Igneous Rocks Lectures

introduction :

Igneous rock (derived from the Latin word ignis meaning fire) is one of the three main rock types, the others being sedimentary and metamorphic. Igneous rock is formed through the cooling and solidification of magma or lava. Igneous rock may form with or without crystallization, either below the surface as intrusive (plutonic) rocks or on the surface as extrusive (volcanic) rocks. This magma can be derived from partial melts of existing rocks in either a planet's mantle or crust. Typically, the melting is caused by one or more of three processes: an increase in temperature, a decrease in pressure, or a change in composition.

Magma definition:

Magma is molten rock that flow within the Earth. It may be completely liquid or, more commonly, a fluid mixture of liquid, solid crystals, and dissolved gases. When magma reaches the Earth's surface, we call it lava, or molten rock that flows above ground.

Magma forms when underground temperatures become high enough to beak the bonds in some in some minerals, causing the rocks containing those minerals to partially melt. The rock then changes from a crystalline solid to fluid mix containing freely moving ions and atoms as well as some sill-solid crystalline fragments. Different minerals melt out of the rock at different temperature as the heat gradually increases, with the minerals having the highest melting points remaining the longest as solid fragments. At the same time, the composition of the magma changes as each newly molten mineral enters and enriches it.

When heat dissipates from magma, its bonds no longer break and new bonds start to form, some of the free atoms and ions in the liquid bond to

form tiny crystals. Next, additional ions and atoms bond at prescribed sites in the crystal structure. The crystals grow until they touch the edges of adjacent crystal. As cooling progresses, different minerals crystallize from the mama, again changing the magma's composition. If cooling continues long enough, the entire body of magma will become solidified as igneous rock.

A Glimpse of the earth's interior

As the earth become differentiated into its major concentric Layers (Fig.1), some upwelling material reached the surface, where it cooled and solidified to form the Earth's earliest crust. Among these low density substances were oxygen and silicon, which combined to form the silicate minerals that abound in the Earth's crust and upper mantle. Some heat-producing radioactive substances, such as uranium and

thorium, also moved toward the surface; because of the heat radiating from these elements, crustal rocks are repeatedly re melted and re-formed into a wide

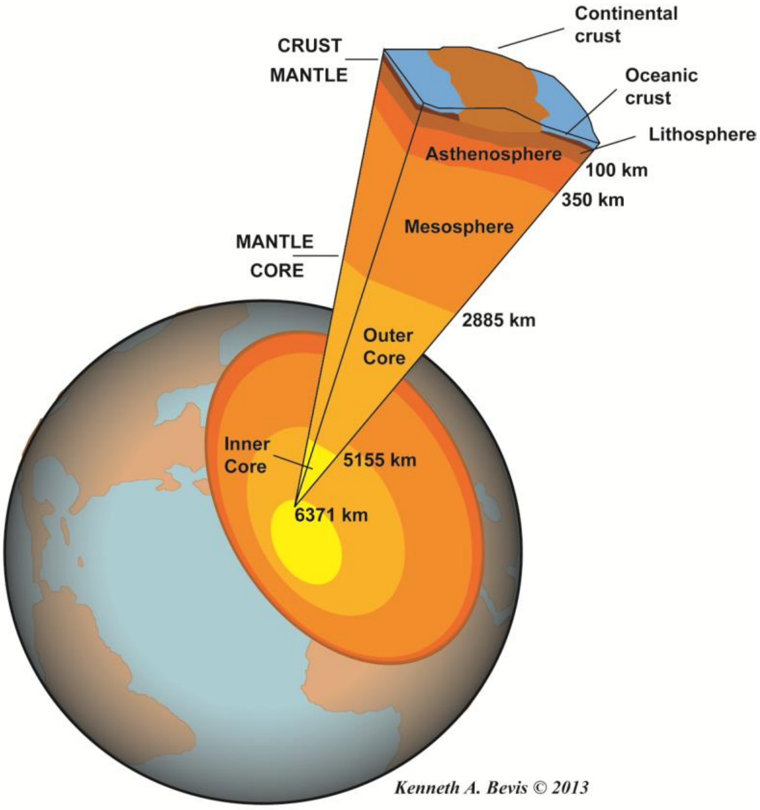


Fig. 1 a simplified model of the earth's interior

Underlying the crust is the mantle, a thick layer of denser rocks. The outer 100 kilometers (60 mile) of the Earth, encompassing both the crust and the uppermost portion of the mantle, is a solid, brittle layer known as the *lithosphere*. Underlying the lithosphere is the *asthenospher,* a zone of heat-softened rock located in the upper mantle roughly 100 to 350 kilometers (60-220 miles) beneath the Earth's surface. Although it remains solid, the heat-softened rock of the asthenosphere actually flows slowly- a phenomenon that drives much of the planet's geological activily. The lithosphere and asthenosphere (Fig. 2) are where such large-scale geological processes as mountain building, volcanism, earthquaks activity, and the creation of ocean basins originate.

Below the mantle and the Earth's center is the core, the densest layer of all. The core is divided into a liquid outer core and a solid inner core, both of which consist primarily of iron and nickel.

