EENS 1110	Physical Geology
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Magmas and Igneous Rocks

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Magma and Igneous Rocks

Igneous Rocks are formed by crystallization from a liquid, or magma. They include two types

- ***Volcanic*** or ***extrusive*** igneous rocks form when the magma cools and crystallizes on the surface of the Earth

- ***Intrusive*** or ***plutonic*** igneous rocks wherein the magma crystallizes at depth in the Earth.

Magma is a mixture of liquid rock, crystals, and gas. Characterized by a wide range of chemical compositions, with high temperature, and properties of a liquid.

Magmas are less dense than surrounding rocks, and will therefore move upward. If magma makes it to the surface it will erupt and later crystallize to form an ***extrusive*** or ***volcanic rock***. If it crystallizes before it reaches the surface it will form an igneous rock at depth called a ***plutonic*** or ***intrusive igneous rock***.

Types of Magma

Chemical composition of magma is controlled by the abundance of elements in the Earth. Si, Al, Fe, Ca, Mg, K, Na, H, and O make up 99.9%. Since oxygen is so abundant, chemical analyses are usually given in terms of oxides. SiO_2 is the most abundant oxide.

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

Gases - At depth in the Earth nearly all magmas contain gas. Gas gives magmas their explosive character, because the gas expands as pressure is reduced.

- Mostly H_2O with some CO_2
- Minor amounts of Sulfur, Cl , and F
- Felsic magmas usually have higher gas contents than mafic magmas.

Temperature of Magmas

- Mafic/Basaltic - 1000-1200^{o}C
- Intermediate/Andesitic - 800-1000^{o}C
- Felsic/Rhyolitic - 650-800^{o}C.

Viscosity of Magmas

Viscosity is the resistance to flow (opposite of fluidity). Depends on composition, temperature, & gas content.

- Higher SiO_2 content magmas have higher viscosity than lower SiO_2 content magmas
- Lower Temperature magmas have higher viscosity than higher temperature magmas.

Summary Table

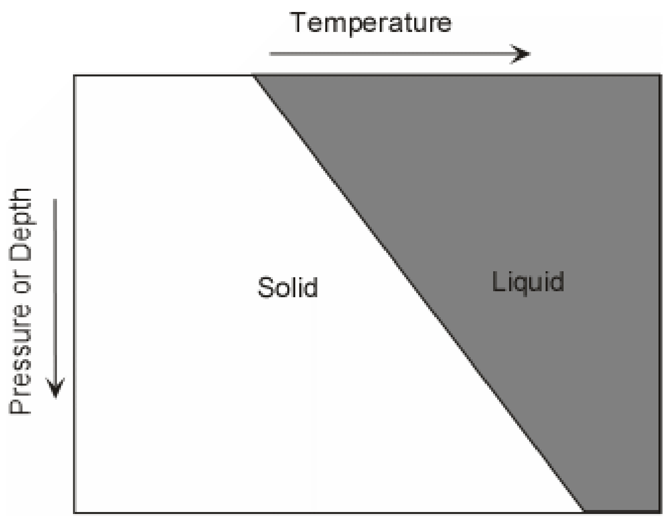
Magma Type	Solidified Volcanic Rock	Solidified Plutonic Rock	Chemical Composition	Temperature	Viscosity	Gas Content
Mafic or Basaltic	Basalt	Gabbro	45-55 SiO_2 %, high in Fe, Mg, Ca, low in K, Na	1000 - 1200 ^oC	Low	Low
Intermediate or Andesitic	Andesite	Diorite	55-65 SiO_2 %, intermediate in Fe, Mg, Ca, Na, K	800 - 1000 ^oC	Intermediate	Intermediate
Felsic or Rhyolitic	Rhyolite	Granite	65-75 SiO_2 %, low in Fe, Mg, Ca, high in K, Na	650 - 800 ^oC	High	High

