EENS 2120	Petrology
Tulane University	Prof. Stephen A. Nelson
Structure of the Earth and the Origin of Magmas	

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Magmas do not form everywhere beneath the surface of the Earth. This is evident from looking at the world distribution of volcanoes. Thus, magmas must require special circumstances in order to form. Before we talk about how and where magmas form, we first look at the interior structure of the Earth.

The Earth's Internal Structure

Evidence from seismology tells us that the Earth has a layered structure. Seismic waves generated by earthquakes travel through the Earth with velocities that depend on the type of wave and the physical properties of the material through which the waves travel.

Types of Seismic Waves

- ***Body Waves*** - travel in all directions through the body of the Earth. There are two types of body waves:
  - ***P - waves*** - are Primary waves. They travel with a velocity that depends on the elastic properties of the rock through which they travel.

    $$V_p = \sqrt{[(K + 4/3\mu)/\rho]}$$

    Where, V_p is the velocity of the P-wave, K is the incompressibility of the material, μ is the rigidity of the material, and ρ is the density of the material.

    P-waves are the same thing as sound waves. They move through the material by compressing it, but after it has been compressed it expands, so that the wave moves by compressing and expanding the material as it travels. Thus the velocity of the P-wave depends on how easily the material can be compressed (the incompressibility), how rigid the material is (the rigidity), and the density of the material. P-waves have the highest velocity of all seismic waves and thus will reach all seismographs first.

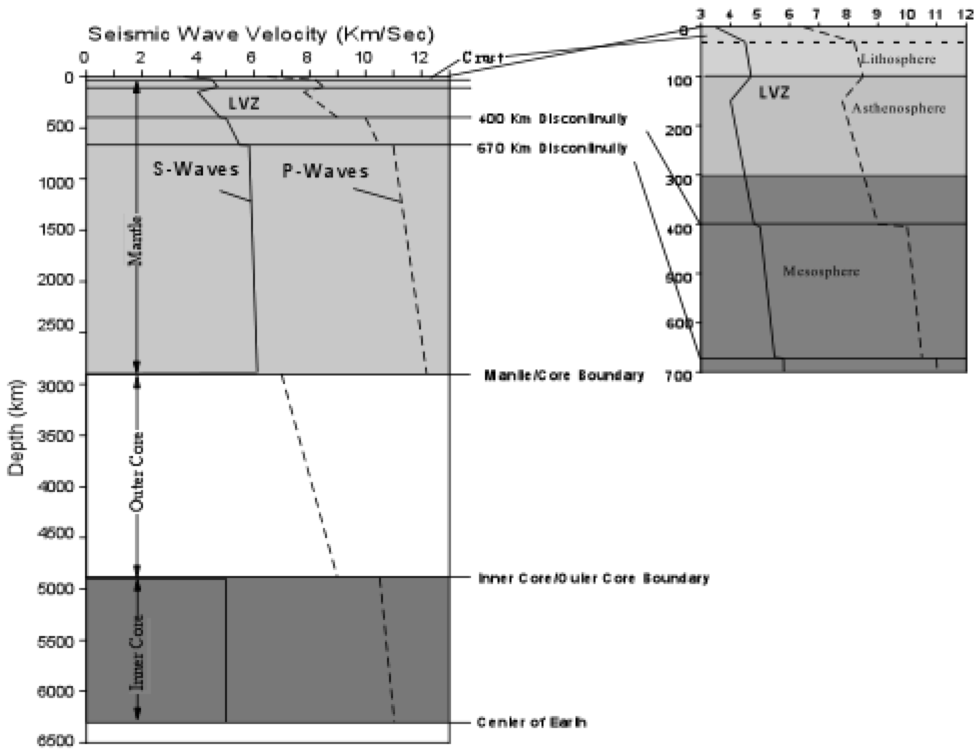
  - ***S-Waves*** - Secondary waves, also called shear waves, travel with a velocity that depends only on the rigidity and density of the material through which they travel:

    $$V_p = \sqrt{[(\mu)/\rho]}$$

    S-waves travel through material by shearing it or changing its shape in the direction perpendicular to the direction of travel. The resistance to shearing of a material is the property called the rigidity. It is notable that liquids have no rigidity, so that the velocity of an S-wave is zero in a liquid. (This point will become important later). Note that S-waves travel slower than P-waves, so they will reach a seismograph after the P-wave.

