

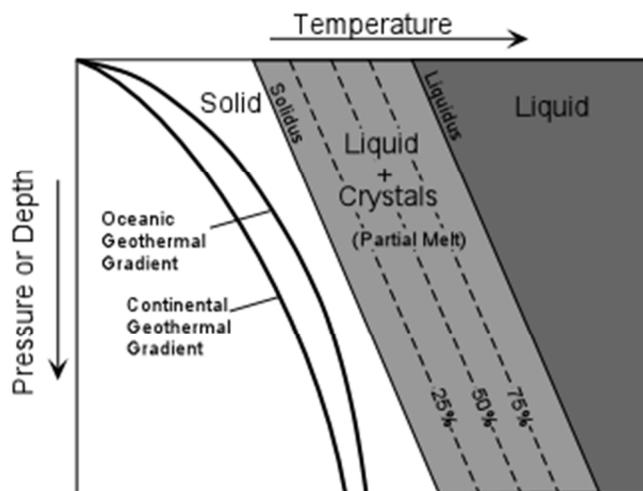
GEOLOGY semester -II

GT 201 – IGNEOUS PETROLOGY

Origin of Magmas

Again, magmas do not form everywhere beneath the surface, so special circumstances are necessary.

Temperature varies with depth or pressure in the Earth along the geothermal gradient. The normal geothermal gradient is somewhat higher beneath the oceans than beneath the continents, at least at shallow levels. If we compare the normal geothermal gradients with the experimentally determined phase diagram for peridotite containing little water or carbon dioxide, we find that the peridotite solidus temperature is everywhere higher than the normal geothermal gradients. Thus, under normal conditions the mantle is solid, as we would suspect from the seismic evidence.



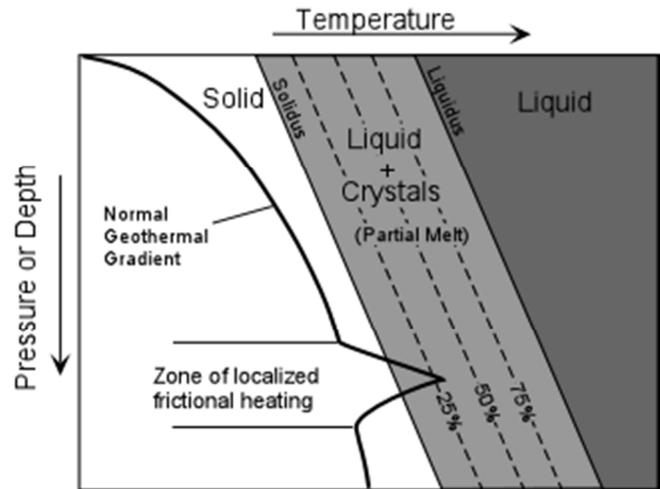
Thus, in order to generate a melt, either we must find a way to increase the geothermal gradient so that it is above the peridotite solidus or reduce the temperature of the peridotite solidus. In either case note that all we have to do is get the temperature in some part of the Earth, as expressed by the geothermal gradient, into the field of partial melt. Partial melting is the most likely case because it requires less of an increase in temperature or less of a decrease in the peridotite solidus. Once a partial melt has formed, the liquid portion can be easily separated from the remaining solids since liquids are more mobile and, in general, have a lower density than solids.

Raising the Geothermal Gradient

- **Radioactive Heat** - Elements like U, Th, K, and Rb have radioactive isotopes. During radioactive decay, sub-atomic particles are released by the decaying isotope and move outward until they collide with other atomic particles. Upon collision, the kinetic energy of the moving particles is converted to heat. If this heat cannot be conducted away, then the temperature will rise. Most of the heat within the Earth is generated by radioactive decay, and this is the general reason why temperature increases with depth in the Earth. But most the radioactive isotopes are concentrated in the crust. Although there are areas in the continental crust where high concentrations of radioactive elements have locally raised the temperature, at least high enough to cause metamorphism, this is a rare occurrence. It is even more unlikely that areas of high

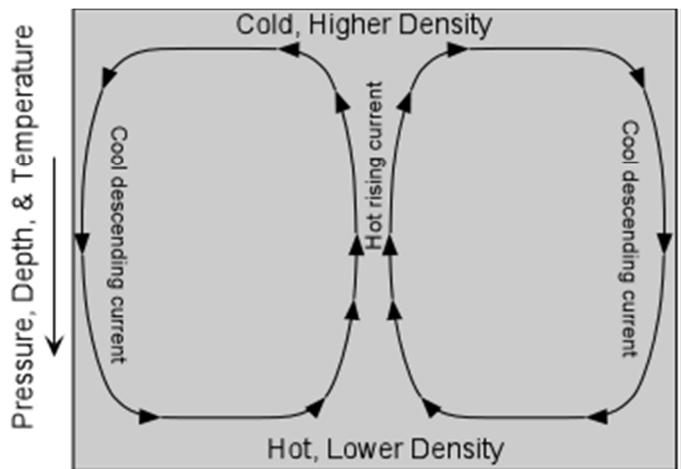
concentration develop within the mantle. Thus, concentrations of radioactive elements is not likely to cause melting.

- Frictional Heat** - In areas where rocks slide past one another, such as at the base of the lithosphere, on at subduction zones, heat could be generated by friction. If this heat cannot be conducted away fast enough, then it may cause a localized rise in temperature within the zone where the sliding or shearing is taking place. This could cause a localized spike on the geothermal gradient that could cause local temperatures to rise above the solidus.



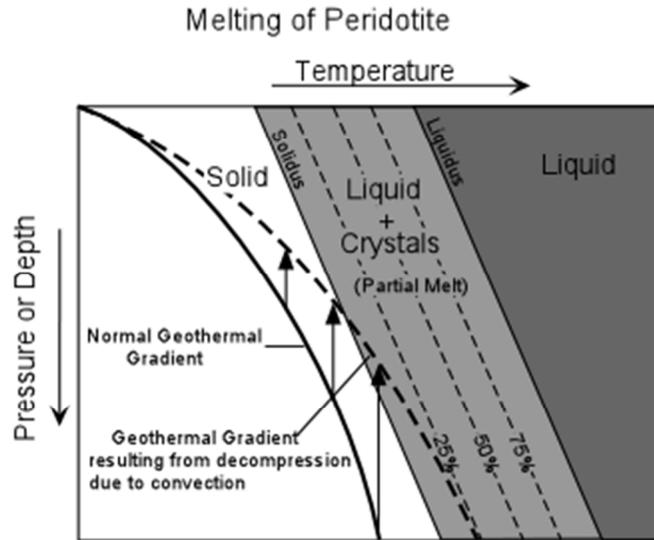
- Decompression due to Convection** - Convection is a form of heat transfer wherein the heat moves with the material. Convection can be induced if the temperature gradient is high enough that material at depth expands so that its density is lower than the material above it. This is an unstable situation and the hotter, lower density material will rise to be replaced by descending cooler material in a convection cell.

The rate of convection depends on both on the temperature gradient and the viscosity of the material (note that solids convect, but the rate is lower than in liquids because solids have higher viscosity). In the Earth, temperature gradients appear to be high enough and viscosity low enough for convection to occur. Plate tectonics appears to be driven by convection in some



form.

Anywhere there is a rising convection current, hotter material at depth will rise carrying its heat with it. As it rises to lower pressure (decompression) it will cool somewhat, but will still have a temperature higher than its surroundings. Thus, decompression will result in raising the local geothermal gradient. If this new geothermal gradient reaches temperatures greater than the peridotite solidus, partial melting and the generation of magma can occur. This mechanism is referred to as *decompression melting*.



Lowering the Solidus Temperature

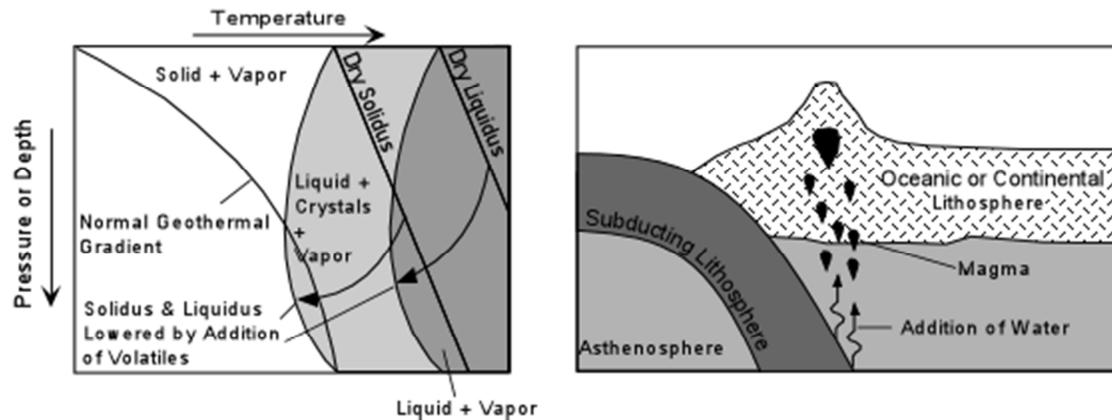
As we saw in our discussion of phase diagrams, mixtures of components begin melting at a lower temperature than the pure components. In a two component system addition of a third component reduces both the solidus and liquidus temperatures. This suggests that if something can be added to the mantle, it could cause the solidus and liquidus temperatures to be lowered to the extent that the solidus could become lower than the geothermal gradient and result in partial melting, without having to raise the geothermal gradient. Such a melting mechanism is referred to as *flux melting*.