Origin of Magma

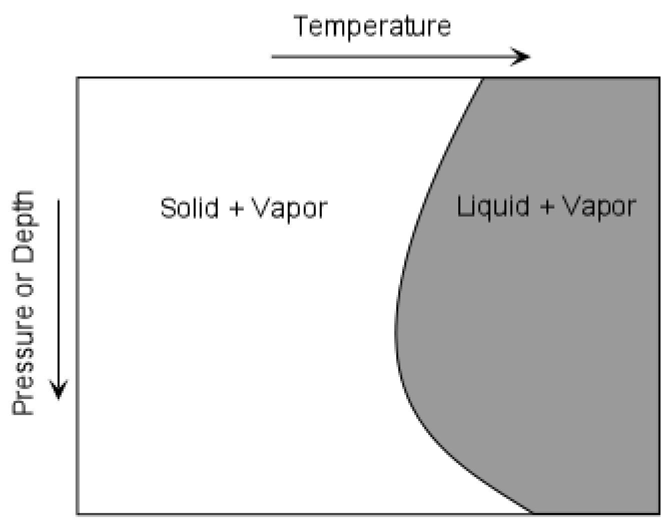
As we have seen the only part of the earth that is liquid is the outer core. But the core is not likely to be the source of magmas because it does not have the right chemical composition. The outer core is mostly Iron, but magmas are silicate liquids. Thus magmas **DO NOT COME FROM THE MOLTEN OUTER CORE OF THE EARTH**. Thus, 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. To understand this we must first look at how rocks and mineral melt.

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

- For a pure dry (no H_2O or CO_2 present) mineral, the melting temperate increases with increasing pressure.

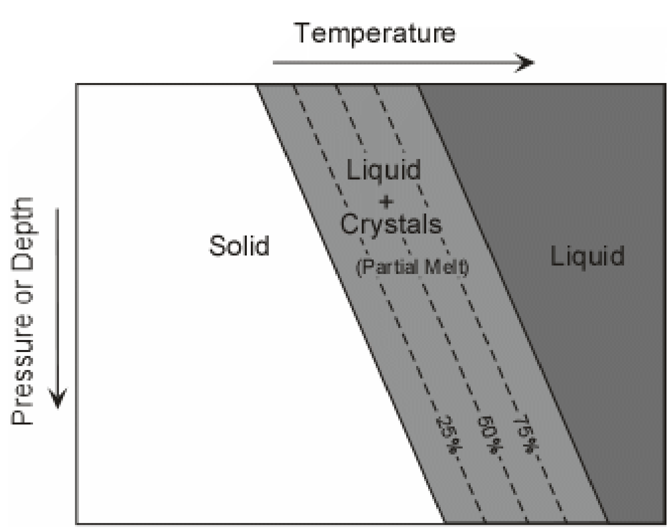


- For a mineral with H_2O or CO_2 present, the melting temperature first decreases with increasing pressure

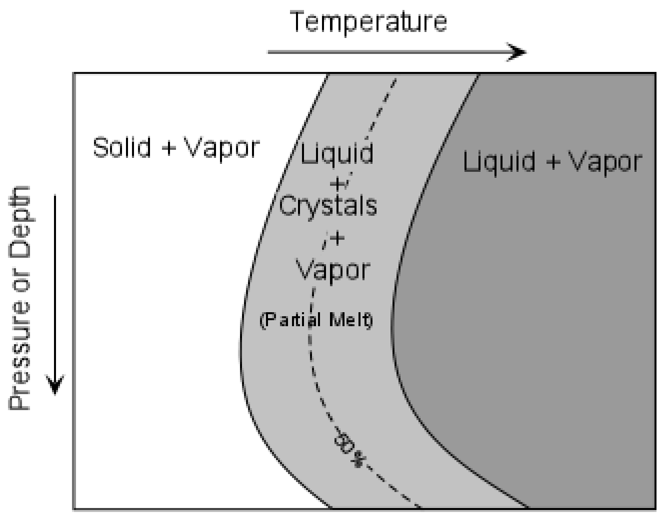


Since rocks mixtures of minerals, they behave somewhat differently. Unlike minerals, rocks do not melt at a single temperature, but instead melt over a range of temperatures. Thus, it is possible to have partial melts from which the liquid portion might be extracted to form magma. The two general cases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

