Magma Formation and Behavior

Introduction: The study of body waves (earthquake waves) as they pass through Earth's interior provides strong evidence that the Earth's mantle is composed almost entirely of solid low silica rock. Yet, under certain circumstances that rock undergoes a process of partial melting to produce large quantities of magma. Many of these magmas are erupted at the surface at volcanoes. Most magmas, however, completely crystallize before reaching Earth's surface.

A big challenge for geologists is to understand the causes of melting of mantle rock, and how magmas change as they ascend through the lithosphere. Important questions to be answered are:

1) What causes mantle rock to undergo the process of partial melting?
2) Are these processes in any way related to plate tectonic setting?
3) Why do rhyolitic (high silica) magmas usually crystallize before reaching Earth's surface.
4) Why are basaltic (low silica) magmas usually erupted at volcanoes?

I. Magma Viscosity

Viscosity - measure of resistance to flow. Has important control on the nature of a volcanic eruption. High viscosity = magma is resistant to flow (flows very slowly). Low viscosity = magma flows freely (flows very quickly).

Controls on viscosity:
1. Magma Composition - higher silica content = higher viscosity (long silica chains)
2. Magma Temperature - higher temperature = lower viscosity (high temperatures make formation of long silica chains less likely)
3. Dissolved Gas - higher amount dissolved gas (H_2O, CO_2, etc.) = lower viscosity (cations such as H^+, C^{4+} form bonds with O^{2-} making formation of long silica chains less likely)

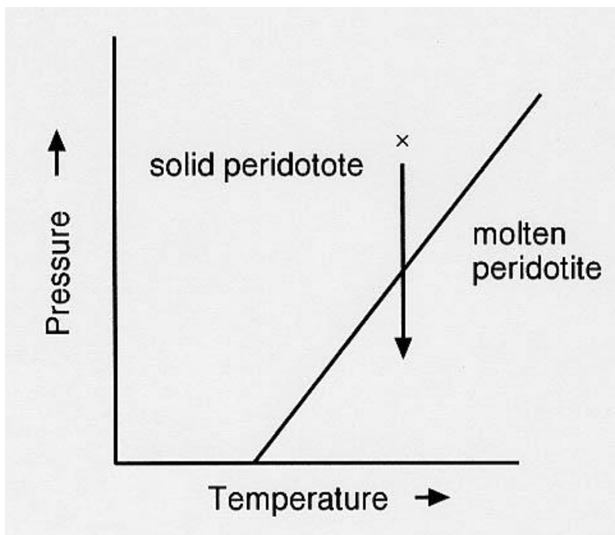
Basaltic Lavas (Hawaii) = Low Viscosity = "Quiet", non-explosive eruptions. Eruptions of basaltic magmas are generally non-explosive. Low viscosity of low silica magma allows dissolved gasses to expand and escape as the magma ascends to the surface. Thus, there is little increase in gas pressure within the magma chamber as the magma approaches the surface.

Andesitic and Rhyolitic Lavas (Mt. St. Helens) = High Viscosity = Explosive eruptions. Eruptions of andesitic/rhyolitic magmas are generally explosive. High viscosity magmas prevents most gasses from expanding during magma ascent. Most gasses explode just as the magma reaches the Earth's surface, resulting in a large increase in gas pressure within the magma chamber. When gas pressure exceed the pressure of what the overlying rock can take, a sudden eruption is triggered in which much of the magma and gas is explosively blown out of the volcano (similar to suddenly releasing the pressure in a shaken bottle of Coke).

II. Processes that Form Magma by Melting of Mantle Rock

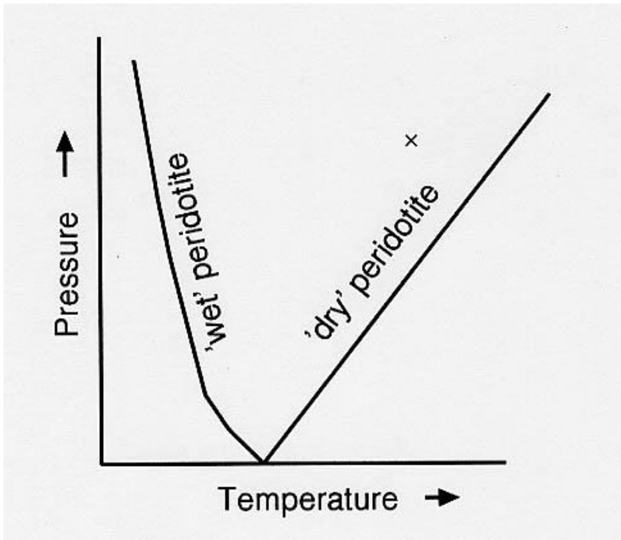
1. Increase in Temperature - The least important cause of magma formation in the mantle! However, at any given temperature above the 'general ' melting temperature of a rock, not all minerals melt at the same temperature. Minerals with high silica content (e.g. quartz) melt at lower temperatures than minerals with low silica content (e.g. olivine). Thus, rocks do not melt at a single temperature, but over a range of temperatures. If a rock undergoes 'partial melting', the resulting magma will have a higher silica content than the rock from which it came from. This is because silicate minerals with high silica contents melt at lower temperatures than silicate minerals with low silica contents.