It's difficult to imagine how solid components could be added to the mantle. But volatile components, for example H_2O and CO_2 , because of their high mobility, could be added to the mantle, particularly at subduction zones.

- Oceanic crust is in contact with sea water, thus water could be in oceanic crust both due to weathering, which produces hydrous minerals like clay minerals, and could be in the pore spaces in the rock.
- Oceanic sediments eventually cover the basaltic oceanic crust produced at oceanic ridges. Much of this sediment consists of clay minerals (which contain water) and carbonate minerals (which contain carbon dioxide).
- As the oceanic lithosphere descends into the mantle at a subduction zone, it will be taken to increasingly higher temperatures as it gets deeper. This will result in metamorphism of both the basalt and the sediment. As we will see later in our discussion of metamorphism, metamorphism is essentially a series of dehydration and decarbonation reactions, i.e. chemical reactions that transform hydrous and carbonate

minerals into nonhydrous minerals and give up H₂O and CO₂ as a fluid phase.

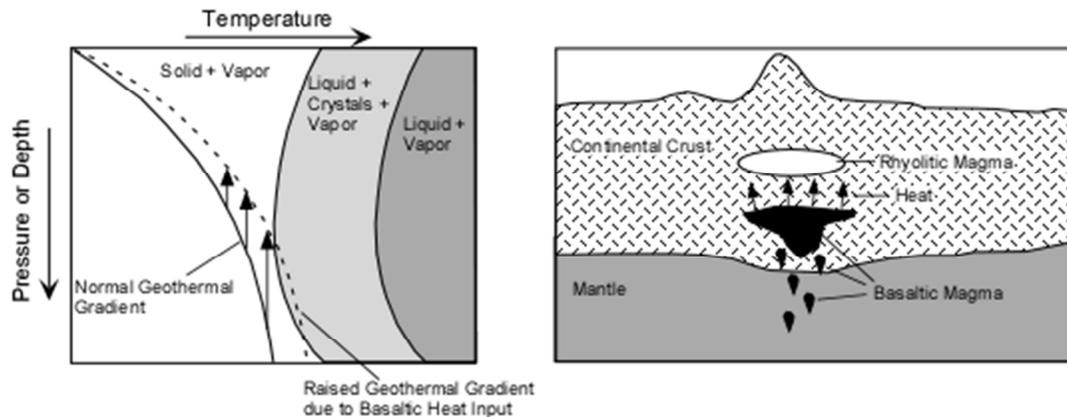
- Addition of this fluid phase, either to the subducted lithosphere or the mantle overlying the subducted lithosphere could lower the solidus and liquidus temperatures enough to cause partial melting.



Crustal Anatexis

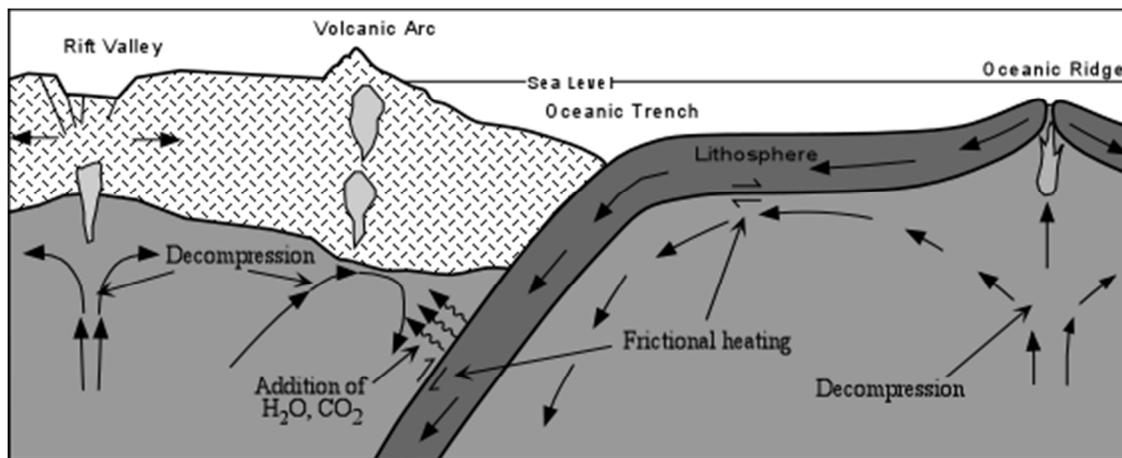
In the continental crust, it is not expected that the normal geothermal gradient will be high enough to cause melting despite the fact that hydrous and carbonate minerals occur in many continental rocks. Furthermore, because continental rocks are at low temperature and have a very high viscosity, convective decompression is not likely to occur. Yet, as we will see, there is evidence that continental crustal rocks sometimes melt. This is called crustal anatexis. The following scenario is one mechanism by which crustal anatexis could occur.

- Basaltic magmas, generated in the mantle, by flux melting, decompression melting or frictional heat, rise into the crust, carrying heat with them.
- Because basaltic liquids have a higher density than crust, they may not make it all the way to the surface, but instead intrude and cool slowly at depth.
- Upon cooling the basaltic magmas release heat into the crust, raising the geothermal gradient (increasing the local temperature).
- Successive intrusions of mantle-derived magma into the same area of the crust may cause further increases in temperature, and eventually cause the geothermal gradient to become higher than the wet solidus of the crustal material, resulting in a partial melt of the crust.



Magmatism and Plate Tectonics

From the discussion above it should be obvious that magmatism is closely related to plate tectonics. The diagram below summarizes melting mechanisms that occur as a result of plate tectonics and may be responsible for the generation of magmas in a variety of plate tectonic settings, such as oceanic ridges, near subduction zones, and at rift valleys.



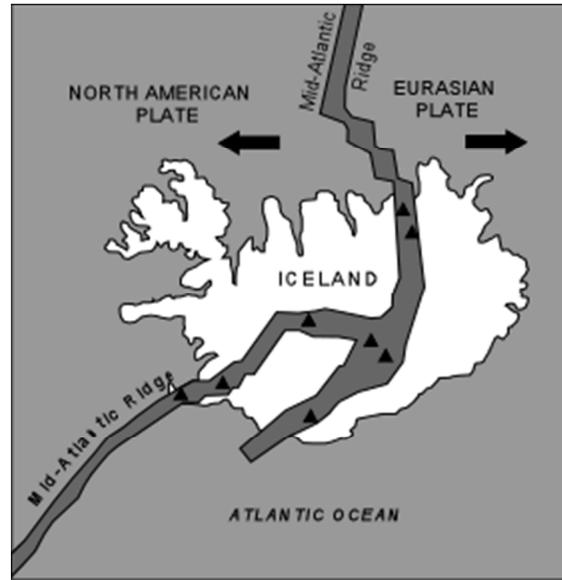
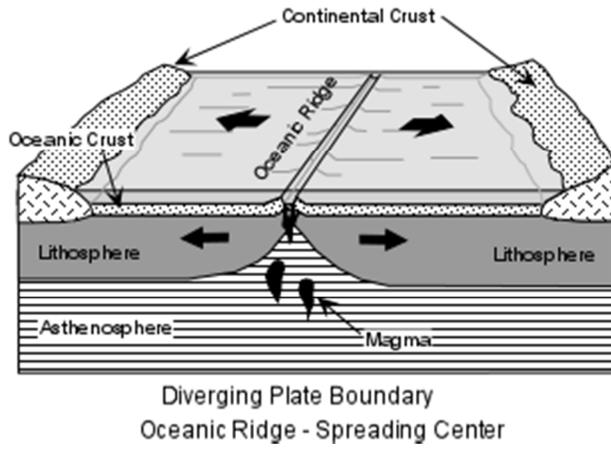
Diverging Plate Boundaries

Diverging plate boundaries are where plates move away from each other. These include oceanic ridges or spreading centers, and rift valleys.