- ***Surface Waves*** - Surface waves differ from body waves in that they do not travel through the Earth, but instead travel along paths nearly parallel to the surface of the Earth. Surface waves behave like S-waves in that they cause up and down and side to side movement as they pass, but they travel slower than S-waves and do not travel through the body of the Earth. Thus they can give us information about the properties of rocks near the surface, but not about the properties of the Earth deep in the interior.

  Because seismic waves reflect from and refract through boundaries where there is sudden change in the physical properties of the rock, by tracing the waves we can see different layers in the Earth. This allows us to look at the structure of the Earth based on layers of differing physical properties. Note that we know that density must increase with depth in the Earth because the density of crustal rocks are about 2,700 kg/m^3 and the average density of the Earth is about 5,200 kg/m^3. Also note from the velocity equations that if density increases, wave velocity decreases. Thus, the other properties, incompressibility and rigidity must increase with depth in the Earth at a greater rate than density increases.



Once we know the seismic wave velocities throughout the Earth, then we can perform experiments on different possible materials and make estimates of what the chemical composition. Thus, we can also divide the Earth into layers of differing chemical composition.

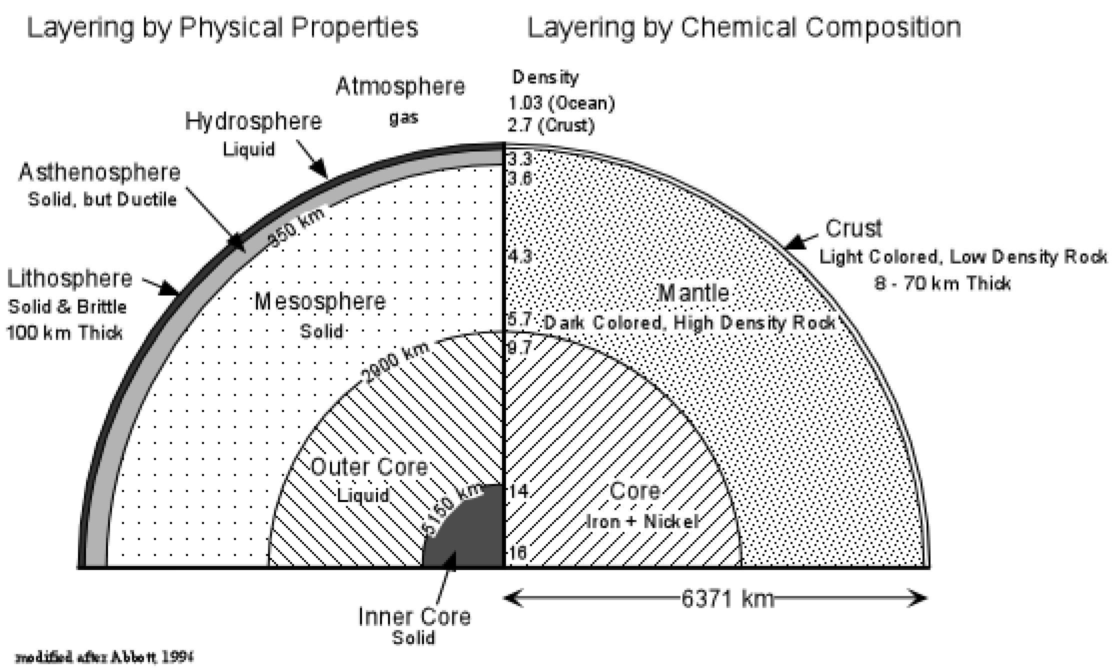
Layers of Differing Chemical Composition

- ***Crust -*** variable thickness and composition
  - Continental 10 - 70 km thick, underlies all continental areas, has an average composition that is andesitic.
  - Oceanic 8 - 10 km thick, underlies all ocean basins, has an average composition that is basaltic

