, a pyroclastic flows called a ***glowing avalanche*** or ***nuée ardentes*** (in French) can also result. Directed blasts often result from sudden exposure of the magma by a landslide or collapse of a lava dome.

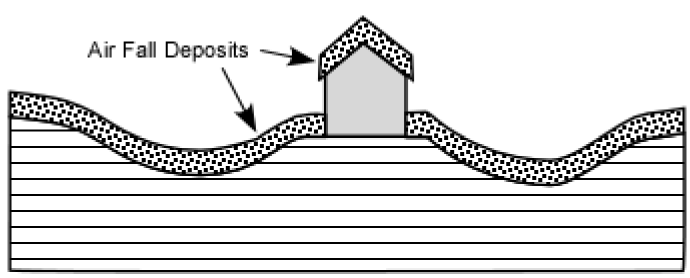



**Pyroclastic Deposits**

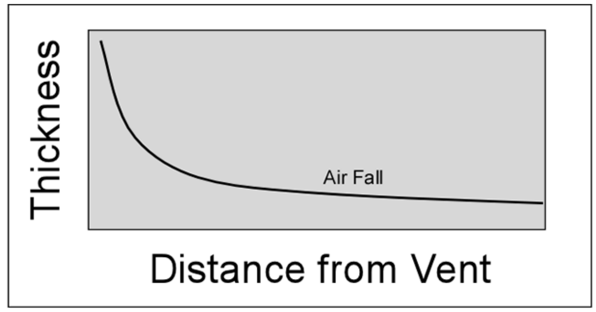
Pyroclastic material ejected explosively from volcanoes becomes deposited on the land surface. The process of deposition leaves clues that allow geologists to interpret the mode of ejection from the volcano.

***Fall Deposits***

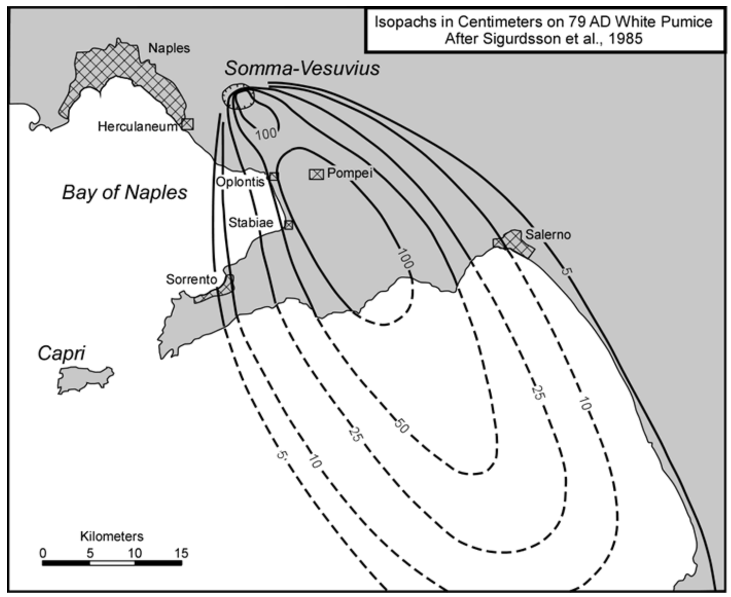
- Material ejected into an eruption column eventually falls back to the earth's surface and blankets the surface similar to the way snow blankets the earth.



- The thickest deposits occur close to vent and get thinner with distance from the vent.




- By measuring the thickness at numerous locations one can construct an isopach map. Such isopach maps help to locate the source volcanic vent (if it is not otherwise known) and provides information about wind direction in the upper levels of the atmosphere during the eruption.