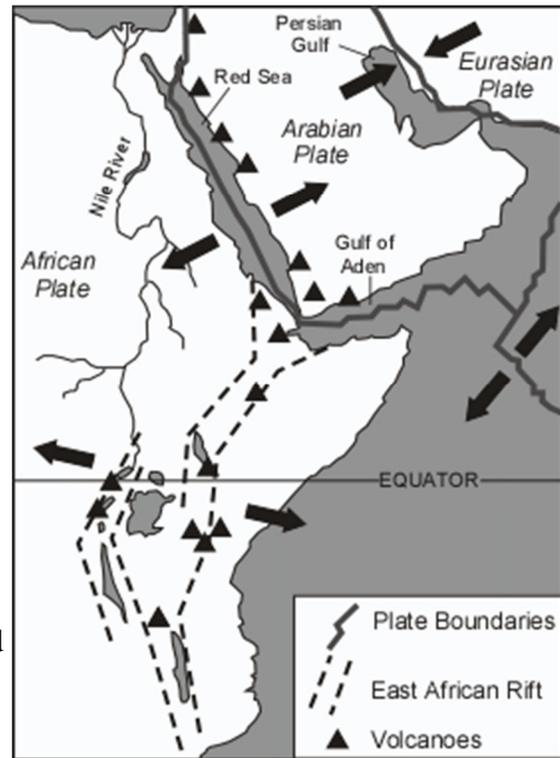
- Oceanic Ridges are areas where mantle appears to ascend due to rising convection currents. Decompression melting could result, generating magmas that intrude and erupt at the oceanic ridges to create new oceanic crust.

Iceland is one of the few areas where the resulting magmatism has been voluminous

enough to built the oceanic ridge above sea level.



- Continental Rift Valleys or Extensional Zones are areas, usually located in continental crust where extensional deformation is occurring. These areas may be incipient spreading centers and may eventually evolve into oceanic ridges, such as has occurred in the Red Sea region. Whether or not they develop into spreading centers, they are likely caused by mantle upwelling below the zone of extension. Mantle upwelling may result in decompression melting of the mantle, and could induce crustal anatexis. A good example of a continental rift valley is the East African Rift Valley. Another example is the Rio Grande Rift in Colorado and New Mexico, which is part of a larger region of extension that includes much of the western U.S. and is called the Basin and Range Province (Eastern California & Oregon, Nevada, Utah, Arizona, & New Mexico).

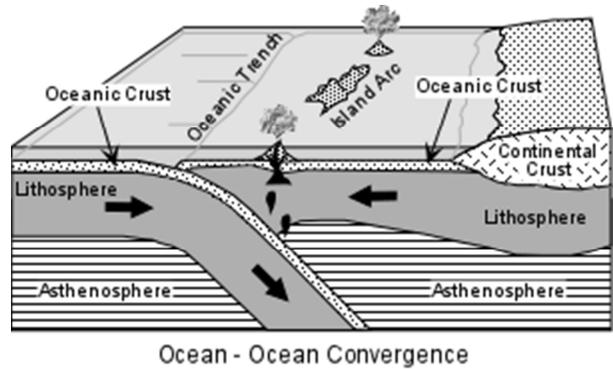


Converging Plate Boundaries

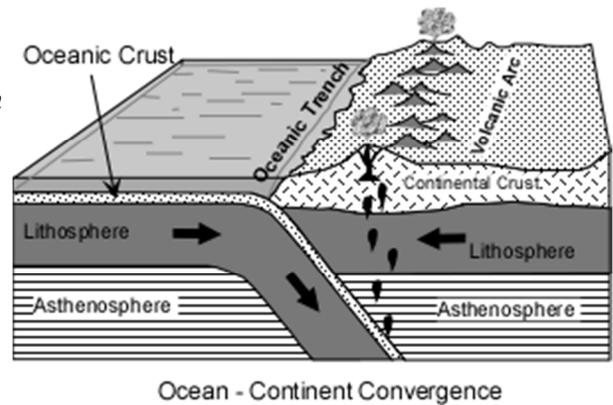
Converging plate boundaries are where plates run into each other. The most common type are where oceanic lithosphere subducts. Several mechanisms could contribute to the generation of magmas in this environment (see diagram at top of this section).

- Frictional heating is likely to occur along the boundary between the subducted plate and the overlying mantle wedge.
- Flux melting of either the subducted lithosphere or the overlying mantle wedge could occur as a result of the release of volatiles as the subducted plate heats and metamorphoses producing water and/or carbon dioxide fluids.
- The process of subduction may drag the overlying mantle wedge down with it. In order to replace the mantle dragged down in this process, part of the mantle wedge will have to rise. This upwelling of the mantle could result in decompression melting.

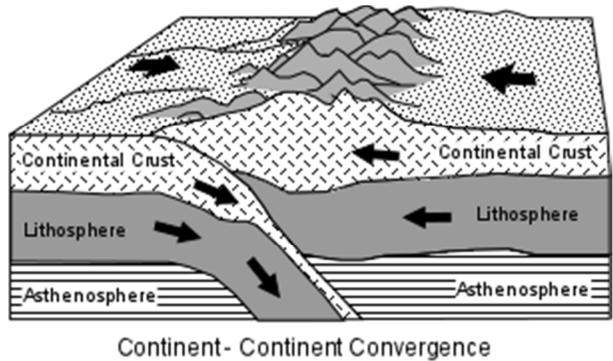
- If an oceanic lithospheric plate subducts beneath another oceanic lithospheric plate, we find *island arcs* on the surface above the subduction zone.



- If an oceanic plate subducts beneath a plate composed of continental lithosphere, we find *continental margin arcs*. If magma generated near the subduction zone intrudes and cools in the crust, it could induce crustal anatexis.



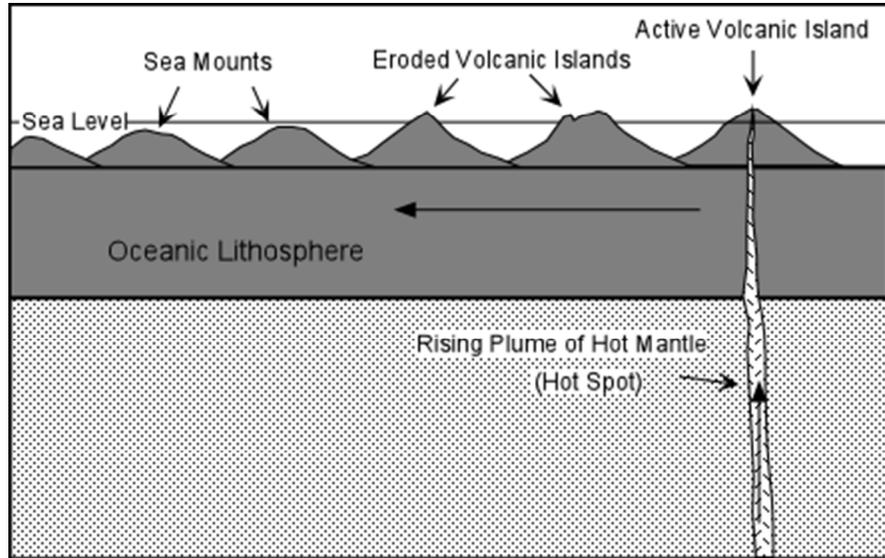
- In areas where two continental lithospheric plates converge fold-thrust mountain ranges develop as the result of compression. If water-bearing crustal rocks are pushed to deeper levels where temperatures are higher, crustal anatexis may result.



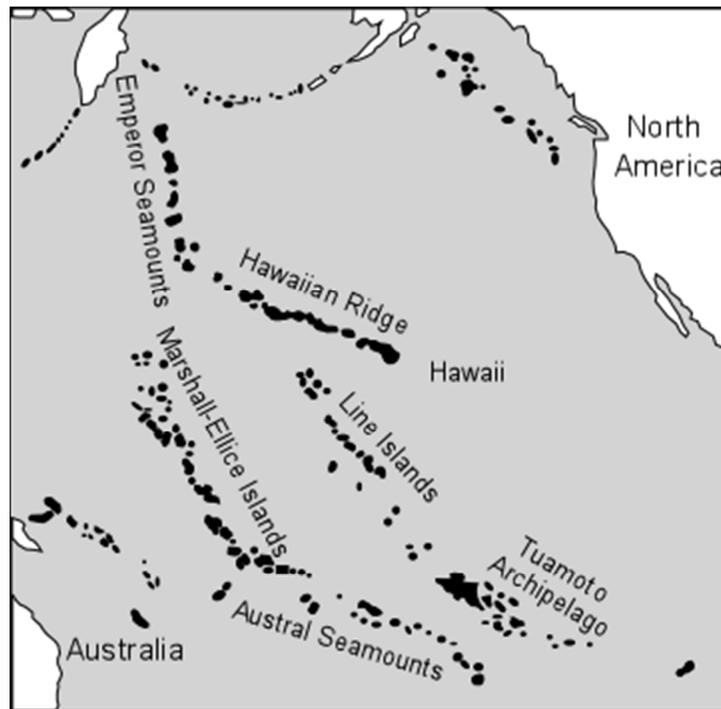
Intraplate Magmatism & Hot Spots

There are a few areas where magmatism does not appear to be related to converging or diverging plate boundaries. These areas occur in the middle of plates, usually far from the plate boundaries. This phenomenon is referred to as *intraplate magmatism*. Intraplate magmatism is thought to be caused by *hot spots* formed when thin plumes of mantle material rise along narrow zones from deep within the mantle. The hot spot remains stationary in the mantle while the plate moves over the hot spot.