- Mantle - 3488 km thick, made up of a rock called peridotite (Olivine + Opx + Cpx). Evidence comes from Seismic wave velocities, experiments, and peridotite ***xenoliths*** (foreign rocks) brought to the surface by magmas. Experimental evidence suggests that the mineralogy of peridotite changes with depth (ant thus pressure) in the Earth. At low pressure, the mineral assemblage is Olivine + Cpx + Opx + Plagioclase (plagioclase peridotite). At higher pressure the assemblage changes to Olivine + Cpx + Opx + Spinel [(Mg,Fe^{+2}) (Cr, Al, $Fe^{+3})_2O_4$] (spinel peridotite). At pressures above about 30 kilobars, the assemblage changes to Olivine + Cpx + Opx + garnet (garnet peridotite). This occurs because Al changes its coordination with increasing pressure, and thus new minerals must form to accommodate the Al.

  At greater depths, such as the 400 km discontinuity and the 670 km discontinuity, olivine and pyroxene likely change to high pressure polymorphs. Despite these changes in mineral assemblage, the chemical composition of the mantle does not appear to change much in terms of its major element composition.

- ***Core*** - 2883 km radius, made up of Iron (Fe) and small amount of Nickel (Ni). Evidence comes from seismic wave velocities, experiments, and the composition of iron meteorites, thought to be remnants of other differentiated planets that were broken apart due to collisions.



Layers of Differing Physical Properties

Lithosphere - about 100 km thick (up to 200 km thick beneath continents, thinner beneath oceanic ridges and rift valleys), very brittle, easily fractures at low temperature. ***Note that the lithosphere is comprised of both crust and part of the upper mantle.*** The plates that we talk about in plate tectonics are made up of the lithosphere, and appear to float on the underlying asthenosphere.

Asthenosphere - about 250 km thick - solid rock, but soft and flows easily (ductile).

The top of the asthenosphere is called the ***Low Velocity Zone (LVZ)*** because the velocities of both P- and S-waves are lower than the in the lithosphere above. But, not that neither P- nor S-wave velocities go to zero, so the LVZ is not completely liquid.
Mesosphere - about 2500 km thick, solid rock, but still capable of flowing.

Outer Core - 2250 km thick - liquid. We know this because S-wave velocities are zero in the outer core. If $V_s = 0$, this implies $\mu = 0$, and this implies that the material is in a liquid state.

Inner core - 1230 km radius, solid

Where do Magmas Come From?

Magmas are **not likely** to come from the only part of the Earth that is in a liquid state, the outer core, because it does not have the right chemical composition. The outer core is made mostly of Fe with some Ni, magmas are silicate liquids.

In the ocean basins, magmas are not likely to come from melting of the oceanic crust, since most magmas erupted in the ocean basins are basaltic. To produce basaltic magmas by melting of the basaltic oceanic crust would require nearly 100% melting, which is not likely.

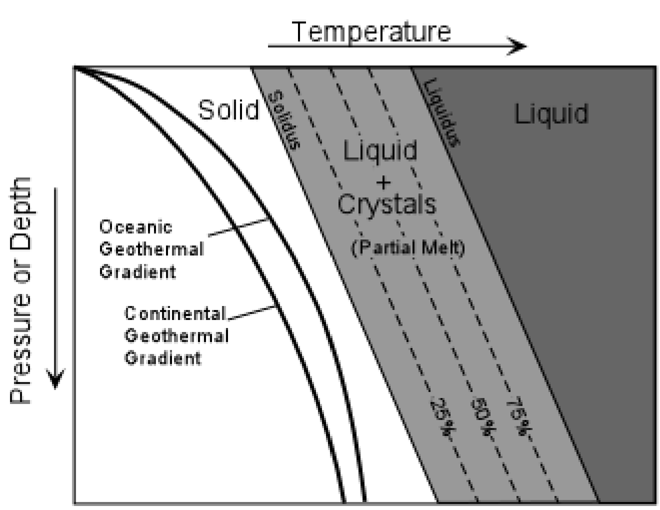
In the continents, both basaltic and rhyolitic magmas are erupted and intruded. Basaltic magmas are not likely to have come from the continental crust, since the average composition is more siliceous, but more siliceous magmas (andesitic - rhyolitic) could come from melting of the continental crust. Basaltic magmas must come from the underlying mantle.