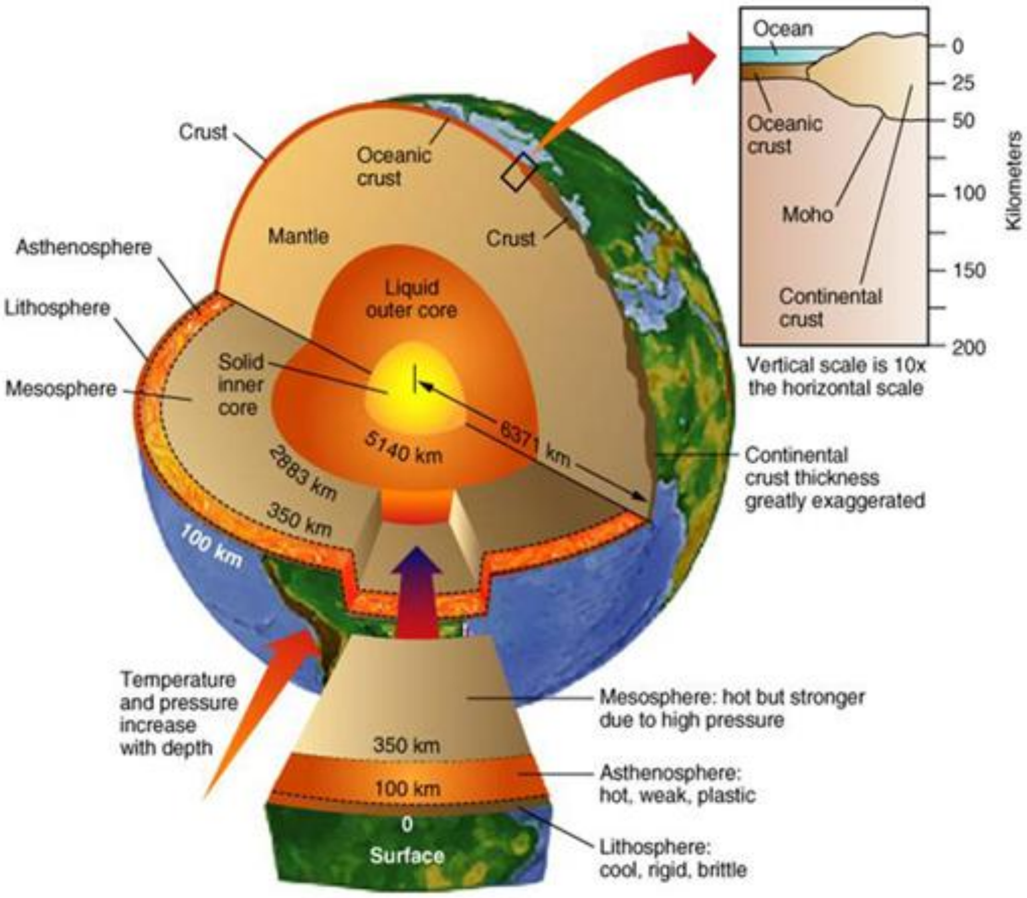


Fig. 2 Lithosphere, asthenosphere

Magma and Magma Formation

Magmas can vary widely in composition, but in general they are made up of only eight elements; in order of importance: oxygen, silicon, aluminum, iron, calcium, sodium, magnesium, and potassium (Figure 3). Oxygen, the most abundant element in magma, comprises a little less than half the total, followed by silicon at just over one-quarter. The remaining elements make up the other one-quarter. Magmas derived from crustal material are dominated by oxygen, silicon, aluminum, sodium, and potassium.

The composition of magma depends on the rock it was formed from (by melting), and the conditions of that melting. Magmas derived from the mantle have higher levels of iron, magnesium, and calcium, but they are still likely to be dominated by oxygen and silicon. All magmas have varying proportions of elements such as hydrogen, carbon, and sulphur, which are converted into gases like water vapour, carbon dioxide, and hydrogen sulphide as the magma cools.

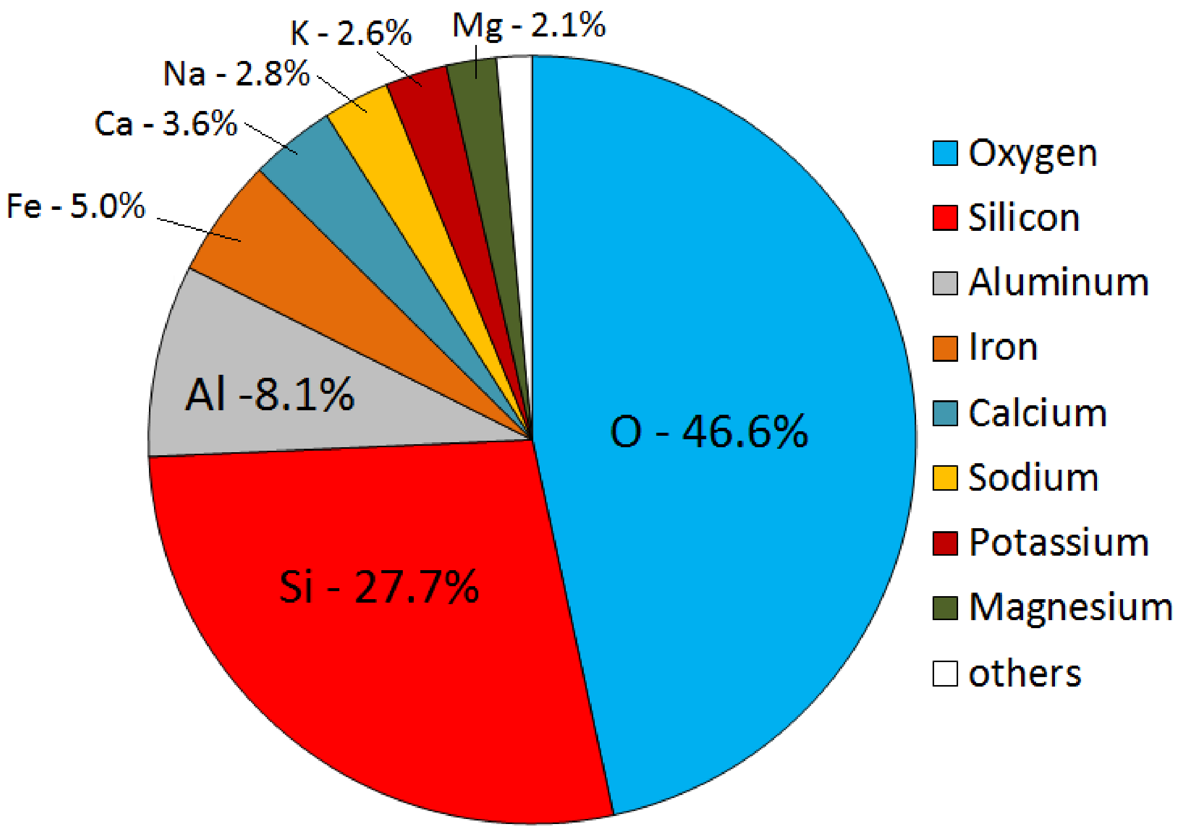


Figure 3 Average elemental proportions in Earth's crust, which is close to the average composition of magmas within the crust [SE]

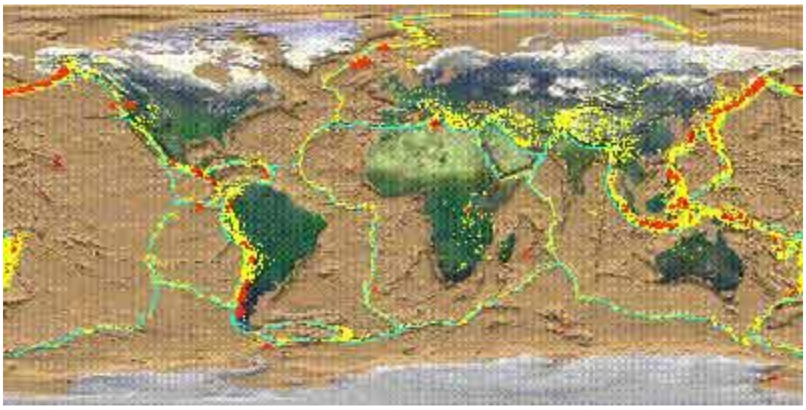
Plate Tectonics and Volcanism

The first question this raises is: what exactly is this "material from the inside"? On our planet, it'smagma, fluid molten rock. This material is partially liquid, partially solid and partially gaseous. To understand where it comes from, we need to consider the structure of planet Earth.

The earth is composed of many layers, roughly divided into three mega-layers: the core, the mantleand the outer crust:

- **We all live on the rigid outer crust, which is 3 to 6 miles (5 to 10 km) thick under the oceans and 20 to 44 miles (32 to 70)thick under the land. This may seem fairly thick to us, but compared to the rest of the planet, it's very thin -- like the outer skin on an apple.**
- **Directly under the outer crust is the mantle, the largest layer of the earth. The mantle is extremely hot, but for the most part, it stays in solid form because the**

pressure deep inside the planet is so great that the material can't melt. In certain circumstances, however, the mantle material does melt, forming magma that makes its way through the outer crust.



The blue lines mark plate boundaries, the red triangles mark active volcanoes and the yellow dots show recent earthquakes.
GRAPHIC COURTESY NASA

In the 1960s, scientists developed a revolutionary theory called plate tectonics. Plate tectonics holds that the lithosphere, a layer of rigid material composed of the outer crust and the very top of the mantle, is divided into seven large plates and several more smaller plates. These plates drift very slowly over the mantle below, which is lubricated by a soft layer called the asthenosphere. The activity at the boundary between some of these plates is the primary catalyst for magma production.