Decompression melting caused by the upwelling plume produces magmas that form a volcano on the sea floor above the hot spot. The volcano remains active while it is over the vicinity of the hot spot, but eventually plate motion results in the volcano moving away from the plume and the volcano becomes extinct and begins to erode.



Because the Pacific Plate is one of the faster moving plates, this type of volcanism produces linear chains of islands and seamounts, such as the Hawaiian - Emperor chain, the Line Islands, the Marshall-Ellice Islands, and the Austral seamount chain.



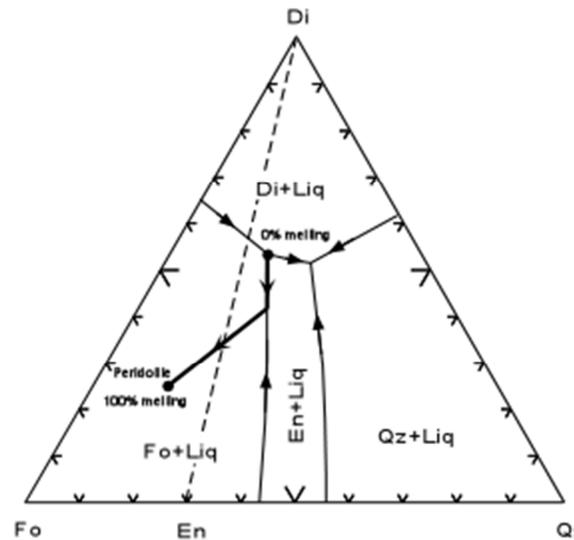
Distinct Melting Events

One possibility that always exists is that the magmas are not related except by some heating event that caused melting. In such a case each magma might represent melting of a different source rock at different times during the heating event. If this were the case, we might not expect the chemical analyses of the rocks produced to show smooth trends on variation diagrams. But, because variation diagrams are based on a closed set of numbers (chemical analyses add up to 100%), if the weight% of one component increases, then the weight percent of some other component must decrease. Thus, even in the event that the magmas are not related, SiO_2 could increase and MgO could decrease to produce a trend. The possibility of distinct melting events is not easy to prove or disprove.

Various Degrees of Partial Melting

We have seen in our study of simple phase diagrams that when a multicomponent rock system melts, unless it has the composition of the eutectic, it melts over a range of temperatures at any given pressure, and during this melting, the liquid composition changes. Thus, a wide variety of liquid compositions could be made by various degrees of partial melting of the same source rock.

To see this, let's look at a simple example of a three component system containing natural minerals, the system Fo - Di - SiO_2 , shown in simplified form here. A proxy for mantle peridotite, being a mixture of Ol, Cpx, and Opx would plot as shown in the diagram. This rock would begin to melt at the peritectic point, where Di, En, Ol, and Liquid are in equilibrium. The composition of the liquid would remain at the peritectic point (labeled 0% melting) until all of the diopside melted. This would occur after about 23% melting. The liquid would then take a path shown by the dark curve, first moving along the En - Ol boundary curve, until the enstatite was completely absorbed, then moving in a direct path toward the peridotite composition.



At 100% melting the liquid would have the composition of the initial peridotite. So long as some of the liquid is left behind, liquids can be extracted at any time during the melting event and have compositions anywhere along the dark line between 0% melting and 100% melting. (Note that the compositions between 0% melting and where the dark line intersects the En-Di join are SiO_2 oversaturated liquids, and those from this point up to 100% melting are SiO_2 undersaturated liquids).

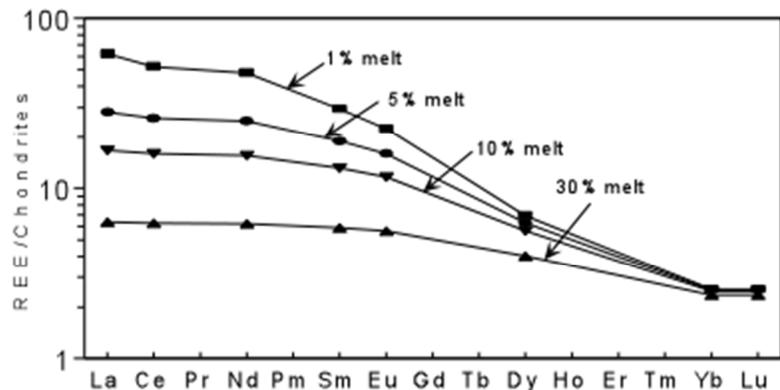
Fractional Melting

Note that it was stated above that some of the liquid must be left behind. If all of the liquid is

melt of a mantle rock will have high concentrations of incompatible elements. As melting proceeds the concentration of these incompatible elements will decrease because (1) there will be less of them to enter the melt, and (2) their concentrations will become more and more diluted as other elements enter the melt. Thus, **incompatible element concentrations will decrease with increasing % melting.**

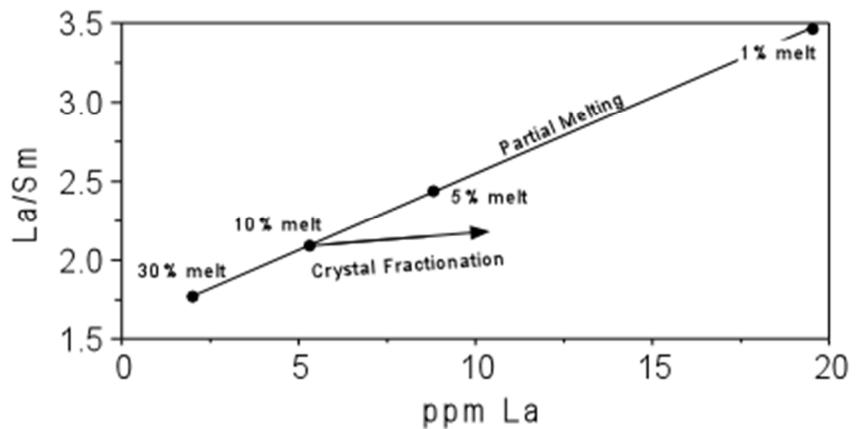
Rare Earth elements are particularly useful in this regard. These elements, with the exception of Eu, have a +3 charge, but their ionic radii decrease with increasing atomic number. i.e. La is largest, Lu is smallest. Thus the degree of incompatibility decreases from La to Lu. This is even more true if garnet is a mineral in the source, because the size of the heavy REEs (Ho - Lu) are more compatible with crystallographic sites in garnet.

Using equations that describe how trace elements are partitioned by solids and liquids, concentrations of REEs in melts from garnet peridotite can be calculated. These are shown in the diagram, where REE concentrations have been normalized by dividing the concentration of each element by the concentration found in chondritic meteorites.



This produces a REE pattern. Note that the low % melts have Light REE enriched patterns, because the low atomic weight REEs (La - Eu) are enriched over the heavier REEs.

Next, we plot the ratio of a highly incompatible element, like La, to a less incompatible element, like Sm, versus the concentration of the highly incompatible element. In the case shown, La/Sm ratio versus La concentration for each % melting. Note the steep slope of the curves connecting the points.



As we'll see in our discussion of crystal fractionation, the ratios of incompatible elements do not change much with crystal fractionation, and therefore produce a trend with a less steep slope. This gives us a method for distinguishing between partial melting and crystal fractionation as the process responsible for magmatic differentiation.