Thus, with the exception of the continents, magmas are most likely to originate in the mantle from melting of mantle peridotite.

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.

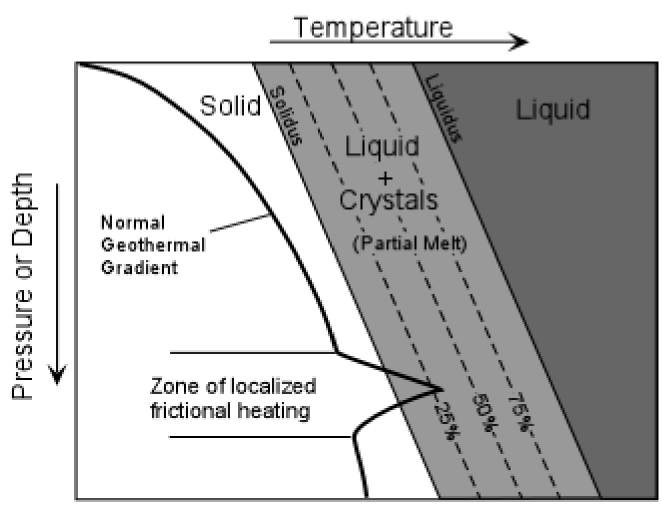


Thus, in order to generate a melt, either we must find a way to increase the geothermal gradient so that it is above the peridotite solidus or reduce the temperature of the peridotite solidus. In either case note that all we have to do is get the temperature in some part of the Earth, as expressed by 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

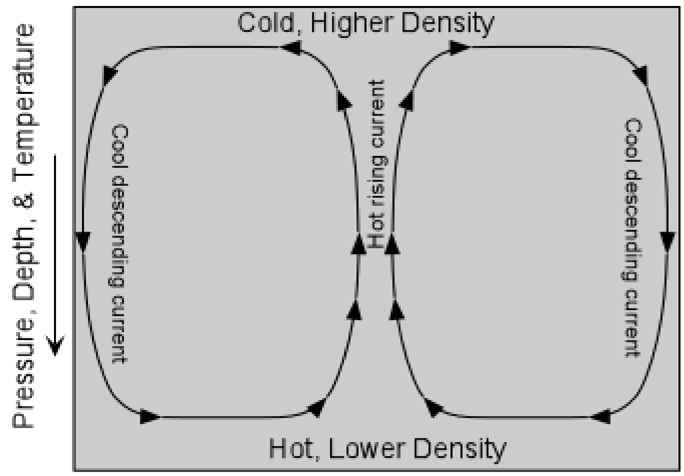
- **Radioactive Heat -** Elements like U, Th, K, and Rb have radioactive isotopes. During radioactive decay, sub-atomic particles are released by the decaying isotope and move outward until they collide with other atomic particles. Upon collision, the kinetic energy of the moving particles is converted 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.

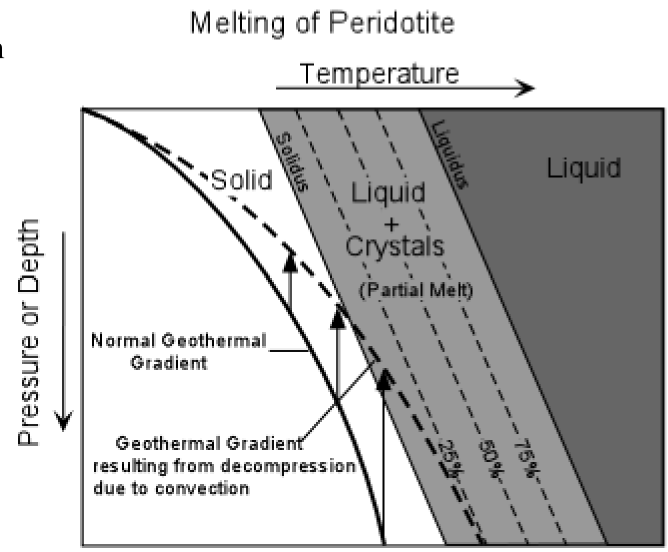
- **Frictional Heat -** In areas where rocks slide past one another, such as at the base of the lithosphere, on at subduction zones, heat could be generated by friction. If this heat cannot be conducted away fast enough, then it may cause a localized rise in temperature within the zone where the sliding 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***.