- 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%



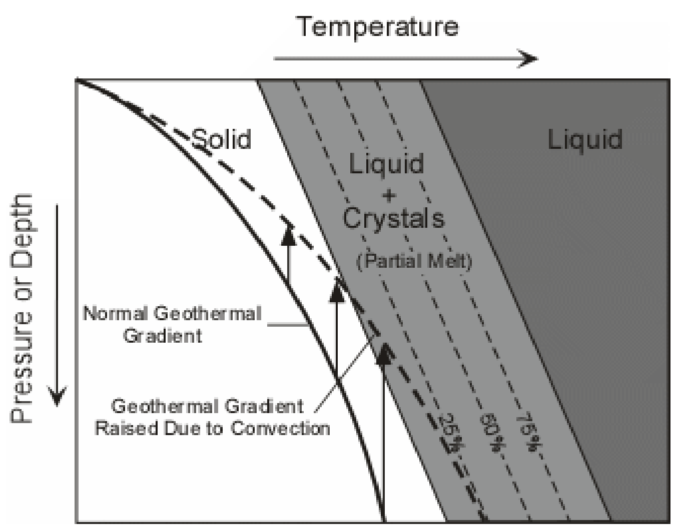
- Melting of rocks containing water or carbon dioxide is similar to melting of wet minerals, melting temperatures initially decrease with increasing pressure, except there is a range of temperature over which there exists a partial melt.



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).

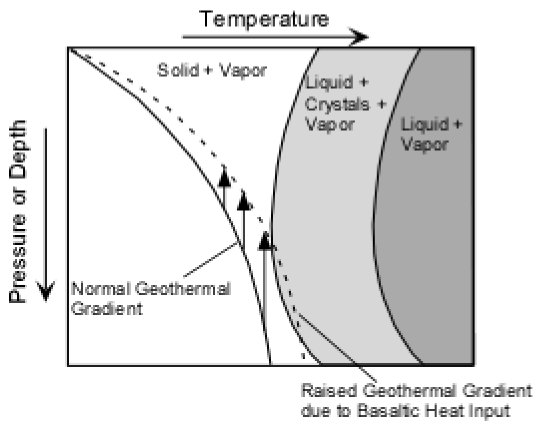
Decompression Melting - Under normal conditions the temperature in the Earth, shown by the geothermal gradient, is lower than the beginning of melting of the mantle. Thus in order for the mantle to melt there has to be a mechanism to raise the geothermal gradient. Once such mechanism is convection, wherein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

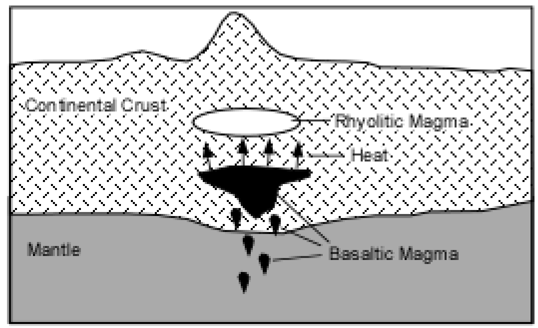


If the raised geothermal gradient becomes higher than the initial melting temperature at any pressure, then a partial melt will form. Liquid from this partial melt can be separated from the remaining crystals because, in general, liquids have a lower density than solids. Basaltic magmas appear to originate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

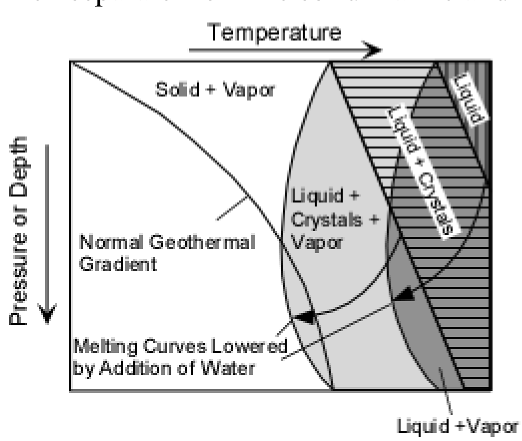
Transfer of Heat- When magmas that were generated by some other mechanism intrude into cold crust, they bring with them heat. Upon solidification they lose this heat and transfer it to the surrounding crust. Repeated intrusions can transfer enough heat to increase the local geothermal gradient and cause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

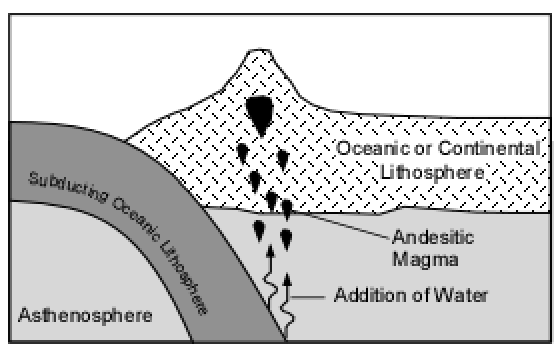




Transfer of heat by this mechanism may be responsible for generating some magmas in continental rift valleys, hot spots, and subduction related environments.