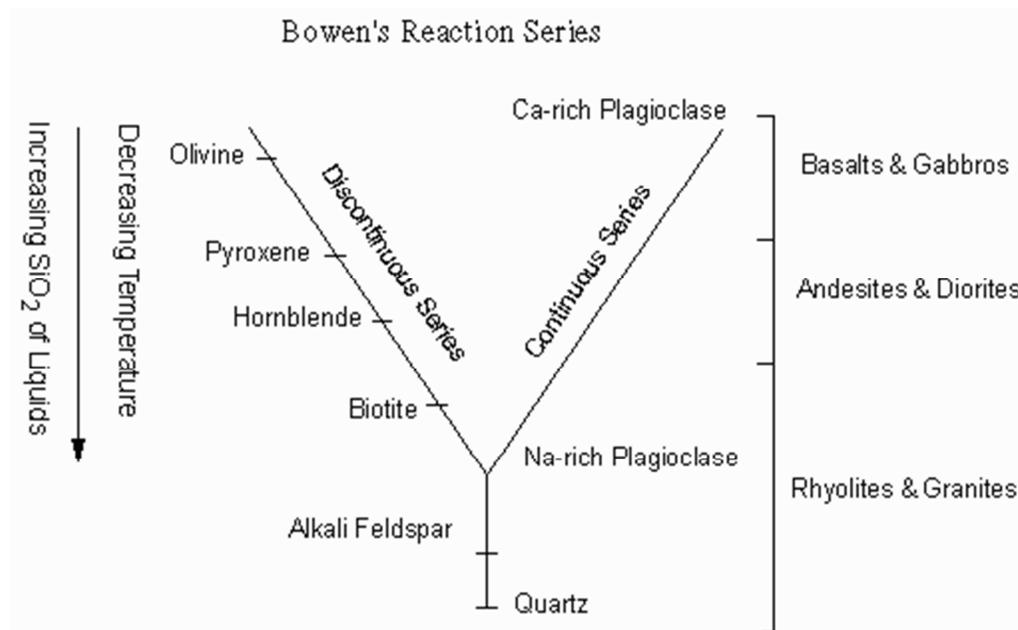
Crystal Fractionation

In our discussion of phase diagrams we saw how liquid compositions can change as a result of

removing crystals from the liquid as they form. In all cases except a eutectic composition, crystallization results in a change in the composition of the liquid, and if the crystals are removed by some process, then different magma compositions can be generated from the initial parent liquid. If minerals that later react to form a new mineral or solid solution minerals are removed, then crystal fractionation can produce liquid compositions that would not otherwise have been attained by normal crystallization of the parent liquid.

Bowen's Reaction Series

Norman L. Bowen, an experimental petrologist in the early 1900s, realized this from his determinations of simple 2- and 3-component phase diagrams, and proposed that if an initial basaltic magma had crystals removed before they could react with the liquid, that the common suite of rocks from basalt to rhyolite could be produced. This is summarized as Bowen's Reaction Series.



Bowen suggested that the common minerals that crystallize from magmas could be divided into a continuous reaction series and a discontinuous reaction series.

- The continuous reaction series is composed of the plagioclase feldspar solid solution series. A basaltic magma would initially crystallize a Ca- rich plagioclase and upon cooling continually react with the liquid to produce more Na-rich plagioclase. If the early forming plagioclase were removed, then liquid compositions could eventually evolve to those that would crystallize a Na-rich plagioclase, such as a rhyolite liquid.
- The discontinuous reaction series consists of minerals that upon cooling eventually react with the liquid to produce a new phase. Thus, as we have seen, crystallization of

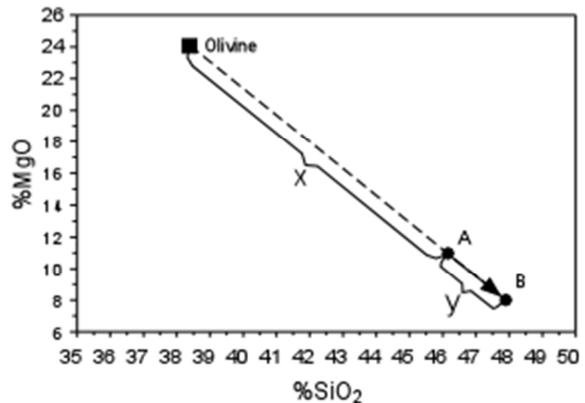
olivine from a basaltic liquid would eventually reach a point where olivine would react with the liquid to produce orthopyroxene. Bowen postulated that with further cooling pyroxene would react with the liquid, which by this time had become more enriched in H₂O, to produce hornblende. The hornblende would eventually react with the liquid to produce biotite. If the earlier crystallizing phases are removed before the reaction can take place, then increasingly more siliceous liquids would be produced.

This generalized idea is consistent with the temperatures observed in magmas and with the mineral assemblages we find in the various rocks. We would expect that with increasing SiO₂ oxides like MgO, and CaO should decrease with higher degrees of crystal fractionation because they enter early crystallizing phases, like olivines and pyroxenes. Oxides like H₂O, K₂O and Na₂O should increase with increasing crystal fractionation because they do not enter early crystallizing phases. Furthermore, we would expect incompatible trace element concentrations to increase with fractionation, and compatible trace element concentrations to decrease. This is generally what is observed in igneous rock suites. Because of this, and the fact that crystal fractionation is easy to envision and somewhat easy to test, crystal fractionation is often implicitly assumed to be the dominant process of magmatic differentiation.

Graphical Representation of Crystal Fractionation

The effects on chemical change of magma (rock) compositions that would be expected from crystal fractionation can be seen by examining some simple variation diagrams.

In a simple case imagine that we have two rocks, A and B, with their SiO₂ and MgO concentrations as shown in the diagram. Also plotted is the analysis of olivine contained in rock A. Removal of olivine from Rock A would drive the liquid composition in a straight line away from A. (This is the same idea we used in phase diagrams). If rock B were produced from rock A by fractionation of olivine, then the composition of rock B should lie on the same line.



This should also be true of all other variation diagrams plotting other oxides against SiO₂. Just like in phase diagrams we can apply the lever rule to determine how much of the olivine had to fractionate from a magma with composition A to produce rock B:

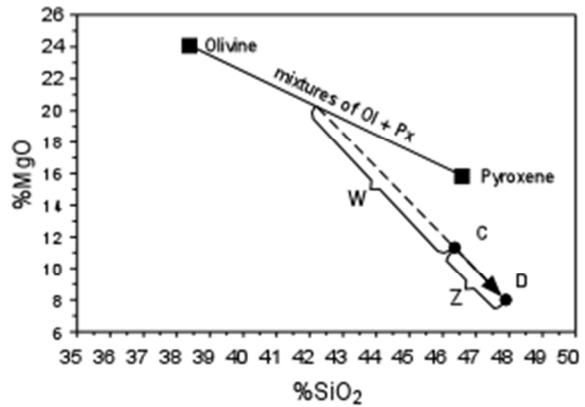
$$\% \text{Olivine Fractionated} = [y/(x + y)] * 100$$

If olivine fractionation were the process responsible for the change from magma A to magma B, then these proportions would have to be the same on all other variation diagrams as well.

In a more complicated case, we next look at what happens if two phases of different composition were involved in the fractionation. Again the rules we apply are the same rules we

used in phase diagrams.

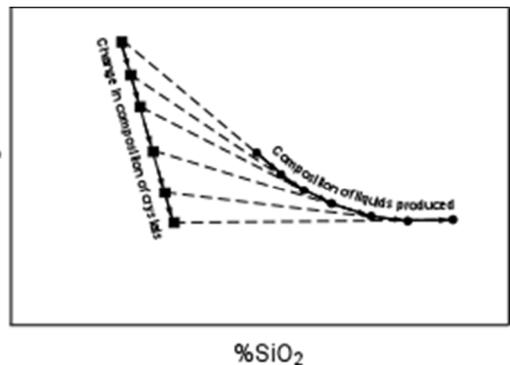
In this case, a mixture of 50% olivine and 50% pyroxene has been removed from magma C to produce magma D. Note that the liquid composition has to change along a line away from the composition of the mixture of solid phases, through the composition of the original liquid (magma C). Again the lever rule would tell us that the percentage of solids fractionated would be:



$$\% \text{solids fractionated} = [z/(w + z)] * 100$$

This works well for small steps in the fractionation sequence. In the real world we find that many minerals expected to crystallize from a magma are solid solutions whose compositions will change as the liquid evolves and temperature drops. We can see how this would affect things with the following example. In this case we look at what happens if an Mg-Fe solid solution mineral is removed as temperature falls.

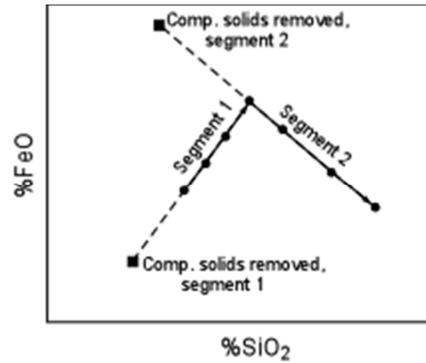
The initial magma has high MgO and low SiO₂. The solid crystallizing from this magma also has high MgO and low SiO₂. Taking the fractionation in small increments, the second magma produced by removing the solids from the original magma will have higher SiO₂ and lower MgO.



But, the second liquid will be crystallizing a solid with lower MgO and higher, SiO₂, so it will evolve along a different path. The net result will be that the variation will show a curved trend on a variation diagram. Thus, a generalization we can make is that in natural magmas we expect the variation to be along smooth curved trends since most of the minerals that crystallize from magmas are solid solutions. Note that different minerals fractionated will produce different trends, but they will still be smooth and curved.

Another complication arises if there is a change in the combination of minerals that are fractionating.