2. Decrease in Pressure - *Very high pressures in mantle rocks prevent atoms within minerals from breaking chemical bonds and moving freely from one another to form magma.* Therefore, most rocks within the mantle do not melt even though their temperature may be greater than that necessary to melt the same rocks at the lower pressures of the Earth's surface. However, if pressure on mantle rock is decreased the atoms may move freely from one another, resulting in partial melting of the rock. This process is called pressure-release melting.

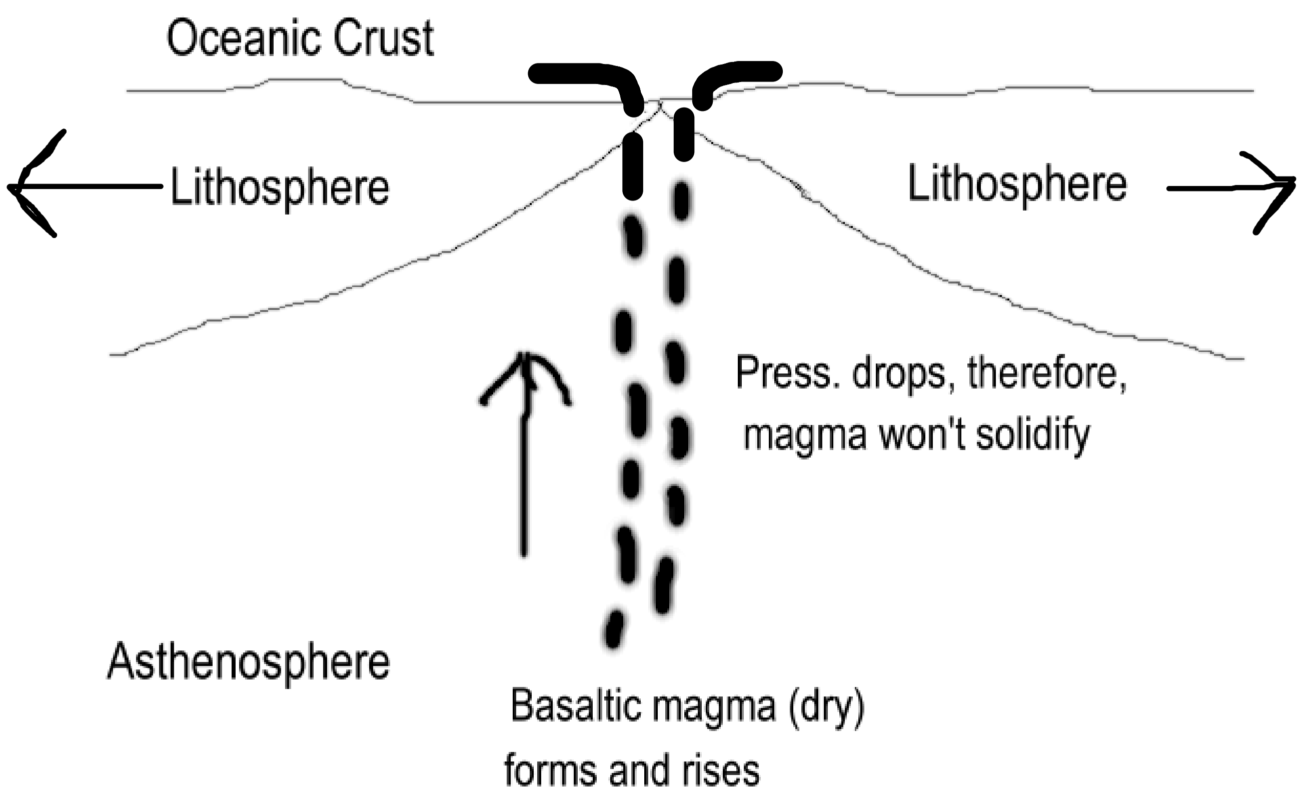


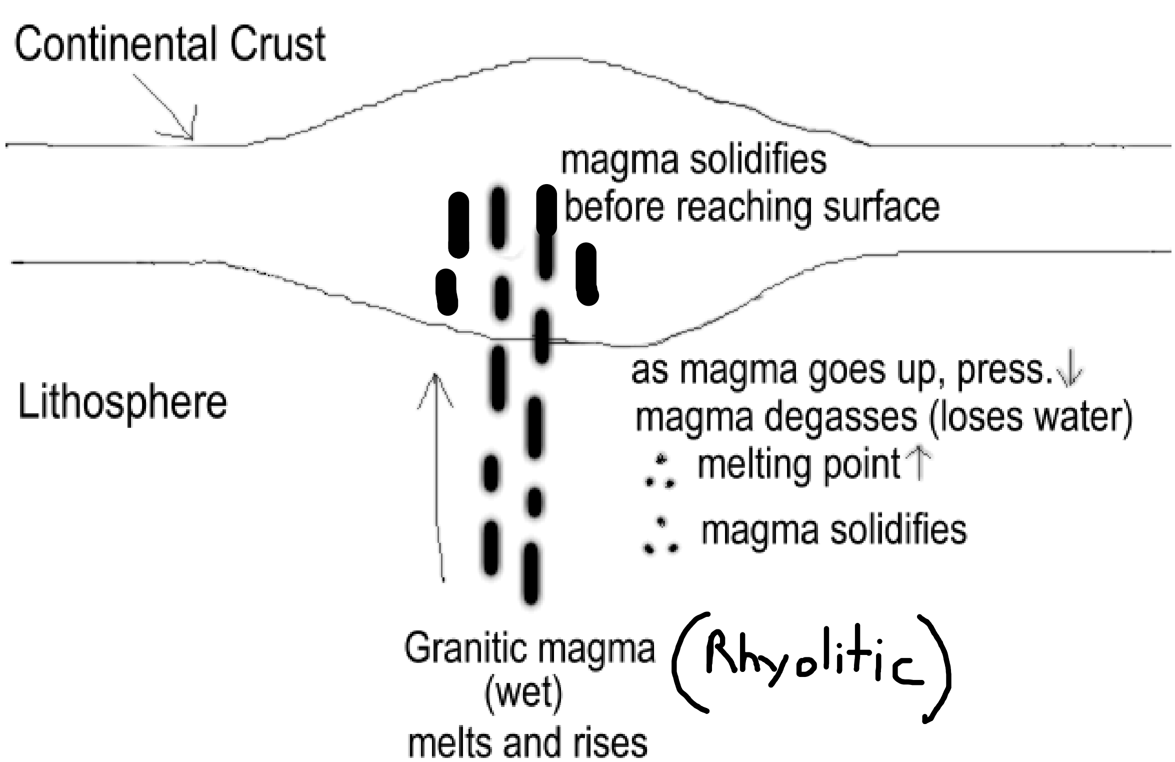
In the above diagram, low silica mantle rock, peridotite, (marked as X) moves toward the Earth's surface. On the graph, the arrow pointing in a direction of decreasing pressure shows this. Note that the pressure on the rock decreases with almost no change in temperature. The diagonal line represents the peridotite melting 'curve'. The melting curve is a phase boundary, separating those regions of the graph over which peridotite exists as a solid phase from those regions where peridotite exists as a liquid phase (melt). When the rock crosses the peridotite melting curve, it starts to melt. This type of partial melting (pressure-release melting) is common along divergent plate margins, and within mantle plumes.

3. Addition of Water - *The addition of small amounts of water to peridotite will result in a decrease in its melting temperature.* This is largely due to the electrically polarized nature of a water molecule (there is an unequal distribution of electrons around the water molecule). The electrical polarization causes a decrease in cation-anion bond strengths within minerals, and so at very high temperatures the bonds may be broken so that atoms may move freely from one another to form magma. This process results in partial melting of the mantle rock.



In the above diagram, the addition of water moves the peridotite melting curve to lower temperatures. The 'dry' peridotite curve is the phase boundary for peridotite in the presence of little or no water. The 'wet' peridotite curve is the phase boundary for peridotite in the presence of water. Note that 'wet' peridotite melts at lower temperature than 'dry' peridotite. Thus, it is not necessary to change the temperature or pressure of a mantle rock (marked as X) in order for it to undergo partial melting. As water is added to 'dry peridotite', the melting curve will shift toward lower temperatures and eventually cross X. At that point, the rock will begin to melt. This type of melting occurs within subduction zones as water is 'squeezed' from the subducted oceanic lithosphere/crust into the overlying ultramafic mantle wedge.