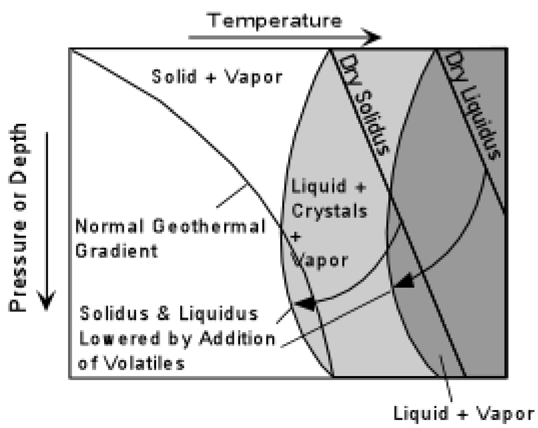
It's difficult to imagine how solid components could be added to the mantle. But volatile components, for example H_2O and CO_2, because of their high mobility, could be added to the mantle, particularly at subduction zones.

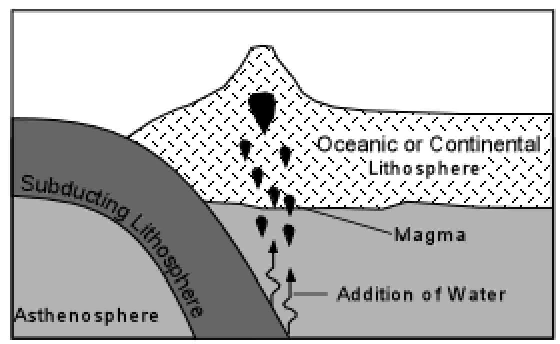
- Oceanic crust is in contact with sea water, thus water could be in oceanic crust both due to weathering, which produces hydrous minerals like clay minerals, and could be in the pore spaces in the rock.
- Oceanic sediments eventually cover the basaltic oceanic crust produced at oceanic

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 H_2O and CO_2 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

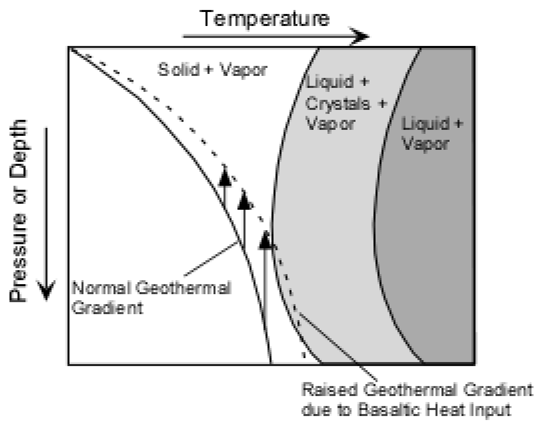
In the continental crust, it is not expected that the normal geothermal gradient will be high enough to cause melting despite the fact that hydrous and carbonate minerals occur in many continental rocks. Furthermore, because continental rocks are at low temperature and have a very high viscosity, convective 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.

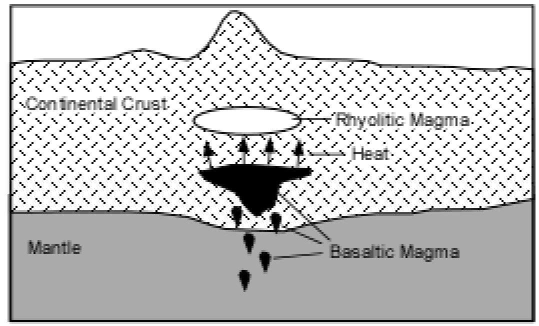
- Basaltic magmas, generated in the mantle, by flux melting, decompression melting or frictional heat, rise into the crust, carrying heat with them.

- 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).