Where the different plates meet, they typically interact in one of four ways:

- **If the two plates are moving away from each other, an ocean ridge or continental ridge forms, depending on whether the plates meet under the ocean or on land. As the two plates separate, the mantle rock from the asthenosphere layer below flows up into the void between the plates. Because the pressure is not as great at this level, the mantle rock will melt, forming magma. As the magma flows out, it cools, hardening to form new crust. This fills in the gap created by the plates diverging. This sort of magma production is called spreading center volcanism.**
- **At the point where two plates collide, one plate may be pushed under the other plate, so that it sinks into the mantle. This process, called subduction, typically forms a trench, a very deep ditch, usually in the ocean floor. As the rigid lithosphere pushes down into the hot, high-pressure mantle, it heats up. Many scientists believe that the sinking lithosphere layer can't melt at this depth, but that the heat and pressure forces the water (the surface water and water from hydrated minerals) out of the plate and into the mantle layer above. The increased water content lowers the melting point of the mantle rock in this**

wedge, causing it to melt into magma. This sort of magma production is called subduction zone volcanism.

- **If the plates collide and neither plate can subduct under the other, the crust material will just "crumple," pushing up mountains. This process does not produce volcanoes. This kind of boundary can develop later into a subduction zone.**
- **Some plates move against each other rather than push or pull apart. These transform plate boundaries rarely produce volcanic activity.**

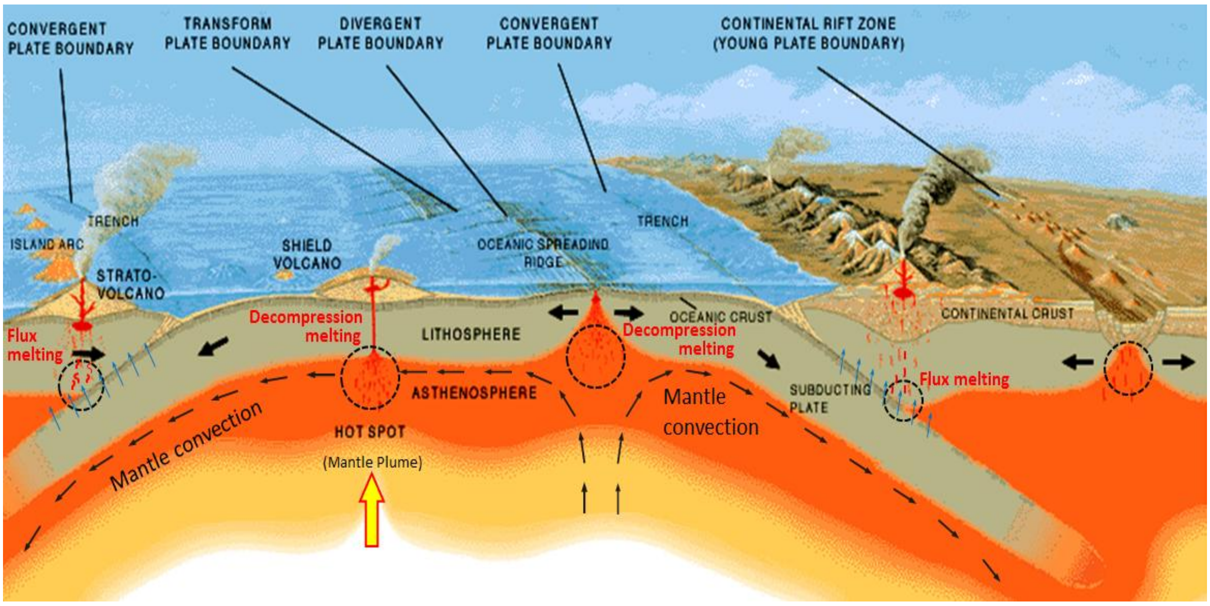


Figure 4 The plate-tectonic settings of common types of volcanism. Composite volcanoes form at subduction zones, either on ocean-ocean convergent boundaries (left) or ocean-continent convergent boundaries (right). Both shield volcanoes and cinder cones form in areas of continental rifting. Shield volcanoes form above mantle plumes, but can also form at other tectonic settings. Sea-floor volcanism can take place at divergent boundaries, mantle plumes and ocean-ocean-convergent boundaries

Magma can also push up under the middle of a lithosphere plate, though this is much less common than magma production around plate boundaries. This interplate volcanic activity is caused by unusually hot mantle material forming in the lower mantle and pushing up into the upper mantle. The mantle material, which forms a plume shape that is from 500 to 1000 km wide, wells up to create a hot spot under a particular point on the earth. Because of the unusual heat of this mantle material, it melts, forming magma just under the earth's crust. The hot spot itself is stationary; but as a continental plate moves over the spot, the magma will create a string of volcanoes,

which die out once they move past the hot spot. The Hawaii volcanoes were created by such a hot spot, which appears to be at least 70 million years old.

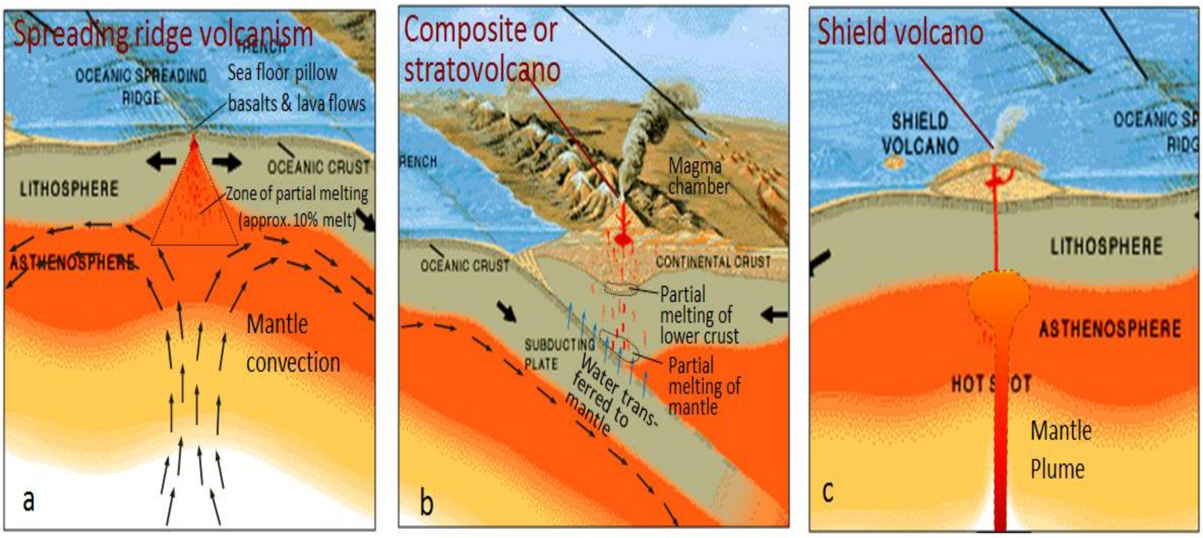
So what happens to the magma formed by these processes? We saw that the magma produced at ocean ridges just hardens to form new crust material, and so doesn't produce spewing land volcanoes. There are a few continental ridge areas, where the magma does spew out onto land; but most land volcanoes are produced by subduction zone volcanism and hot spot volcanism.