Oceanic Crust
Lithosphere
Lithosphere
Press. drops, therefore,
magma won't solidify
Asthenosphere
Basaltic magma (dry)
forms and rises


Continental Crust
magma solidifies
before reaching surface
Lithosphere
as magma goes up, press.↓
magma degasses (loses water)
∴ melting point↑
∴ magma solidifies
Granitic magma
(wet)
melts and rises
(Rhyolitic)

III. The Effect of Partial Melting on Magma Composition

Rocks such as peridotite contain a mixture of several different minerals, each with its own melting temperature. Minerals with the lowest melting temperatures generally melt first while minerals with higher melting temperatures remain solid. This process is called partial melting.
In general, minerals with higher silica contents melt at lower temperatures. Thus, a magma will generally have a higher silica content than the rock which was melted to produce it. For example, partial melting of a very low silica rock such as peridotite will result in formation of a low silica (basaltic) magma with a higher silica content than the original peridotite. This explains why basaltic lavas are erupted along mid-ocean ridges, even though the underlying mantle rock from which the magmas are derived by partial melting peridotite in composition.

IV. Magma Behavior

Why do rhyolitic magmas commonly crystallize beneath the Earth's surface to form intrusive rocks, while basaltic magmas commonly rise to the Earth's surface to erupt at volcanoes?

1. Silica content – *Rhyolitic magmas contain significantly greater amounts of silica than do basaltic magmas*, resulting in higher viscosity (greater resistance to flow). High viscosity rhyolitic magmas require longer periods of time to ascend toward the Earth's surface and are therefore more likely to cool and crystallize as intrusive igneous bodies.

2. H_2O content - *Rhyolitic magmas contain significantly greater amounts of dissolved H_2O than do basaltic magmas.* As rhyolitic magmas ascend to the Earth's surface, pressure on the magma slowly decreases and the dissolved H_2O escapes as steam. The effect of water in rhyolitic magma is the same as that discussed above for the effect of water on the melting of peridotite. So, this resulting decrease in dissolved H_2O content causes an increase in the magma's crystallization temperature (the 'crystallization' curve shifts to higher temperatures). Therefore, because the magma is very hot and cooling very slowly, it is more likely to completely solidify as an intrusive igneous body before reaching Earth's surface.

Basaltic magmas typically contain much less dissolved H_2O than rhyolitic magmas. Therefore, loss of H_2O as a basaltic magma travels through the crust has a relatively small effect on the temperature at which the magma solidifies. basaltic magmas also flow more readily than rhyolitic magmas, making it easier for them to 'squeeze' their way to the surface along fractures and faults in the Earth's crust. For these reasons, most of the Earth's volcanic rocks are basalts. In fact, basalt is the most common rock type on the Earth's surface - it covers the ocean basin floors.

Summary:

1. To crystallize magma: a) decrease the temperature, or b) increase the pressure, or c) remove water

2. To melt a rock: a) increase the temperature, or b) decrease the pressure, or c) add water

Magma Formation and Behavior Questions

1. What is meant by the term 'viscosity'?

2. What are the three most important controls on magma viscosity? How does each affect magma viscosity?

    1.

    2.

    3.

3. What is the relationship between magma composition (silica content) and its viscosity?

   How might this effect volcano explosivity?

4. What are the three possible ways to melt a rock in the Earth's mantle?

    1. 2. 3.

5. Of the three possible ways to melt a rock in the Earth's mantle, which is the least likely or important?

6. What is the cause of melting of mantle rock beneath mid-ocean ridges(divergent boundaries) and within mantle plumes?

7. What is the cause of melting of mantle rock within subduction zones?

8. How does the addition of water to peridotite change its melting/crystallization temperature?

9. How does the loss of water from rhyolitic magma change its melting/crystallization temperature?

10. Which is more likely to have a higher temperature, a basaltic magma or rhyolitic magma? Why?

11. Which has a higher silicate content, a basaltic magma or rhyolitic magma?

12. Which has higher water content, a basaltic magma or rhyolitic magma?

13. How does silicate content affect magma viscosity? Why?

14. How does temperature affect magma viscosity? Why?

15. Which has a higher viscosity, a basaltic magma or rhyolitic magma? Why?

16. Which is more likely to be erupted at a volcano, a basaltic magma or rhyolitic magma? Why?

17. What is the most common rock type on the Earth's surface? Why?