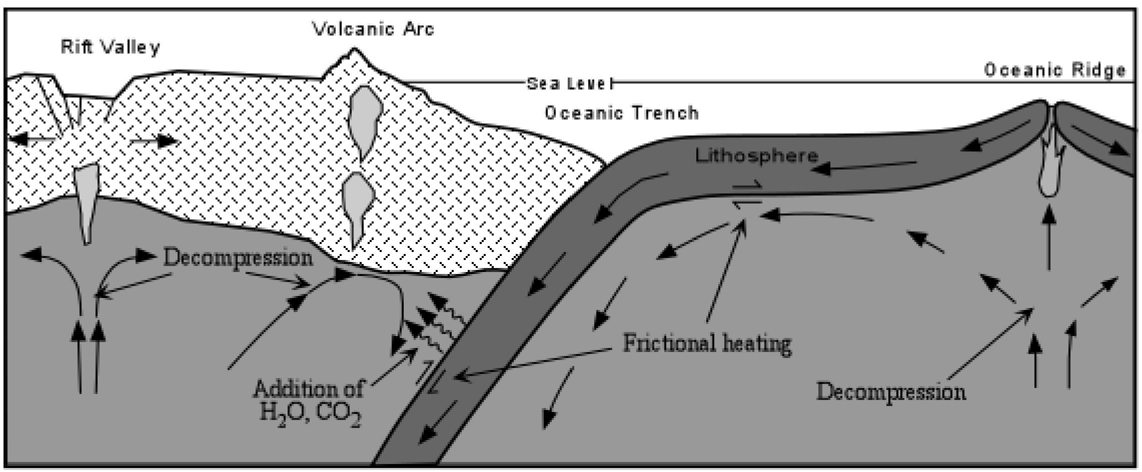
- Successive intrusions of mantle-derived mantle into the same area of the crust may cause further increases in temperature, and eventually cause the geothermal gradient to become higher than the wet solidus of the crustal material, resulting in a partial melt of the crust.





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.

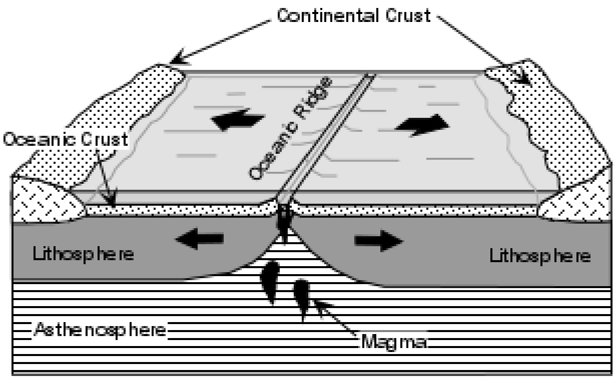


Diverging Plate Boundaries

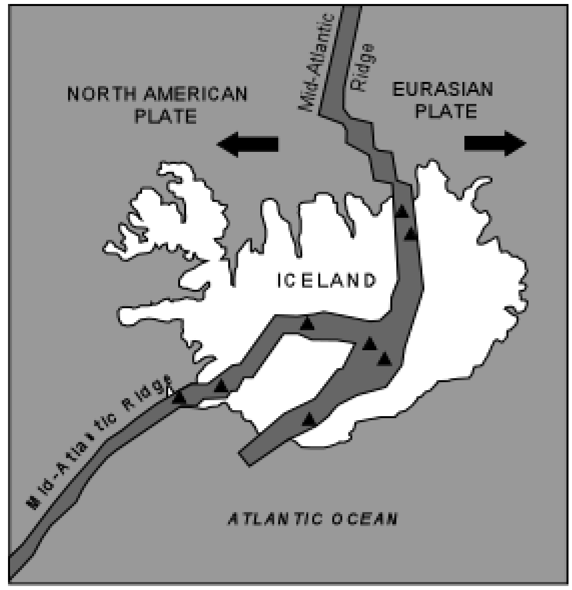
Diverging plate boundaries are where plates move away from each other. These include oceanic ridges or spreading centers, and rift valleys.

- 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.