When the solid rock changes form to a more liquid rock material, it becomes less dense than the surrounding solid rock. Because of this difference in density, the magma pushes upward with great force (for the same reason the helium in a balloon pushes up through the denser surrounding air and oil pushes upward through denser surrounding water). As it pushes up, its intense heat melts some more rock, adding to the magma mixture.

The magma keeps moving through the crust unless its upward pressure is exceeded by the downward pressure of the surrounding solid rock. At this point, the magma collects in magma chambers below the surface of the earth. If the magma pressure rises to a high enough level, or a crack opens up in the crust, the molten rock will spew out at the earth's surface.

If this happens, the flowing magma (now called lava) forms a volcano. The structure of the volcano, and the intensity of the volcanic eruption, is dependent on a number of factors, primarily the composition of the magma. In the next section, we'll look at some different magma types and see how they erupt.

The mantle and crustal processes that take place in areas of volcanism are illustrated in Figure 5. At a spreading ridge, hot mantle rock moves slowly upward by convection (cm/year), and within about 60 km of the surface, partial melting starts because of decompression. Over the triangular area shown in Figure 5a, about 10% of the ultramafic mantle rock melts, producing mafic magma that moves upward toward the axis of spreading (where the two plates are moving away from each other). The magma fills vertical fractures produced by the spreading and spills out onto the sea floor to form basaltic pillows(more on that later) and lava flows. There is spreading-ridge volcanism taking place about 200 km offshore from the west coast of Vancouver Island.



Magma Composition and Eruption Style

As noted in the previous section, the types of magma produced in the various volcanic settings can differ significantly. At divergent boundaries and oceanic mantle plumes, where there is little interaction with crustal materials and magma fractionation to create felsic melts does not take place, the magma tends to be consistently mafic. At subduction zones, where the magma ascends through significant thicknesses of crust, interaction between the magma and the crustal rock — some of which is quite felsic — leads to increases in the felsic character of the magma.

As shown in Figure 6, several processes can make magma that is stored in a chamber within the crust more felsic, and can also contribute to development of vertical zonation from more mafic at the bottom to more felsic at the top. Partial melting of country rock and country-rock xenoliths increases the overall felsic character of the magma; first, because the country rocks tends to be more felsic than the magma, and second, because the more felsic components of the country rock melt preferentially. Settling of ferromagnesian crystals from the upper part of the magma, and possible remelting of those crystals in the lower part can both contribute to the vertical zonation from relatively mafic at the bottom to more felsic at the top.

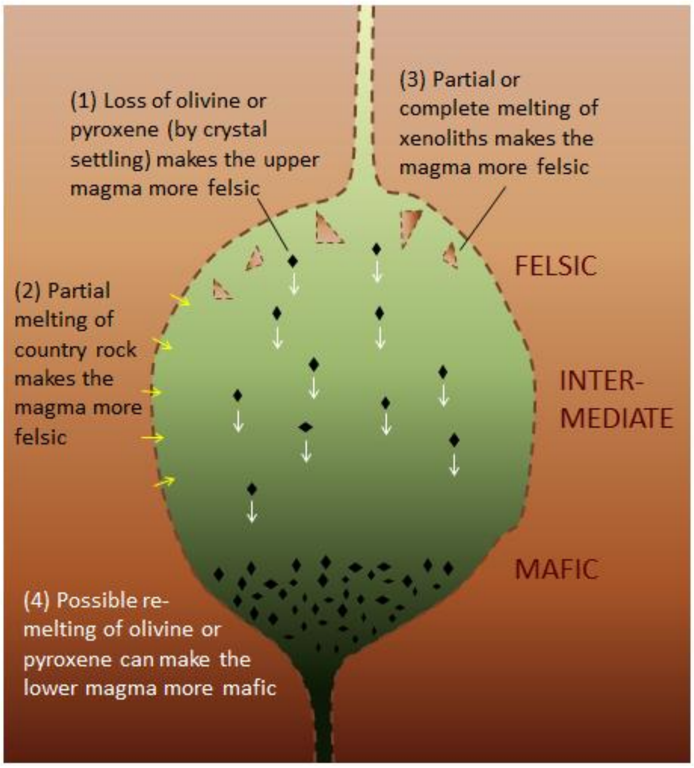


Figure 6 The important processes that lead to changes in the composition of magmas stored within magma chambers within relatively felsic rocks of the crust.

From the perspective of volcanism there are some important differences between felsic and mafic magmas. First, as we've already discussed, felsic magmas tend to be more viscous because they have more silica, and hence more polymerization. Second, felsic magmas tend to have higher levels of volatiles; that is, components that behave as gases during volcanic eruptions. The most abundant volatile in magma is water (H_2O), followed typically by carbon dioxide (CO_2), and then by sulphur dioxide (SO_2). The general relationship between the SiO_2 content of magma and the amount of volatiles is shown in Figure 4.8. Although there are many exceptions to this trend, mafic magmas typically have 1% to 3% volatiles, intermediate magmas have 3% to 4% volatiles, and felsic magmas have 4% to 7% volatiles.