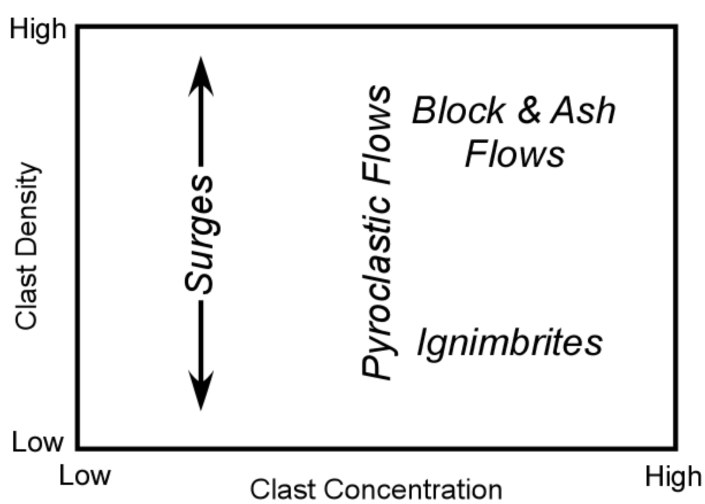

- Fall deposits are usually fairly well-sorted, meaning that the clast size does not vary too much within the individual deposit. The clast size can be ash as in a cinder cone

- or can be clasts of pumice that range in size from blocks close to the vent to lapilli at greater distances from the vent to fine ash at great distances from the vent.  They may also contain clasts of rock fragments (called lithic fragments) that are pieces of the volcanic structure ripped from the sides of the conduit during the explosive eruption.

***Pyroclastic Flows***

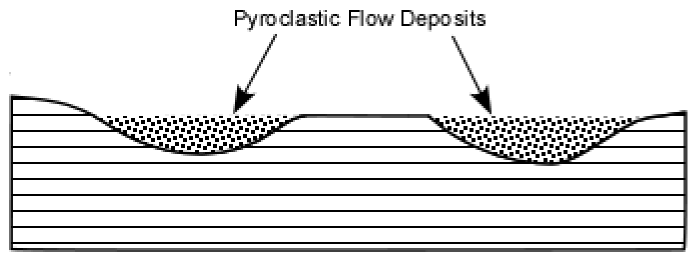
Pyroclastic flows are also sometimes called pyroclastic density currents (PDCs).   They can range from surges which can have a range of clast densities from low to high with generally low concentration of  of solid clasts (high amonts of gases) to high clast concentration clouds of ash and gas (pyroclastic flows).

If the pyroclastic flows consist of solid clasts with high density along with ash fragments, they are called block and ash flows.   If the pyroclastic flows have low density clasts (pumice) along with ash, they are called ignimbrites.   There are no definitive boundary between pyroclastic flows and surges as they grade into one another continuously.  Similarly, ignimbrites grade into block and ash flows as the clast density increases.



Pyroclastic Flow Deposits

Pyroclastic flows tend to follow valleys or low lying areas of topography. The material deposited, thus tends to fill valleys, rather than uniformly blanket the topography like fall deposits.




- Block and Ash Flow Deposits

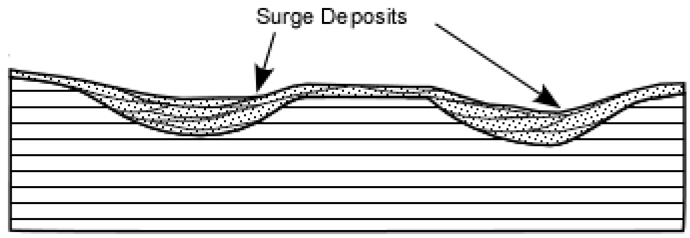
  As defined above, block and ash flows consist of an unsorted mixture of blocks and ash with the blocks being mostly rock fragments.

- Ignimbrites

  Ignimbrites contain blocks of pumice in an unsorted mixture of ash, lapilli, pumice blocks, and lithic fragments. Sometimes one finds concentrated zones of pumice or lithic fragments in the deposits.

Surge Deposits

Surges tend to hug the ground as they flow over the surface and thus tend to produce thicker deposits in valleys with thinner deposits over ridges. This helps to distinguish surge deposits from flow deposits and fall deposits.