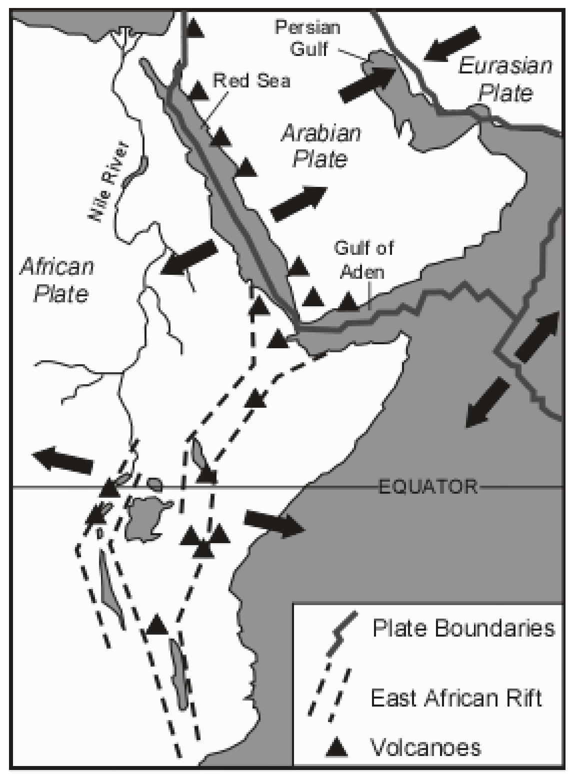
  Iceland is one of the few areas where the resulting magmatism has been voluminous enough to built the oceanic ridge above sea level.



Diverging Plate Boundary
Oceanic Ridge - Spreading Center



- 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).

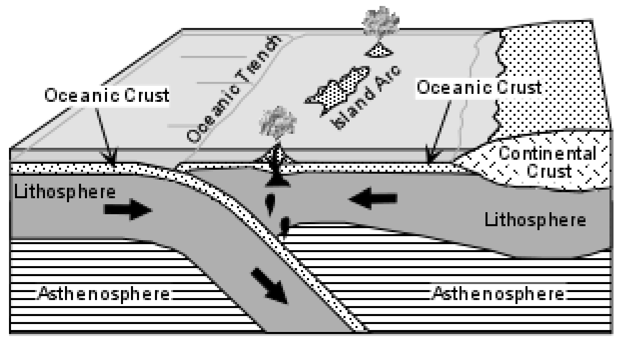
1. Frictional heating is likely to occur along the boundary between the subducted plate and

the overlying mantle wedge.

2. 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.

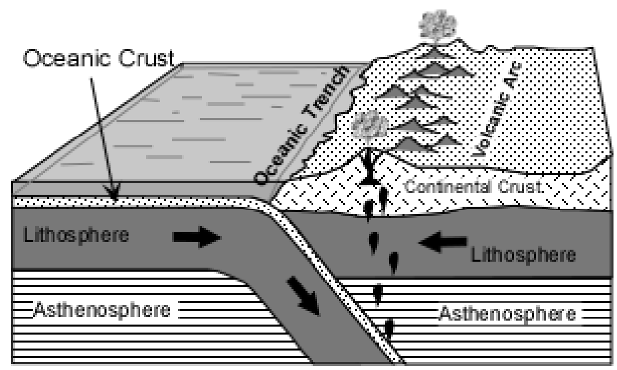
3. The process of subduction may drag the overlying mantle wedge down with it. In order to replace the mantle dragged down in this process, part of the mantle wedge will have to rise. This upwelling of the mantle could result in decompression melting.

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



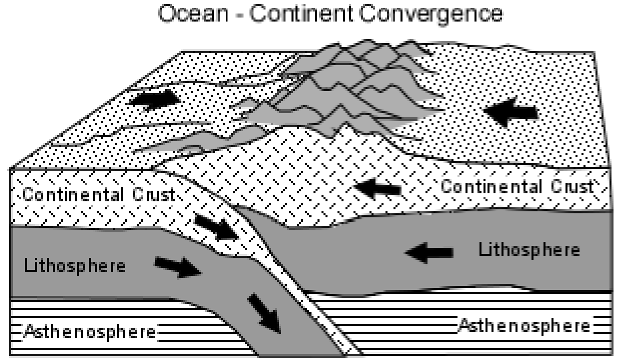
Ocean - Ocean Convergence

- 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.