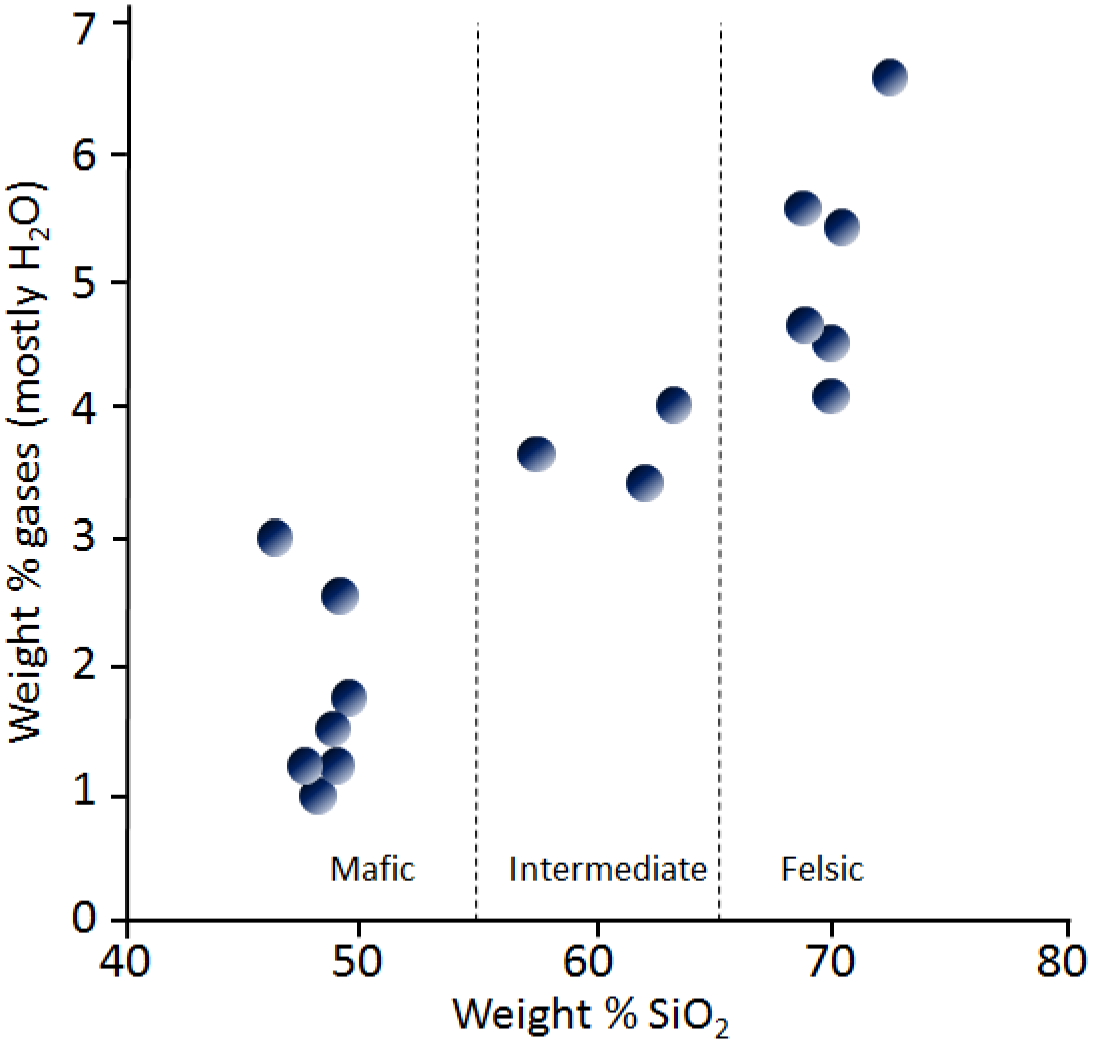


Figure 7 Variations in the volatile compositions of magmas as a function of silica content [SE after Schminke, 2004, (Schminke, H-U., 2004, Volcanism, Springer-Verlag, Heidelberg)]

Differences in viscosity and volatile level have significant implications for the nature of volcanic eruptions. When magma is deep beneath the surface and under high pressure from the surrounding rocks, the gases remain dissolved. As magma approaches the surface, the pressure exerted on it decreases. Gas bubbles start to form, and the more gas there is in the magma, the more bubbles form. If the gas content is low or the magma is runny enough for gases to rise up through it and escape to surface, the pressure will not become excessive. Assuming that it can break through to the surface, the magma will flow out relatively gently. An eruption that involves a steady non-violent flow of magma is called effusive.

Volcanoes vary a great deal in their destructive power. Some volcanoes explode violently, destroying everything in a mile radius within minutes, while other volcanoes seep out lava so slowly that you can safely walk all around them. The severity of the eruption depends mostly on the composition of the magma.

The first question to address is: why does the magma erupt at all? The erupting force generally comes from internal gas pressure. The material that forms magma contains alot of dissolved gases -- gases that have been suspended in the magma solution. The gases are kept in this dissolved state as long as the confining pressure of the surrounding rock is greater than the vapor pressure of the gas. When this balance shifts and vapor pressure becomes greater than the confining pressure, the dissolved gas is allowed to expand, and forms small gas bubbles, called vesicles, in the magma. This happens if one of two things occurs:

Gas vents from Kilauea Volcano in Hawaii

- **The confining pressure decreases, due to decompression from the magma rising from a higher pressure point to a lower pressure point.**
- **The vapor pressure increases because the magma cools, initiating a crystallization process that enriches the gas content of the magma.**

In either case, what you get is magma filled with tiny gas bubbles, which have a much lower density than the surrounding magma, and so push out to escape. This is the same thing that happens when you open a bottle of soda, particularly after shaking it up. When you decompress the soda (by opening the bottle), the tiny gas bubbles push out and escape. If you shake the bottle up first, the bubbles are all mixed up in the soda so they push a lot of the soda out with them. This is true for volcanoes as well. As the bubbles escape, they push the magma out, causing a spewing eruption.

The nature of this eruption depends mainly on the gas content and the viscosity of the magma material. Viscosity is just the ability to resist flow -- essentially, it is the opposite of fluidity. If the magma has a high viscosity, meaning it resists flow very well, the gas bubbles will have a hard time escaping from the magma, and so will push more material

up, causing a bigger eruption. If the magma has a lower viscosity, the gas bubbles will be able to escape from the magma more easily, so the lava won't erupt as violently.

An effusive lava flow from Pu`u `O`o Cone on Kilauea Volcano in Hawaii.

Of course, this is balanced with gas content -- if the magma contains more gas bubbles, it will erupt more violently, and if it contains less gas, it will erupt more calmly. Both factors are determined by the composition of the magma. Generally, viscosity is determined by the proportion of silicon in the magma, because of the metal's reaction to oxygen, an element found in most magmas. Gas content varies depending on what sort of material melted to form the magma.

As a general rule, the most explosive eruptions come from magmas that have high gas levels and high viscosity, while the most subdued eruptions come from magmas with low gas levels and low viscosity. Volcanic eruptions don't often fall into easy categories, however. Most eruptions occur in several stages, with varying degrees of destructiveness.

If the viscosity and the gas pressure are low enough, lava will flow slowly onto the earth's surface when the volcano erupts, with minimal explosion. While these effusive lava flows can reap considerable damage on wildlife and manmade structures, they are not particularly dangerous to people because they move so slowly -- you have plenty of time to get out of the way.

If there is a good deal of pressure, however, a volcano will begin its eruption with an explosive launch of material into the air. Typically, this eruption column is composed of

hot gas, ash and pyroclastic rocks -- volcanic material in solid form. There are many sorts of explosive eruptions, varying significantly in size, shape and duration.

TEXTURES OF THE IGNEOUS ROCKS

Structure - large-scale features recognizable in the field, such as banding, lineation, jointing, and vesicularity

Texture - refers to degree of crystallinity, grain size, and geometrical relationships between the constituents of a rock (fabric).

I. Igneous Textures

A. Degree of Crystallinity

Holocrystalline - composed wholly of crystals

Hypocrystalline - contains both glass and crystals

Holohayline - consists entirely of glass

Microlites - minute incipient crystals which are birefringent

Crystallites - smaller than microlites, spherical, rod- and hair-like isotropic forms

B. Grain Size or Granularity

Cryptocrystalline - crystals cannot be distinguished even with a microscope

Aphanitic - crystals not visible to the unaided eye

Phaneritic - grains readily distinguished with the unaided eye

If the grains of the rock are roughly the same size:

Fine < 1 mm

Medium 1-5 mm

Coarse 5 mm-3 cm

Very coarse > 3 cm

C. Shape of Crystals

1. Euhedral (idiomorphic) - grains completely bounded by crystal faces

Subhedral (hypidiomorphic) - grains only partly bounded by crystal faces

Anhedral (allotriomorphic) - grains completely devoid of crystal boundaries

2. Habit - columnar, acicular, fibrous, tabular, prismatic, and flaky

3. Order of crystallization

a. When one mineral is surrounded by another, the enclosing mineral is younger.

b. Early crystals are generally euhedral or at least more nearly so than later crystals.

c. If both large and small crystals occur together, the large ones are those that began to develop first

d. There are numerous exception to these rules.

D. Granular Texture - most of the minerals of a rock are approximately equidimensional or equant.

Panidiomorphic-granular (automorphic-granular) - the chief minerals are euhedral

Hypidiomorphic-granular (hypautomorphic-granular or granitic) - some constituents are euhedral, some subhedra, and the rest anhedral

Microgranitic - texture developed only on a microscopic scale

Allotriomorphic-granular (xenomorphic-granular or aplitic or sugary or saccaharoidal) - almost all of the constituents are anhedral

E. Porphyritic Textures - notably inequigranular rocks

Megaphenocrysts - recognizable to unaided eye

Microphenocrysts - microscope is needed to recognize the phenocrysts. Texture is microporphyritic.