Because they move close to ground, friction with ground tends to produce cross stratification in the deposits. Individual layers can be well-sorted, but overall the deposits tend to be poorly sorted.

**Types of Volcanic Eruptions**

Volcanic eruptions, especially explosive ones, are very dynamic phenomena. That is the behavior of the eruption is continually changing throughout the course of the eruption. This makes it very difficult to classify volcanic eruptions. Nevertheless they can be classified according to the principal types of behavior that they exhibit. An important point to remember, however, is that during a given eruption the type of eruption may change between several different types.

- ***Hawaiian*** - These are eruptions of low viscosity basaltic magma. Gas discharge produces a fire fountain that shoots incandescent lava up to 1 km above the vent. The lava, still molten when it returns to the surface flows away down slope as a lava flow. Hawaiian Eruptions are considered non-explosive eruptions. Very little pyroclastic material is produced.

- ***Strombolian*** - These eruptions are characterized by distinct blasts of basaltic to andesitic magma from the vent. These blasts produce incandescent bombs that fall near the vent, eventually building a small cone of tephra (cinder cone). Sometimes lava flows erupt from vents low on the flanks of the small cones. Strombolian eruptions are considered mildly explosive, and produce low elevation eruption columns and pyroclastic fall deposits.

- ***Vulcanian*** - These eruptions are characterized by sustained explosions of solidified or highly viscous andesite or rhyolite magma from a the vent. Eruption columns can reach several km above the vent, and often collapse to produce pyroclastic flows. Widespread pyroclastic falls are common that contain mostly angular blocks. Vulcanian eruptions are considered very explosive.

- ***Pelean*** - These eruptions result from the collapse of an andesitic or rhyolitic lava dome, with or without a directed blast, to produce glowing avalanches or nuée ardentes, as a type of pyroclastic flow known as a ***block-and-ash flow.*** They may also produce surges with resulting surge deposits. Pelean eruptions are considered violently explosive.

- ***Plinian*** - These eruptions result from a sustained ejection of andesitic to rhyolitic magma into eruption columns that may extend up to 45 km above the vent. Eruption columns produce wide-spread fall deposits with thickness decreasing away from the vent, and may exhibit eruption column collapse to produce pyroclastic flows and surges. Plinian ash clouds can circle the Earth in a matter of days. Plinian eruptions are considered violently explosive.

- ***Phreatomagmatic*** - These eruptions are produced when magma comes in contact with shallow groundwater causing the groundwater to flash to steam and be ejected along with pre-existing fragments of the rock and tephra from the magma. Because the water expands so rapidly, these eruptions are violently explosive although the distribution of pyroclasts around the vent is much less than in a Plinian eruption. Surge deposits are usually produced.

- ***Phreatic*** (also called ***steam blast*** eruptions) - result when magma encounters shallow groundwater, flashing the groundwater to steam, which is explosively ejected along with pre-exiting fragments of rock. No new magma reaches the surface. Surge deposits may result from these eruptions.

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**Questions on this material that could be asked on an exam**

1. What are the three major types of magma and how are they distinguished from one another in terms of their chemical compositions and physical properties? (Note that you should be able to answer this question in relative terms - you would not be expected to cite exact numbers).

2. How do each of the three types of magma originate in terms of melting mechanism and part of the earth where they form?

3. What are the major gases in magma? What are the minor gases in magma? Why is the amount of gas in magma important in relation to volcanic eruptions?

4. What chemical and physical characteristics of magma are most important in whether the magma erupts explosively or non-exzplosively?

5. Define the following terms (a) viscosity, (b) block, (c) bomb, (d) ash, (e) eruption column, (f) pyroclastic flow, (g) lateral blast.

6. How would one distinguish ash fall deposits from pyroclastic flow and surge deposits?
7. How would one distinguish pyroclastic flow deposits from suge deposits?
8. Compare and contrast the different types of volcanic eruptions.

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