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 Variability 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.
>
> **Fractional Crystallization** - When magma crystallizes 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. The processes is called magmatic differentiation by Fractional Crystallization.
> Because mafic minerals like olivine and pyroxene crystallize first, the process results in removing Mg, Fe, and Ca, and enriching the liquid in silica. Thus crystal fractionation can change a mafic magma into a felsic magma.
>
> 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. i.e.

● ● ● ● ●	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	

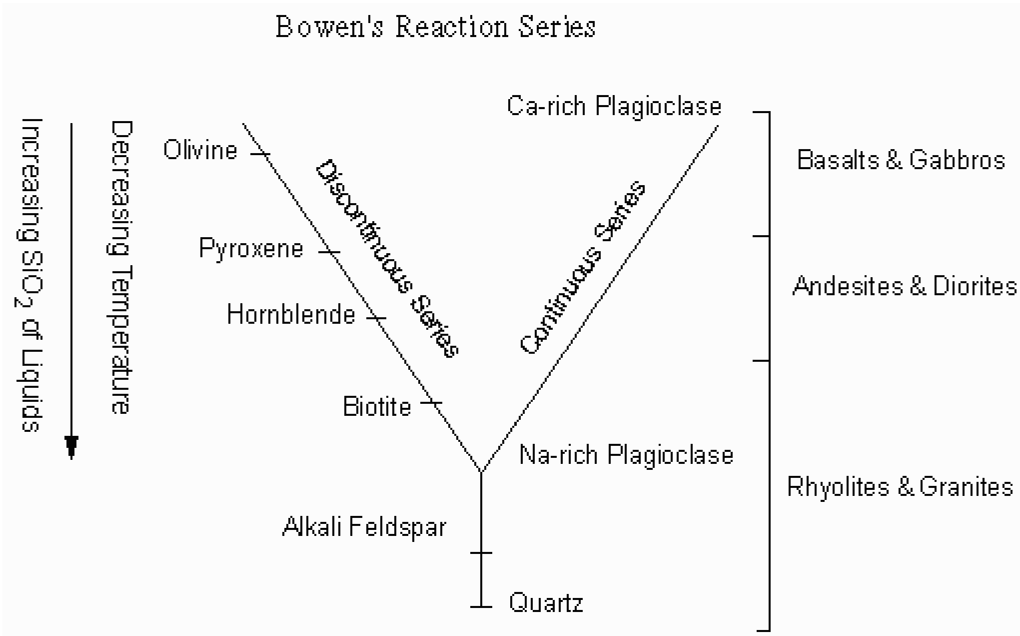
If we continue the process one more time by removing one more MgO molecule

● ● ●	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.

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



Igneous Environments and Igneous Rocks

The environment in which magma completely solidifies to form a rock determines:

1. The type of rock
2. The appearance of the rock as seen in its texture
3. The type of rock body.

In general there are two environments to consider:

The intrusive or plutonic environment is below the surface of the earth. This environment is characterized by higher temperatures which result in slow cooling of the magma. Intrusive or plutonic igneous rocks form here.

Where magma erupts on the surface of the earth, temperatures are lower and cooling of the magma takes place much more rapidly. This is the extrusive or volcanic environment and results in extrusive or volcanic igneous rocks.

Extrusive Environments

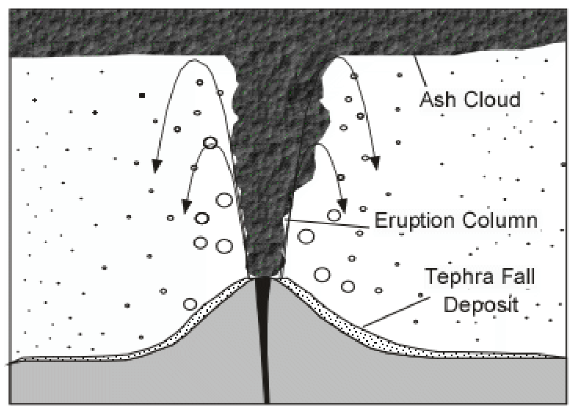
When magmas reach the surface of the Earth they erupt from a vent called a volcano. They may erupt explosively or non-explosively.