In the example shown a series of magmas are produced along segment 1 by fractionating a combination of solids with low FeO and low SiO₂. The last magma produced along segment 1 of the variation diagram has different mineral phases in equilibrium. These phases (probably including a mineral with high FeO, like magnetite) have a much higher FeO concentration. Removal of these phases from this magma causes the trend of variation to make a sharp bend, and further fractionation causes liquids to evolve along segment 2.

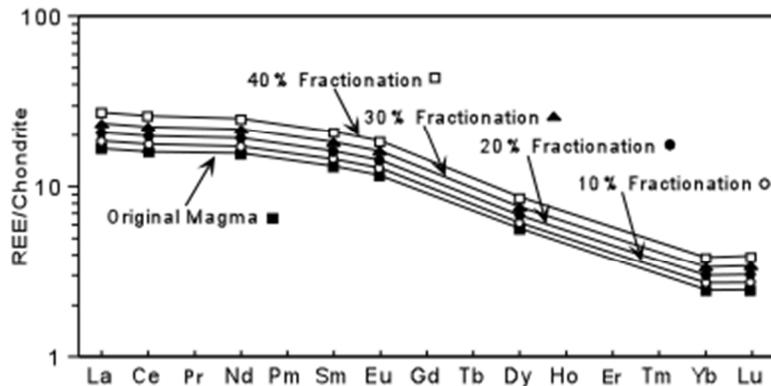


Thus, sudden changes in the trends on variation diagrams could mean that there has been a change in the mineral assemblage being fractionated.

Trace Elements and Crystal Fractionation

As we might expect, elements that are excluded from crystals during fractionation should have their concentrations increase in the fractionated magmas. This is true for trace elements as well. The concentration of incompatible trace elements should thus increase with increasing crystal fractionation, and the concentration of compatible trace elements should decrease with fractionation. To see how this works with incompatible trace elements, we'll look at the REEs. The diagram shows how the REEs behave as calculated from theoretical equations for trace element distribution.

Note that the REE patterns produced by higher percentages of crystal fractionation show higher concentrations, yet the patterns remain nearly parallel to one another. Thus, a suite of rocks formed as a result of crystal fractionation should show nearly parallel trends of REE patterns.

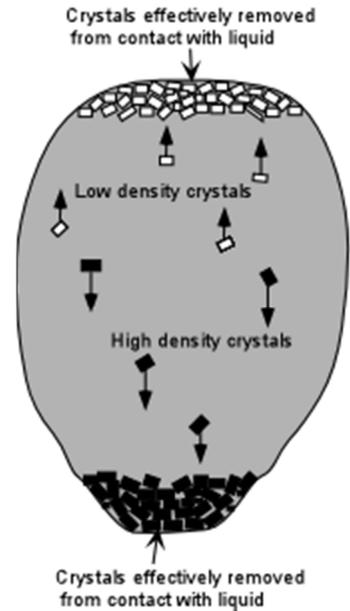


Referring back to our discussion of REEs during partial melting, recall that we said that during crystal fractionation the ratios of incompatible elements show little change, and that we can use this factor to distinguish between crystal fractionation and partial melting.

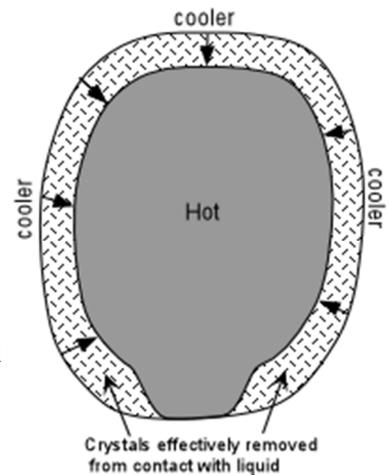
Mechanisms of Crystal Fractionation

In order for crystal fractionation to operate there must be a natural mechanism that can remove crystals from the magma or at least separate the crystals so that they can no longer react with the liquid. Several mechanisms could operate in nature.

- Crystal Settling/Floating - In general, crystals forming from a magma will have different densities than the liquid.
 - If the crystals have a higher density than the liquid, they will tend to sink or settle to the floor of the magma body. The first layer that settles will still be in contact with the magma, but will later become buried by later settling crystals so that they are effectively removed from the liquid.
 - If the crystals have a lower density in the magma, they will tend to float or rise upward through the magma. Again the first layer that accumulates at the top of the magma body will initially be in contact with the liquid, but as more crystals float to the top and accumulate, the earlier formed layers will be effectively removed from contact with the liquid.



- Inward Crystallization - Because a magma body is hot and the country rock which surrounds it is expected to be much cooler, heat will move outward away from the magma. Thus, the walls of the magma body will be coolest, and crystallization would be expected to take place first in this cooler portion of the magma near the walls. The magma would then be expected to crystallize from the walls inward. Just like in the example above, the first layer of crystals precipitated will still be in contact with the liquid, but will eventually become buried by later crystals and effectively be removed from contact with the liquid.



- Filter pressing - this mechanism has been proposed as a way to separate a liquid from a crystal-liquid mush. In such a situation where there is a high concentration of crystals the liquid could be forced out of the spaces between crystals by some kind of tectonic squeezing that moves the liquid into a fracture or other free space, leaving the crystals behind. It would be kind of like squeezing the water out of a sponge. This mechanism is difficult to envision taking place in nature because (1) unlike a sponge the matrix of crystals is brittle and will not deform easily to squeeze the liquid out, and (2) the fractures required for the liquid to move into are generally formed by extensional forces and the mechanism to get the liquid into the fractures involves compressional forces. Filter pressing is a common method used to separate crystals from liquid in industrial processes, but has not been shown to have occurred in nature.

Magma Mixing

If two or more magmas with different chemical compositions come in contact with one another beneath the surface of the Earth, then it is possible that they could mix with each other to produce compositions intermediate between the end members. If the compositions of the magmas are greatly different (i.e. basalt and rhyolite), there are several factors that would tend to inhibit mixing.

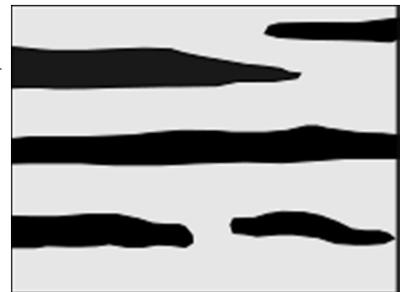
- Temperature contrast - basaltic and rhyolitic magmas have very different temperatures. If they come in contact with one another the basaltic magma would tend to cool or even crystallize and the rhyolitic magma would tend to heat up and begin to dissolve any crystals that it had precipitated.
- Density Contrast- basaltic magmas have densities on the order of 2600 to 2700 kg/m³, whereas rhyolitic magmas have densities of 2300 to 2500 kg/m³. This contrast in density would mean that the lighter rhyolitic magmas would tend to float on the heavier basaltic magma and inhibit mixing.
- Viscosity Contrast- basaltic magmas and rhyolitic magmas would have very different viscosities. Thus, some kind of vigorous stirring would be necessary to get the magmas to mix.

Despite these inhibiting factors, there is evidence in rocks that magmas do sometimes mix. The smaller the difference in chemical composition between two magmas, the smaller will be the contrasts in temperature, density, and viscosity.

If magmas of contrasting composition come in contact and begin to mix some kind of stirring mechanism would first be necessary. Such stirring could be provided by convection, with the hotter magma rising through the cooler magma.

Evidence for Mixing

- **Mingling of magmas.** If, in the initially stages of such mixing, the magma were erupted, then we might expect to find rocks that show a "marble cake" appearance, with dark colored mafic rock intermingled with lighter colored rhyolitic rock. This, however, is mingling of magmas. Note that differences in color are not always due to differences in composition, so even in rocks that show this banding, mingling of magmas may not have occurred.

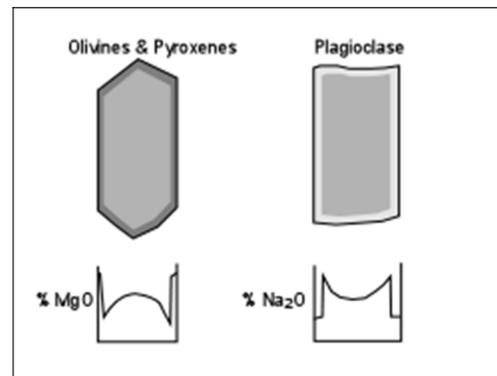


- **Disequilibrium Mineral Assemblages.** If convective stirring progresses beyond the point of mingling, some evidence might still be preserved if the crystals present in one of the magmas does not completely dissolve or react. This might leave disequilibrium mineral assemblages. For example, if a basaltic magma containing Mg-rich olivine mixed with a rhyolite magma containing quartz, and the magma was erupted before the quartz or olivine could be redissolved or made over into another mineral, then we would

produce a rock containing mineral that are out of equilibrium.