Ocean - Continent Convergence

- 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.

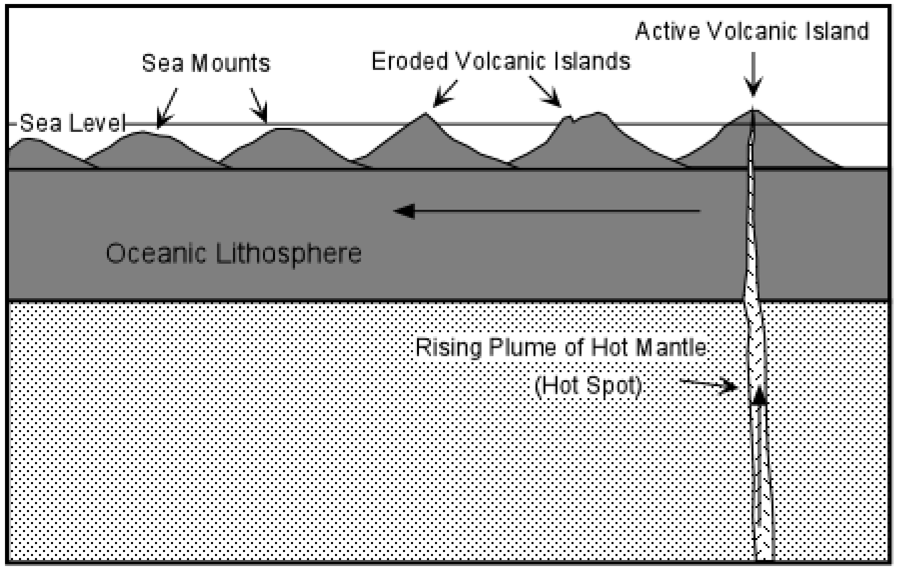


Continent- Continent Convergence

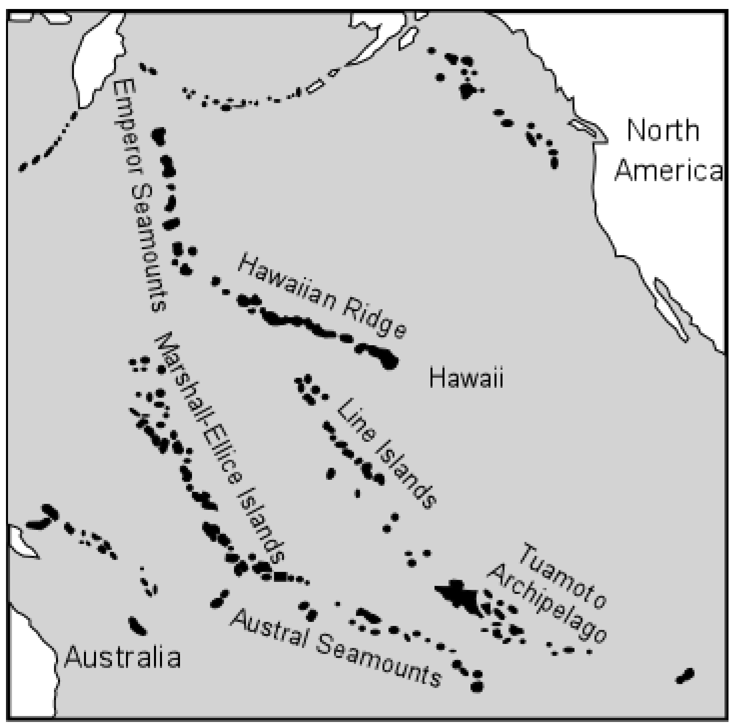
Intraplate Magmatism & Hot Spots

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.



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

1. What are the main layers in the earth in terms of (a) chemical composition and (b) physical properties?

2. Define the following; (a) Low Velocity Zone. (b) geothermal gradient (c) decompression melting, (d) flux melting, (e) crustal anatexis

3. What could cause melting to occur in each of the following tectonic settings (for each setting give all possible mechanisms? (a) divergeing plate boundary, (b) island arc or continental margin arc, (c) continental rift valley, (d) intraplate ocieanic island

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