- Non-explosive eruptions are favored by low gas content and low viscosity magmas (basaltic to andesitic magmas and sometimes rhyolitic magma).
    - Usually begin with fire fountains due to release of dissolved gases

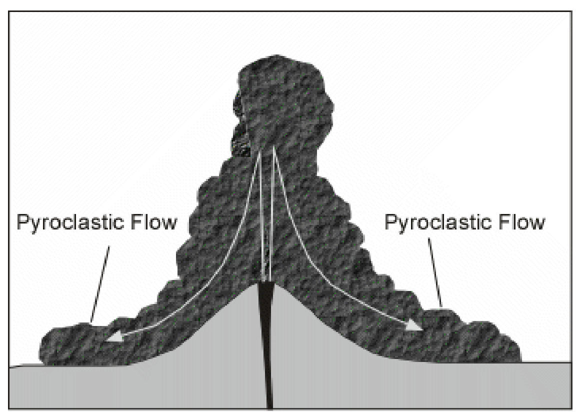
- Produce lava flows on surface
- Produce Pillow lavas if erupted beneath water

- Explosive eruptions are favored by high gas content and high viscosity (andesitic to rhyolitic magmas).
  - Expansion of gas bubbles is resisted by high viscosity of magma - results in building of pressure
  - High pressure in gas bubbles causes the bubbles to burst when reaching the low pressure at the Earth's surface.
  - Bursting of bubbles fragments the magma into ***pyroclasts*** and ***tephra (ash).***
  - Cloud of gas and tephra rises above volcano to produce an ***eruption column*** that can rise up to 45 km into the atmosphere.

Tephra that falls from the eruption column produces a ***tephra fall deposit.***



If eruption column collapses a ***pyroclastic flow*** may 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***.

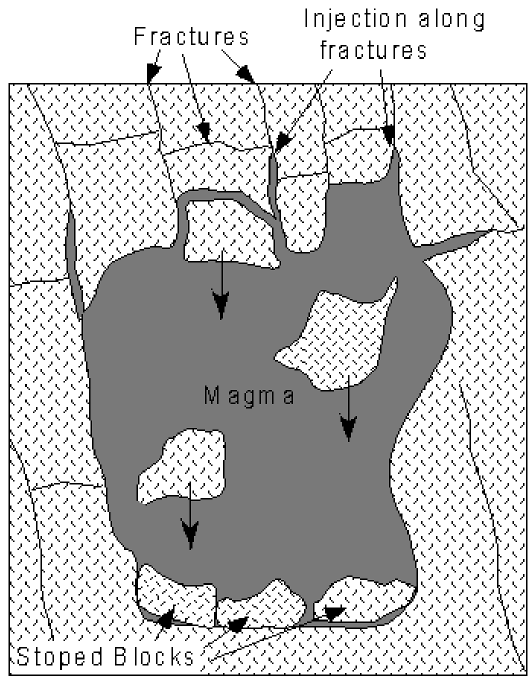


Intrusive Environments

Magma that cools at depth form bodies of rocks called intrusive bodies or plutonic bodies called plutons, from Greek god of the underworld - Pluto. When magma intrudes it usually affects the surrounding rock and is also affected by the surrounding rock. It may metamorphose the surrounding rocks or cause hydrothermal alteration. The magma itself may also cool rapidly near the contact with the surrounding rock and thus show a chilled margin next to the contact.