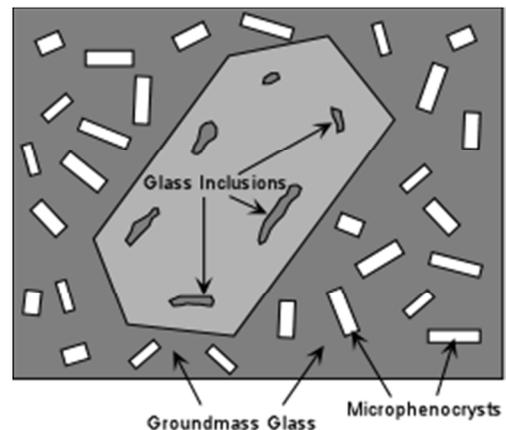
- **Reverse Zoning in Minerals.** When a mineral is placed in an environment different than the one in which it originally formed, it will tend to react to retain equilibrium. Instead of dissolving completely or remaking their entire composition, solid solution minerals may just start precipitating a new composition that is stable in the new chemical environment or at the new temperature. This can result in zoned crystals that show reversals of the zoning trends. For Example:

Mg-Fe solid solution minerals normally zone from Mg-rich cores to Fe-rich rims. If a Fe-rich olivine or pyroxene is mixed into a Mg-rich magma that is precipitating Mg-rich olivine or pyroxene, it may precipitate the more Mg-rich composition on the rims of the added crystals. Analyses of such crystals would reveal a reversal in zoning. Similarly, if a Na-rich plagioclase originally crystallizing from a rhyolitic magma were mixed into a basaltic magma precipitating a Ca-rich plagioclase, a Ca-rich rim may be added to the Na-rich plagioclase.



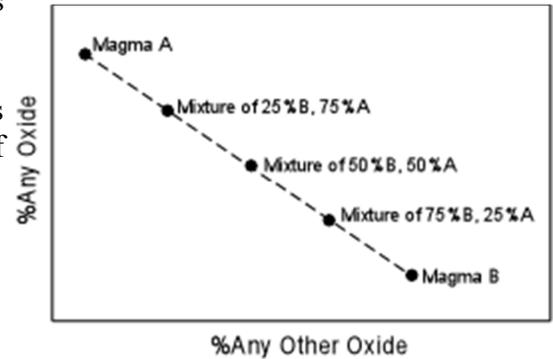
- **Glass Inclusions.** Crystal growth from liquids is sometimes not perfect. Sometimes the crystal grows incompletely trapping liquid inside. If that liquid is quenched on the surface and a thin section is cut through the crystal this trapped liquid will be revealed as glass inclusions in the crystal.

Since the glass inclusions should represent the composition of the magma that precipitated the crystal, chemical analysis of glass inclusions give us the composition of the liquid in which the crystal formed. The groundmass may also contain glass representing the composition of the liquid in which the crystal resided at eruption. If the composition of glass inclusions is different from glass in the groundmass, and if the groundmass composition is not what is expected from normal crystallization of the



minerals present, this provides evidence of magma mixing.

- **Chemical Evidence.** If the mixing process proceeds to the point where other evidence is erased, evidence for mixing will still be preserved in the composition of the mixed magmas. On oxide-oxide variation diagrams mixtures will lie along a straight line. Thus if diagrams show a group of rocks that lie along the same straight line, and the proportional distances are the same on all diagrams, one could hypothesize that the chemical variation resulted from magma mixing.



Crustal Assimilation/Contamination

Because the composition of the crust is generally different from the composition of magmas which must pass through the crust to reach the surface, there is always the possibility that reactions between the crust and the magma could take place. If crustal rocks are picked up, incorporated into the magma, and dissolved to become part of the magma, we say that the crustal rocks have been assimilated by the magma. If the magma absorbs part of the rock through which it passes we say that the magma has become contaminated by the crust. Either of these processes would produce a change in the chemical composition of the magma unless the material being added has the same chemical composition as the magma.

In a sense, bulk assimilation would produce some of the same effects as mixing, but it is more complicated than mixing because of the heat balance involved. In order to assimilate the country rock enough heat must be provided to first raise the country rock to its solidus temperature where it will begin to melt and then further heat must be added to change from the solid state to the liquid state. The only source of this heat, of course, is the magma itself.

Let's imagine a simple case of a pure mineral making up the country rock that is to be assimilated. In order to raise the temperature of the country rock from its initial temperature, T_i , to its melting temperature, T_m , heat must be provided. The amount of heat required is determined by the heat capacity of the rock, C_p (the p subscript stands for constant pressure).

$$dH/dT = C_p \text{ or}$$

$$\Delta H = C_p (T_m - T_i)$$

Once the temperature has risen to T_m , further heat must be added to melt the rock. This heat is known as the heat of melting, ΔH_m , also sometimes called the latent heat of fusion.

As stated above the heat required for this process must be supplied by the magma. In our example we'll take a simple case where the magma has a eutectic composition and therefore melts at a single temperature. This time we'll assume that the magma is at a temperature, T_L , somewhat above its melting Temperature, T_m .

In order to provide the heat for assimilation it would first have to cool. The amount of heat it would give up would then be:

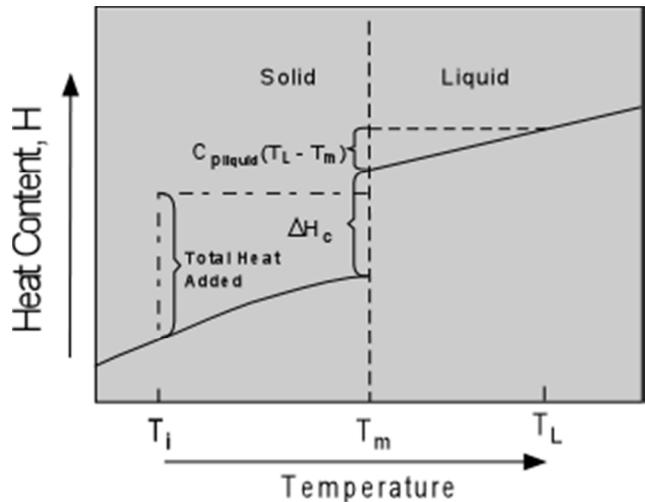
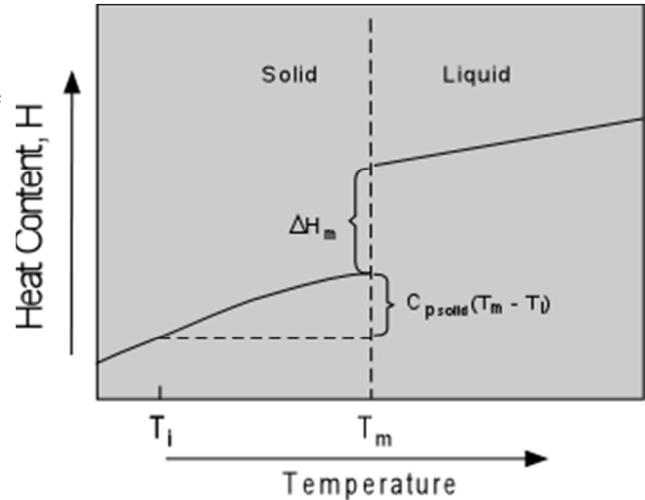
$$\Delta H = C_{p\text{Liquid}} (T_m - T_i)$$

Once it reached T_m the only other source of heat must be provided by crystallization to release the latent heat of

crystallization, ΔH_c . Note that in the case shown here, the total heat released by the magma in cooling to T_m and crystallizing is still not enough to melt the country rock.

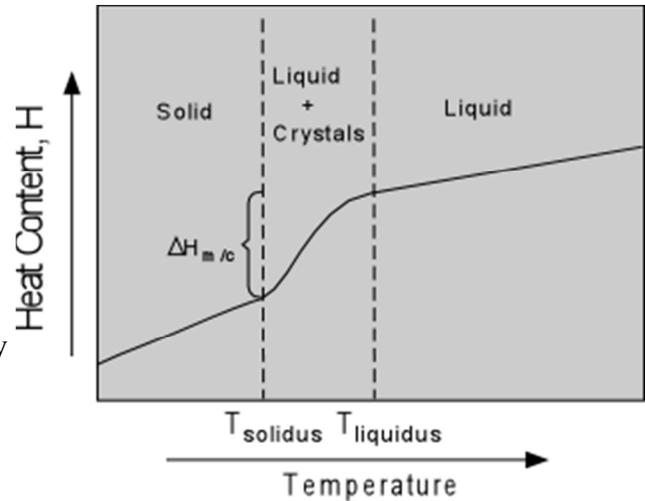
Furthermore, in this process the magma has completely crystallized, so assimilation cannot take place. There are two ways to overcome this problem: (1) If the initial temperature of the magma were much higher, then it could provide the heat by simply cooling to its melting temperature. This is unrealistic, however, because magmas are probably relatively close to or below their liquidus temperature after having passed through cooler country rocks. (2) If the country rock had an initial temperature closer to its melting temperature, less heat would have to be provided by the magma. This could happen if there were successive batches of magma passing through and releasing heat into the country rock.