Vitrophyric - matrix is glass

Felsophyric - groundmass is a dense intergrowth of quartz and feldspar

Glomeroporphyritic - phenocrysts are gathered in distinct clusters

F. Textural Terms Related to Mineral Relationships

1. Graphic - quartz intergrown with alkali feldspar. Quartz appears as runic inscriptions on a background of feldspar.

2. Myrmekitic - minute worm-like or finger-like bodies of quartz enclosed in sodic plagioclase, usually oligoclase

3. Ophitic - feldspar laths largely or entirely enclosed in pyroxene Subophitic - average length of feldspar laths exceeds that of pyroxene grains, so the feldspar laths are only partly enclosed Hyalophitic - glass takes the place of pyroxene

4. Poikilitic - numerous grains of various minerals in random orientation are completely enclosed within large, optically continuous crystals of different composition

5. Coronas (reaction rims) - one mineral rims another Kelyphitic rims - concentric shells with a radial fibrous texture. Common in basic and ultrabasic rocks

6. Intergranular - angular interstices between the feldspars occupied by ferromagnesian granules Intersertal - interstices filled with glass, cryptocrystalline material, or non-granular deuteric and secondary minerals Hyalopilitic - typical of many lavas in which glass occupies minute interspaces between microlites of feldspar in haphazard orientation

7. Felted - matrix composed of a crowded mass of microlites, generally of feldspar, interwoven in irregular fashion Pilotaxitic (trachytic) - crowded microlites of feldspar are disposed in a subparallel manner as a result of flow and their interstices are occupied by micro- or crypto-crystalline material

8. Vesicles - cavities formed by expanding gases. Usually spherical or ovoid, but many are highly irregular. Amygdules - filling of the cavities (vesicles) with deuteric or secondary minerals

9. Miarolitic cavities - found in plutonic rocks - large subhedral and euhedral crystals projecting into irregular cavities

10. Spherulites - found in siliceous lavas and shallow intrusive rocks - radial aggregates of acicular and fibrous minerals

Varioles - radial or sheaf-like bodies in basic rocks. Usually consist of divergent plagioclase fibers. The texture is called variolitic.

Bostonitic - radial texture found in certain medium- and fine-grained dike rocks. Consists of irregular interlocking laths of alkali feldspar, arranged in crudely divergent groups.

11. Ocellar - phenocrysts in porphyritic rocks resemble eyes partly or wholly enveloped by tangentially or radially arranged crystals of later growth

G. Clastic Textures - the rock constituents have a fractured appearance

Pyroclastic - fragmental products of volcanoes

Protoclastic (autoclastic) - magmas continue to move even after they are almost wholly crystallized so that many of their crystals become granulated and rounded by rubbing together during differential flow

Cataclastic - crushing and fragmentation of crystals due to post-consolidation movements

Mylonitic - granulation and shearing of the crystals are extreme

II. Pyroclastic Rocks

A. Size Distinctions

Bombs - fragments more than 32 mm in diameter which were partly or wholly molten when discharged. The resulting rock is called an agglomerate.

Blocks - fragments more than 32 mm across which were entirely solid when ejected. The resulting rock is called a volcanic breccia.

Lapilli - fragments measuring between 4 and 32 mm in diameter irrespective of their condition on discharge. The resulting rock is called a lapilli tuff.

Ashes - fragments whose diameter is less than 4 mm irrespective of their condition on discharge. The resulting rock is called a tuff

B. Distinction Based on Mode of Origin

Essential (juvenile) - fresh magmatic ejecta

Accessory - solid fragments of volcanic rock derived from the conduit and crater walls of an eruptive cone

Accidental - solid chips torn from the sub-volcanic basement, no matter whether igneous, metamorphic, or sedimentary

C. Distinction Based on Content of Glass, Crystals, and Rock Debris

Vitric ash (tuff) - ashes and tuffs composed mainly of glassy particles

Crystal ash (tuff) - ashes and tuffs made up chiefly of crystals

Lithic ash (tuff) - ashes and tuffs in which accessory and accidental rock fragments predominate

***Terms and definitions selected from: Williams, Turner, and Gilbert (1954) Petrography. W. H. Freeman and Company**

Classification of Igneous rocks

Classification of igneous rocks is one of the most confusing aspects of geology. This is partly due to historical reasons, partly due to the nature of magmas, and partly due to the

various criteria that could potentially be used to classify rocks.

- **Early in the days of geology there were few rocks described and classified. In those days each new rock described by a geologist could have shown characteristics different than the rocks that had already been described, so there was a tendency to give the new and different rock a new name. Because such factors as cooling conditions, chemical composition of the original magma, and weathering effects, there is a potential to see an infinite variety of igneous rocks, and thus a classification scheme based solely on the description of the rock would eventually lead to a plethora of rock names. Still, because of the history of the science, many of these rock names are firmly entrenched in the literature, so the student must be aware of all of these names, or at least know where to look to find out what the various rocks names mean.**

- **Magmas, from which all igneous rocks are derived, are complex liquid solutions. Because they are solutions, their chemical composition can vary continuously within a range of compositions. Because of the continuous variation in chemical composition there is no easy way to set limits within a classification scheme.**

- **There are various criteria that could be used to classify igneous rocks. Among them are:**

    1. **Minerals Present in the Rock (the *mode*). The minerals present in a rock and their relative proportions in the rock depend largely on the chemical composition of the magma. This works well as a classification scheme if all of the minerals that could potentially crystallize from the magma have done so - usually the case for slowly cooled plutonic igneous rocks. But, volcanic rocks usually have their crystallization interrupted by eruption and rapid cooling on the surface. In such rocks, there is often glass or the minerals are too small to be readily identified. Thus a system of classification based solely on the minerals present can only be used.**

        We can easily the inadequacy of a mineralogical classification based on minerals present if you look at the classification schemes for volcanic rocks given in introductory geology textbooks. For example, most such schemes show that a dacite is a rock that contains small amounts of quartz, somewhat larger amounts of sanidine or alkali feldspar, plagioclase, biotite, and hornblende, In all the years I have been looking at igneous rocks (since about the mid-cretaceous) I have yet to see a dacite that contains alkali feldspar. Does this mean that the intro geology textbooks lie? Not really, these are the minerals that should crystallize from a dacite magma, but don't because the crystallization history is interrupted by rapid cooling on the surface.

    2. **Texture of the Rock. Rock texture depends to a large extent on cooling history of the magma. Thus rocks with the same chemical composition and same minerals present could have widely different textures. In fact we generally use textural criteria to subdivide igneous rocks in to plutonic (usually medium to coarse grained) and volcanic (usually fine grained,**

glassy, or porphyritic.) varieties.