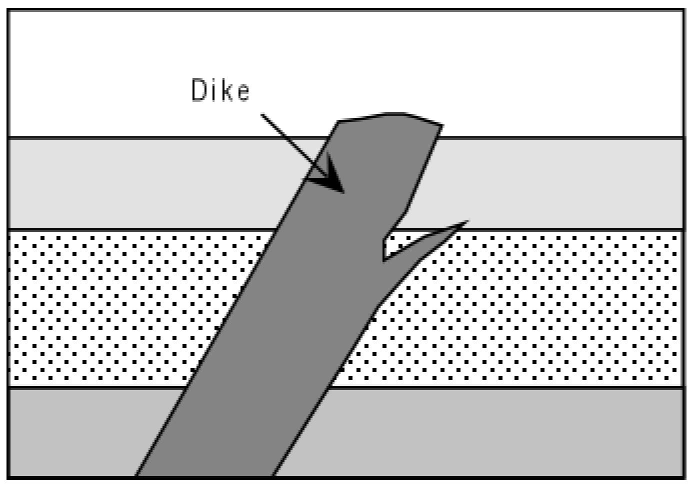
It may also incorporate pieces of the surrounding rocks without melting them. These incorporated pieces are called ***xenoliths*** (foreign rocks).

Magma intrudes by injection into fractures in the rock and expanding the fractures. The may also move by a process called stoping, wherein bocks are loosened by magma at the top of the magma body with these blocks then sinking through the magma to accumulate on the floor of the magma body.

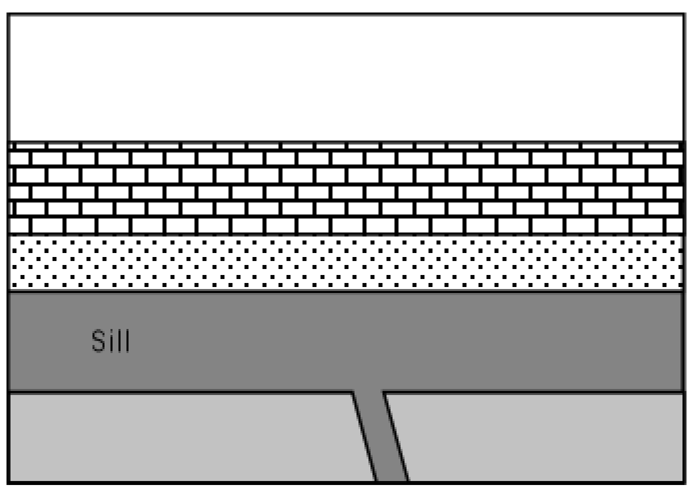


In relatively shallow environments intrusions are usually tabular bodies like dikes and sills or domed roof bodies called laccoliths.

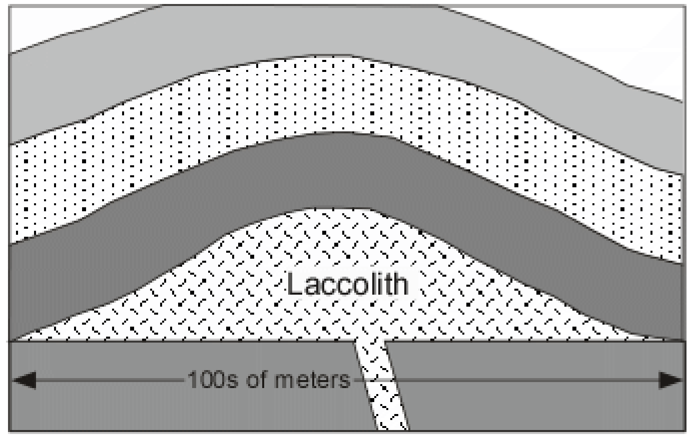
- **Dikes** are small (<20 m wide) shallow intrusions that show a discordant relationship to the rocks in which they intrude. Discordant means that they cut across preexisting structures. They may occur as isolated bodies or may occur as swarms of dikes emanating from a large intrusive body at depth.



- **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.

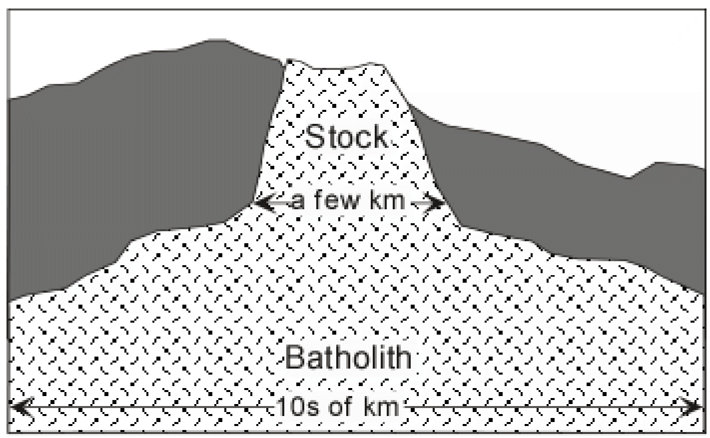


Deeper in the earth intrusion of magma can form bulbous bodies called plutons and the coalescence of many plutons can form much larger bodies called batholiths.