Nevertheless, this heat budget analysis illustrates the difficulty involved in bulk assimilation of



country rock by magmas, and makes the process less attractive as a process to explain the chemical diversity of a suite of rocks. Note also that the heat budget will still likely involve crystallizing some of the magma, so if assimilation takes place it will likely involve a combined process of crystal fractionation and assimilation.

In a more realistic natural situation things will be slightly different because both the country rock and the magma will melt/crystallize over a range of temperatures, rather than at a single temperature. Even still, the amount of heat required to melt the rock must be provided over a relatively narrow range of temperature. But, partial assimilation of the country rock would be possible because the country rock would only have to be partially melted to produce a liquid that could mix with the magma. In this case we would say that the magma has been contaminated by the country rock.



Evidence for Assimilation/Contamination

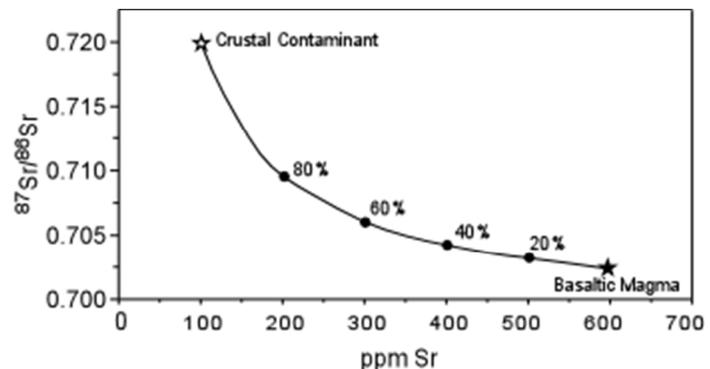
As magma passes upward through the crust pieces of the country rock through which it passes may be broken off and assimilated by the magma. Just as in magma mixing, various stages of this process may be preserved in the magma and rock that results. Xenoliths (meaning foreign rock) are pieces of rock sometimes found as inclusions in other rocks. The presence of xenoliths does not always indicate that assimilation has taken place, but if the xenoliths show evidence of having been disaggregated with their minerals distributed throughout the rest of the rock it is likely that some contamination of the magma has taken place. This may result in disequilibrium mineral assemblages and reversely zoned minerals, just as in the case of magma mixing. And, if the assimilation goes to completion, with all of the xenoliths being dissolved in the magma, the only evidence left may be chemical, and again similar to the straight line mixing patterns produced by mixing.

Perhaps the best evidence of assimilation/contamination comes from studies of radiogenic isotopes. Here we give an example using the systematics of the Rb - Sr system.

- ^{87}Rb is a radioactive isotope that decays to ^{87}Sr with a half life of 47 billion years.
- Because Rb is an incompatible element, it has been extracted from the mantle by magmas and added to the crust. Thus the concentration of Rb in the crust (avg. about 100 ppm) is much higher than it is in the mantle (avg. about 4 ppm).

- ^{86}Sr is a stable, non radiogenic isotope whose concentration does not change with time.
- Because ^{87}Rb decays to produce ^{87}Sr and because there is more Rb in the crust than in the mantle, the $^{87}\text{Sr}/^{86}\text{Sr}$ of the crust has, over time, changed to much higher values than the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in the mantle.
- The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the mantle is generally in the range between 0.702 - 0.705. Thus, rocks derived from melting of the mantle should have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in this range.
- $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of crustal rocks will depend on their age and concentration of Rb. Older crustal rocks will have high values of $^{87}\text{Sr}/^{86}\text{Sr}$ in the range 0.705 - 0.720, younger crustal rocks having been recently derived from the mantle will $^{87}\text{Sr}/^{86}\text{Sr}$ ratios more similar to the mantle.
- If mantle derived magmas assimilate or are contaminated by older crustal rocks, then we would expect to find ratios of $^{87}\text{Sr}/^{86}\text{Sr}$ in these contaminated rocks that are higher than those found in the mantle and extend up to values found in older crustal rocks.

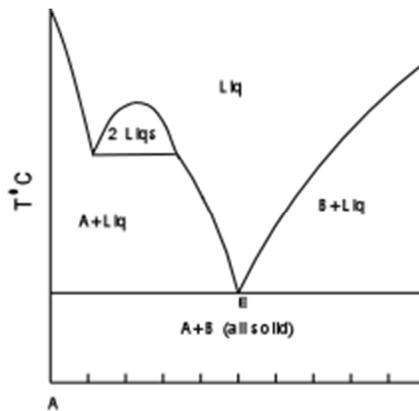
- For a suite of rocks affected by contamination, $^{87}\text{Sr}/^{86}\text{Sr}$ ratio plotted against Sr concentration would plot along a hyperbolic mixing curve. Note that magma mixing could produce similar trends if the two end member have different concentrations of Sr and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. Crystal fractionation, on the other hand does not change radiogenic isotopic ratios.



Liquid Immiscibility

Liquid immiscibility is where liquids do not mix with each other. We are all familiar with this phenomenon in the case of oil and water/vinegar in salad dressing. We have also discussed immiscibility in solids, for example in the alkali feldspar system. Just like in the alkali feldspar system, immiscibility is temperature dependent.

For example, in a two component system if there is a field of immiscibility it would appear as in the diagram shown here. Cooling of a liquid with a composition of 25%B & 75%A would eventually result in the liquid separating into two different compositions. With further cooling one liquid would become more enriched in A and the other more enriched in B. Eventually both liquids would reach a temperature where crystals of A would start to form. Note that both liquids would be in equilibrium with crystals of A at the same temperature. Further cooling would result in the disappearance of the A-rich liquid.



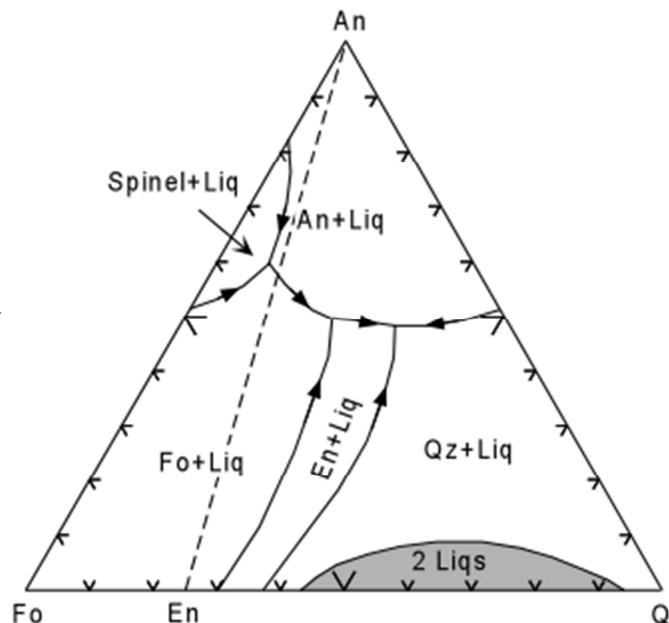
This points out two important properties of immiscible liquids.

1. If immiscible liquids are in equilibrium with solids, both liquids must be in equilibrium with the same solid compositions.
2. Extreme compositions of the two the liquids will exist at the same temperature.

Liquid immiscibility was once thought to be a mechanism to explain all magmatic differentiation. If so, requirement 2, above, would require that siliceous liquids and mafic liquids should form at the same temperature. Since basaltic magmas are generally much hotter than rhyolitic magmas, liquid immiscibility is not looked upon favorably as an explanation for wide diversity of magmatic compositions. Still, liquid immiscibility is observed in experiments conducted on simple rock systems.

For example, in the system Fo-An-Qz a field of immiscible liquids is observed for compositions rich in SiO₂. But these compositions are outside of the range of compositions that occur in nature. This is true of almost all simple systems wherein liquid immiscibility has been observed. There are however, three exceptions where liquid immiscibility may play a role.

1. Sulfide liquids may separate from mafic silicate magmas.



2. Highly alkaline magmas rich in CO_2 may separate into two liquids, one rich in carbonate, and the other rich in silica and alkalis. This process may be responsible for forming the rare carbonatite magmas
3. Very Fe-rich basaltic magmas may form two separate liquids - one felsic and rich in SiO_2 , and the other mafic and rich in FeO .

Combined Processes

As pointed out previously, if any of these processes are possible, then a combination of the processes could act to produce chemical change in magmas. Thus, although crystal fractionation seems to be the dominant process affecting magmatic differentiation, it may not be the only processes. As we have seen, assimilation is likely to be accompanied by crystallization of magmas in order to provide the heat necessary for assimilation. If this occurs then a combination of crystal fractionation and assimilation could occur. Similarly, magmas could mix and crystallize at the same time resulting in a combination of magma mixing and crystal fractionation. In nature, things could be quite complicated.