3. **Color. Color of a rock depends on the minerals present and on their grain size. Generally, rocks that contain lots of feldspar and quartz are light colored, and rocks that contain lots of pyroxenes, olivines, and amphiboles (ferromagnesium minerals) are dark colored. But color can be misleading when applied to rocks of the same composition but different grain size. For example a granite consists of lots of quartz and feldspar and is generally light colored. But a rapidly cooled volcanic rock with the same composition as the granite could be entirely glassy and black colored (i.e. an obsidian). Still we can divide rocks in general into *felsic rocks* (those with lots of feldspar and quartz) and *mafic rocks* (those with lots of ferromagnesium minerals). But, this does not allow for a very detailed classification scheme.**

4. **Chemical Composition. Chemical composition of igneous rocks is the most distinguishing feature.**

- **The composition usually reflects the composition of the magma, and thus provides information on the source of the rock.**
- **The chemical composition of the magma determines the minerals that will crystallize and their proportions.**
- **A set of hypothetical minerals that could crystallize from a magma with the same chemical composition as the rock (called the *Norm*), can facilitate comparison between rocks.**
- **Still, because chemical composition can vary continuously, there are few natural breaks to facilitate divisions between different rocks.**
- **Chemical composition cannot be easily determined in the field, making classification based on chemistry impractical.**

Because of the limitations of the various criteria that can used to classify igneous rocks, geologists use an approach based on the information obtainable at various stages of examining the rocks.

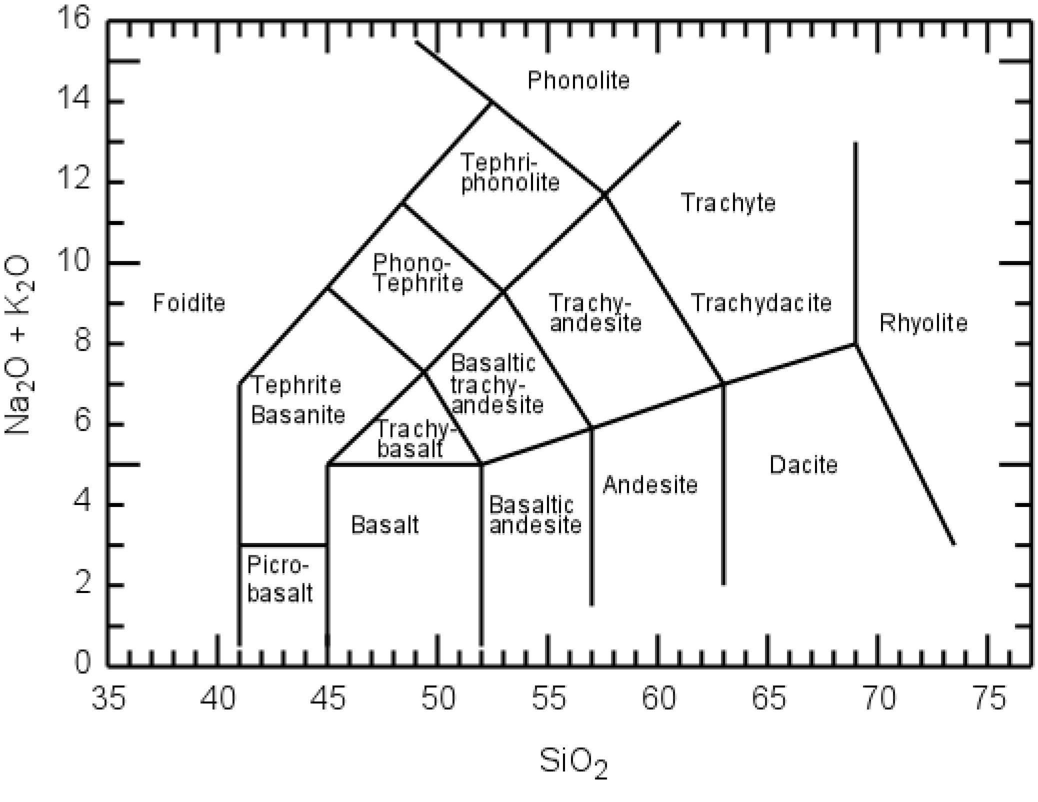
1. **In the field, a simple field based classification must be used. This is usually based on mineralogical content and texture. For plutonic rocks, the IUGS system of classification can be used. For volcanic rocks, the following table can be used.**

Simple Field Classification of Volcanic Rocks (For use in EENS 212)		
Rock Name	**Essential Minerals***	**Other Minerals (may or may not be present)**
Basalt	**Olivine**	**Cpx, Opx, Plag.**

Basanite	**Olivine + Feldspathoid (Nepheline/ Leucite)**	**Cpx, Plag.**
Andesite	**No olivine, abundant Plagioclase**	**Cpx, Opx, Hornblende**
Trachyte	**Sanidine + Plagioclase**	**Na-Cpx, Hornblende, Biotite**
Dacite	**Plagioclase + Hornblende**	**Cpx, Opx, Biotite**
Rhyolite	**Quartz**	**Sanidine, Biotite, Plag., Hornblende, Cpx, Opx**
*** The amount of glass in the groundmass increases, in general, from the top to the bottom of the chart.**		

2. **Once the rocks are brought back to the laboratory and thin sections can be made, these are examined, mineralogical content can be more precisely determined, and refinements in the mineralogical and textural classification can be made.**

3. **Chemical analyses can be obtained, and a chemical classification, such as the LeBas et al., IUGS chemical classification of volcanic rocks (based on total alkalies [Na_2O + K_2O] vs. SiO_2 diagram shown below)**



Note that at each stage of the process, the classification may change, but it is important to keep in mind that each stage has limitations, and that classification at each stage is for the purposes of describing the rock, not only for the individual investigator, but anyone else. Thus, the classification scheme should be employed in a consistent manner so that later investigators can understand what you are talking about at each stage of the process.

General Chemical Classifications

SiO_2 (Silica) Content

> 66 wt. % - Acid

52-66 wt% - Intermediate

45-52 wt% - Basic

< 45 wt % - Ultrabasic

This terminology is based on the onetime idea that rocks with a high % SiO_2 were precipitated from waters with a high concentration of hyrdosilicic acid H_4SiO_4. Although we now know this is not true, the acid/base terminology is well entrenched in the literature.

Silica Saturation

If a magma is oversaturated with respect to Silica then a silica mineral, such as quartz, cristobalite, tridymite, or coesite, should precipitate from the magma, and be present in the rock. On the other hand, if a magma is undersaturated with respect to silica, then a silica mineral should not precipitate from the magma, and thus should not be present in the rock. The silica saturation concept can thus be used to divide rocks in silica undersaturated, silica saturated, and silica oversaturated rocks. The first and last of these terms are most easily seen.

- Silica Undersaturated Rocks - In these rocks we should find minerals that, in general, do not occur with quartz. Such minerals are:

Nepheline- $NaAlSiO_4$
Forsteritic Olivine - Mg_2SiO_4
Nosean - $6NaAlSiO_4 \cdot Na_2SO_4$
Perovskite - $CaTiO_3$
Melilite - $(Ca,Na)_2(Mg,Fe^{+2},Al,Si)_3O_7$
Leucite - $KAlSi_2O_6$
Sodalite - $3NaAlSiO_4 \cdot NaCl$
Haüyne - $6NaAlSiO_4 \cdot (Na_2,Ca)SO_4$
Melanite - $Ca_2Fe^{+3}Si_3O_{12}$

Thus, if we find any of these minerals in a rock, with an exception that we'll see in a moment, then we can expect the rock to be silica undersaturated.

If we calculate a CIPW Norm (we'll see how to do this in lab) the normative minerals that occur in silica undersaturated rocks are nepheline and/or leucite.