- **Plutons** are large intrusive bodies, of any shape that intrude in replace rocks in an irregular fashion.

- **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.

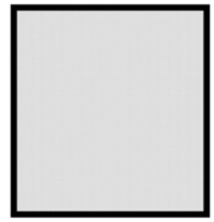
- If multiple intrusive events occur in the same part of the crust, the body that forms is called a **batholith.** Several large batholiths occur in the western U.S. - The Sierra Nevada Batholith, the Coast Range Batholith, and the Idaho Batholith, for example (See figure 6.10d in your text).



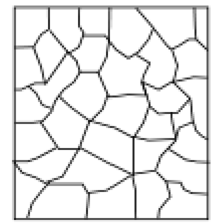
During a magmatic event there is usually a close relationship between intrusive activity and extrusive activity, but one cannot directly observe the intrusive activity. Only after erosion of the extrusive rocks and other rock above the intrusions has exposed the intrusions do they become visible at the earth's surface (see figure 6.10a in your text).

The rate of cooling of magma depends largely on the environment in which the magma cools. Rapid cooling takes place on the Earth's surface where there is a large temperature contrast between the atmosphere/ground surface and the magma. Cooling time for material erupted into air and water can be as short as several seconds. For lava flows cooling times are on the order of days to weeks. Shallow intrusions cool in months to years and large deep intrusions may take millions of years to cool.

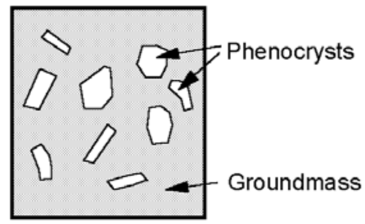
Because cooling of the magma takes place at a different rate, the crystals that form and their interrelationship (texture) exhibit different properties.



- Fast cooling on the surface results in many small crystals or quenching to a glass. Gives rise to ***aphanitic texture*** (crystals cannot be distinguished with the naked eye), or ***obsidian*** (volcanic glass).



- Slow cooling at depth in the earth results in fewer much larger crystals, gives rise to ***phaneritic texture***.



- ***Porphyritic texture*** develops when slow cooling is followed by rapid cooling. ***Phenocrysts*** = larger crystals, ***matrix*** or ***groundmass*** = smaller crystals.

Classification of Igneous Rocks

Igneous rocks are classified on the basis of texture and chemical composition, usually as reflected in the minerals that from due to crystallization. You will explore the classification of igneous rocks in the laboratory portion of this course.

Extrusive/Volcanic Rocks

Basalts, Andesites, and Rhyolites are all types of volcanic rock distinguished on the basis of their mineral assemblage and chemical compostion (see figure 6.13 in your text). These rocks tend to be fine grained to glassy or porphyritic. Depending on conditions present during eruption and cooling, any of these rock types may form one of the following types of volcanic rocks.

- ***Obsidian*** - dark colored volcanic glass showing concoidal fracture and few to no crystals. Usually rhyolitic .
- ***Pumice -*** light colored and light weight rock consisting of mostly holes (***vesicles***) that were once occupied by gas, Usually rhyolitic or andesitic.
- ***Vesicular*** rock - rock filled with holes (like Swiss cheese) or vesicles that were once occupied by gas. Usually basaltic and andesitic.
- If vesicles in a vesicular basalt are later filled by precipitation of calcite or quartz, the fillings are termed amygdules and the basalt is termed an amygdularl basalt.
- ***Pyroclasts*** = hot, broken fragments. Result from explosively ripping apart of magma. Loose assemblages of pyroclasts called ***tephra***. Depending on size, tephra can be classified as bombs. lapilli, or ash.

- Rock formed by accumulation and cementation of tephra called a ***pyroclastic rock*** or tuff. Welding, compactioncause tephra (loose material) to be converted in pyroclastic rock.