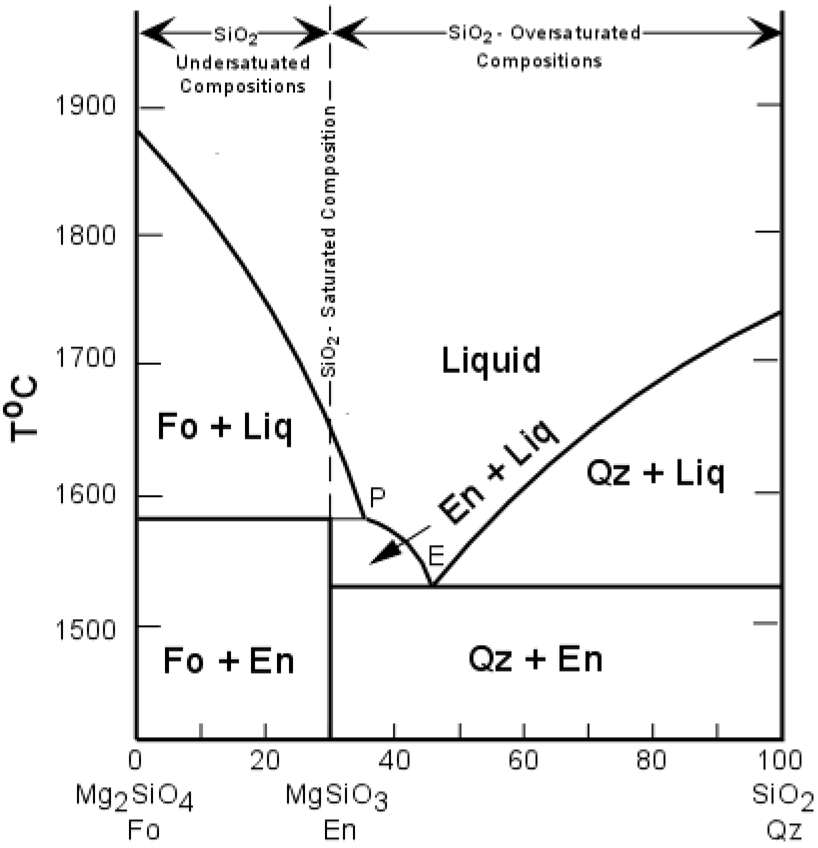
- Silica Oversaturated Rocks. These rocks can be identified as possibly any rock that doesnot contain one of the minerals in the above list.

If we calculate a CIPW Norm, silica oversaturated rocks will contain

normative quartz.

- **Silica Saturated Rocks. These are rocks that contain just enough silica that quartz does not appear, and just enough silica that one of the silica undersaturated minerals does not appear. In the CIPW norm, these rocks contain olivine, or hypersthene + olivine, but no quartz, no nepheline, and no leucite.**

To get an idea about what silica saturation means, let's look at a simple silicate system - the system Mg_2SiO_4 - SiO_2



Note how compositions between Fo and En will end their crystallization with only Fo olivine and enstatite. These are SiO_2-undersaturated. compositions. All compositions between En and SiO_2 will end their crystallization with quartz and enstatite. These are SiO_2 - oversaturated compositions.

Note also that this can cause some confusion in volcanic rocks that do not complete their crystallization due to rapid cooling on the surface. Let's imagine first a composition in the silica-undersaturated field. Cooling to anywhere on the liquidus will result in the crystallization of Fo-rich olivine. If this liquid containing olivine is erupted and the rest of the liquid quenches to a glass, then this will produce a rock with phenocrysts of olivine in a glassy groundmass.

Applying the criteria above for identifying silica undersaturated rocks would tell us that this is a silica-undersaturated rock, which we know to be correct. Next, let's look at a silica oversaturated composition, such as one just to the left of the point labeled 'P' in the diagram. If this liquid is cooled to the liquidus and olivine is allowed to crystallize, and is then quenched on the surface, it will contain phenocrysts of Fo-rich olivine in a glassy groundmass. Applying the criteria above would suggest that this rock is also silica undersaturated, but we know it is not. This illustrates one of the difficulties of applying

any criteria of classification to volcanic rocks where incomplete crystallization/reaction has not allowed all minerals to form.

Alumina (Al_2O_3) Saturation

After silica, alumina is the second most abundant oxide constituent in igneous rocks. Feldspars are, in general, the most abundant minerals that occur in igneous rocks. Thus, the concept of alumina saturation is based on whether or not there is an excess or lack of Al to make up the feldspars. Note that Al_2O_3 occurs in feldspars in a ratio of 1 Al to 1 Na, 1K, or 1 Ca:

$KAlSi_3O_8$ -- $1/2K_2O : 1/2Al_2O_3$

$NaAlSi_3O_8$ -- $1/2Na_2O : 1/2Al_2O_3$

$CaAl_2Si_2O_8$ -- $1CaO : 1Al_2O_3$

Three possible conditions exist.

1. If there is an excess of Alumina over that required to form feldspars, we say that the rock is *peraluminous*. This condition is expressed chemically on a molecular basis as:

   $Al_2O_3 > (CaO + Na_2O + K_2O)$

   In peraluminous. rocks we expect to find an Al_2O_3-rich mineral present as a modal mineral - such as muscovite [$KAl_3Si_3O_{10}(OH)_2$], corundum [Al_2O_3], topaz [$Al_2SiO_4(OH,F)_2$], or an Al_2SiO_5- mineral like kyanite, andalusite, or sillimanite.

   Peraluminous rocks will have corundum [Al_2O_3] in the CIPW norm and no diopside in the norm.

2. *Metaluminous* rocks are those for which the molecular percentages are as follows:

   $Al_2O_3 < (CaO + Na_2O + K_2O)$ and $Al_2O_3 > (Na_2O + K_2O)$

   These are the more common types of igneous rocks. They are characterized by lack of an Al_2O_3-rich mineral and lack of sodic pyroxenes and amphiboles in the mode.

3. *Peralkaline* rocks are those that are oversaturated with alkalies ($Na_2O + K_2O$), and thus undersaturated with respect to Al_2O_3. On a molecular basis, these rocks show:

   $Al_2O_3 < (Na_2O + K_2O)$

   Peralkaline rocks are distinguished by the presence of Na-rich minerals like aegerine [$NaFe^{+3}Si_2O_6$], riebeckite [$Na_2Fe_3^{+2}Fe_2^{+3}Si_8O_{22}(OH)_2$], arfvedsonite [$Na_3Fe_4^{+2}(Al,Fe^{+3})Si_8O_{22}(OH)_2$], or aenigmatite [$Na_2Fe_5^{+2}TiO_2Si_6O_{18}$] in the mode.

   In the CIPW norm, acmite [$NaFe^{+3}Si_2O_6$] and/or sodium metasilicate Na_2SiO_3 will

occur as normative minerals.

Alkaline/Subalkaline Rocks

One last general classification scheme divides rocks that alkaline from those that are subalkaline. Note that this criteria is based solely on an alkali vs. silica diagram, as shown below. Alkaline rocks should not be confused with peralkaline rocks as discussed above. While most peralkaline rocks are also alkaline, alkaline rocks are not necessarily peralkaline. On the other hand, very alkaline rocks, that is those that plot well above the dividing line in the figure below, are also usually silica undersaturated.