Intrusive/Plutonic Igneous Rocks

Shallow intrusions like dikes and sills are usually fine grained and sometimes porphritic because cooling rates are similar to those of extrusive rocks. Classification is similar to the classification for volcanic/extrusive rocks. Coarse grained rocks, formed at deeper levels in the earth include gabbros, diorites, and granites. Note that these are chemically equivalent to basalts, andesites, and rhyolites, but may have different minerals or different proportions of mineral because their crystallization history is not interrupted as it might be for extrusive rocks (see figure 6.13 in your text).

Pegmatites are very coarse grained igneous rocks consisting mostly of quartz and feldspar as well as some more exotic minerals like tourmaline, lepidolite, muscovite. These usually form dikes related to granitic plutons.

Distribution of Igneous Activity

Igneous activity is currently taking place as it has in the past in various tectonic settings. These include diverging and converging plate boundaries, hot spots, and rift valleys.

Divergent Plate Boundaries

At oceanic ridges, igneous activity involves eruption of basaltic lava flows that form pillow lavas at the oceanic ridges and intrusion of dikes and plutons beneath the ridges. The lava flows and dikes are basaltic and the plutons mainly gabbros. These processes form the bulk of the oceanic crust as a result of sea floor spreading. Magmas are generated by decompression melting as hot solid asthenosphere rises and partially melts.

Convergent Plate Boundaries

Subduction at convergent plate boundaries introduces water into the mantle above the subduction and causes flux melting of the mantle to produce basaltic magmas. These rise toward the surface differentiating by assimilation and crystal fractionation to produce andesitic and rhyolitic magmas. The magmas that reach the surface build island arcs and continental margin volcanic arcs built of basalt, andesite, and rhyolite lava flows and pyroclastic material. The magmas that intrude beneath these arcs can cause crustal melting and form plutons and batholiths of diorite and granite

Hot Spots

As discussed previously, hot spots are places are places where hot mantle ascends toward the surface as plumes of hot rock. Decompression melting in these rising plumes results in the production of magmas which erupt to form a volcano on the surface or sea floor, eventually building a volcanic island. As the overriding plate moves over the hot spot, the volcano moves off of the hot spot and a new volcano forms over the hot spot. This produces a hot spot track consisting of lines of extinct volcanoes leading to the active volcano at the hot spot. A hot spot located beneath a continent can result in heat transfer melting of the continental crust to produce large rhyolitic volcanic centers and plutonic granitic plutons below. A good example of a continental hot spot is at Yellowstone in the western U.S. Occasionally a hot spot is coincident with an oceanic ridge. In such a case, the hot spot produces larger volumes of magma than normally occur at ridge and thus build a volcanic island on the ridge. Such is the case for Iceland which sits atop the Mid-Atlantic Ridge.

Rift Valleys

Rising mantle beneath a continent can result in extensional fractures in the continental crust to form a rift valley. As the mantle rises it undergoes partial melting by decompression, resulting in the production of basaltic magmas which may erupt as flood basalts on the surface. Melts that get trapped in the crust can release heat resulting in melting of the crust to form rhyolitic magmas that can also erupt at the surface in the rift valley. An excellent example of a continental rift valley is the East African Rift.

Large Igneous Provinces

In the past, large volumes of mostly basaltic magma have erupted on the sea floor to form large volcanic plateaus, such as the Ontong Java Plateau in the eastern Pacific. Such large volume eruptions can have affects on the oceans because they change the shape of ocean floor and cause a rise in sea level, that sometimes floods the continents. The plateaus form obstructions which can drastically change ocean currents. These changes in the ocean along with massive amounts of gas released by the magmas can alter climate and have drastic effects on life on the planet.

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

1. What are the three main types of magma and how are they distinguished in terms of their chemical composition, temperature, and viscosity?
2. What is the main difference between the way that pure minerals melt and the way the rocks melt? What effect does the addition of volatiles like H_20 and CO_2 have?
3. What are the main gases that occur in magma?
4. What are three ways that magma can be generated? Explain each.
5. Define the following: (a) dike, (b) sill, (c) xenolith, (d) stoping, (e) batholith, (f) obsidian, (g) pumice, (h) pyroclast, (i) pegmatite. (Use drawings if it helps).
6. What does the texture of an igneous rocks tell us about cooling history?
7. Describe the following igneous textures (a) aphanitic, (b) phaneritic, (c) porphyritic.
8. Describe the distribution of igneous activity on Earth.

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