

{ Lecture notes 2nd semester unit-2 }
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 see 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 into 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.

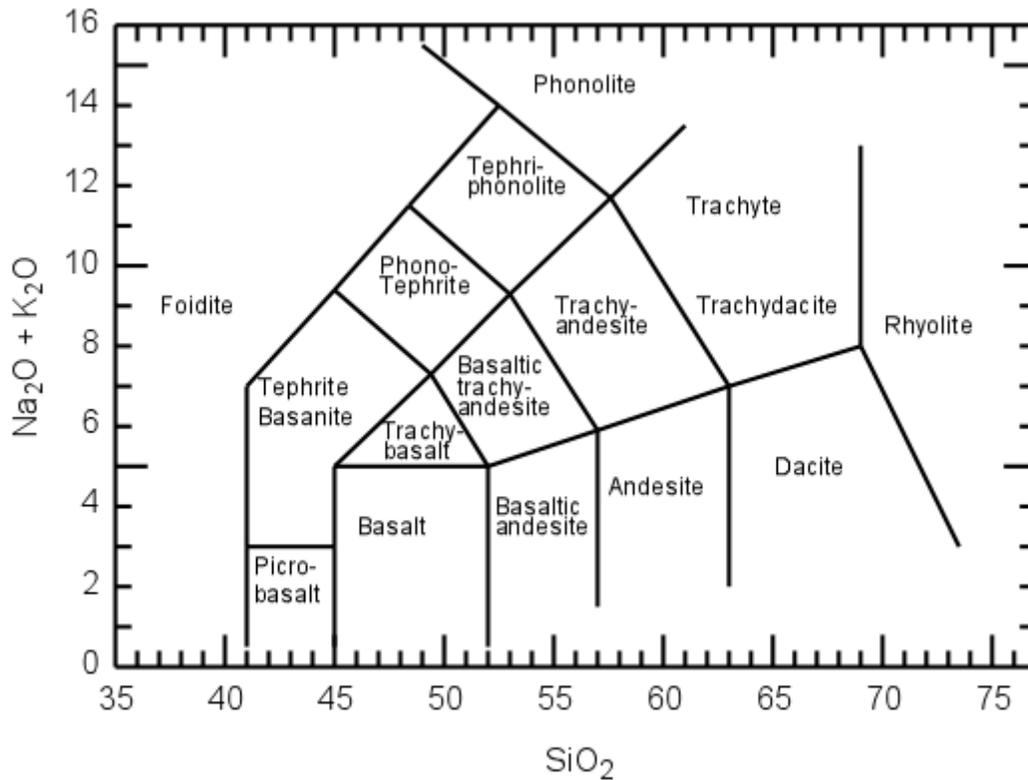
Because of the limitations of the various criteria that can be used to classify igneous rocks, geologists use an approach based on the information obtainable at various stages of examining the rocks.

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 [Na₂O + K₂O] vs. SiO₂ 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

SiO₂ (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 % SiO₂ were precipitated from waters with a high concentration of hydrosilicic acid H₄SiO₄. 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

Leucite - KAlSi_2O_6

Forsteritic Olivine - Mg_2SiO_4

Sodalite - $3\text{NaAlSiO}_4 \cdot \text{NaCl}$

Nosean - $6\text{NaAlSiO}_4 \cdot \text{Na}_2\text{SO}_4$

Häüyne - $6\text{NaAlSiO}_4 \cdot (\text{Na}_2, \text{Ca})\text{SO}_4$

Perovskite - CaTiO_3

Melanite - $\text{Ca}_2\text{Fe}^{+3}\text{Si}_3\text{O}_{12}$

Melilite - $(\text{Ca}, \text{Na})_2(\text{Mg}, \text{Fe}^{+2}, \text{Al}, \text{Si})_3\text{O}_7$

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 does **not** contain one of the minerals in the above list.

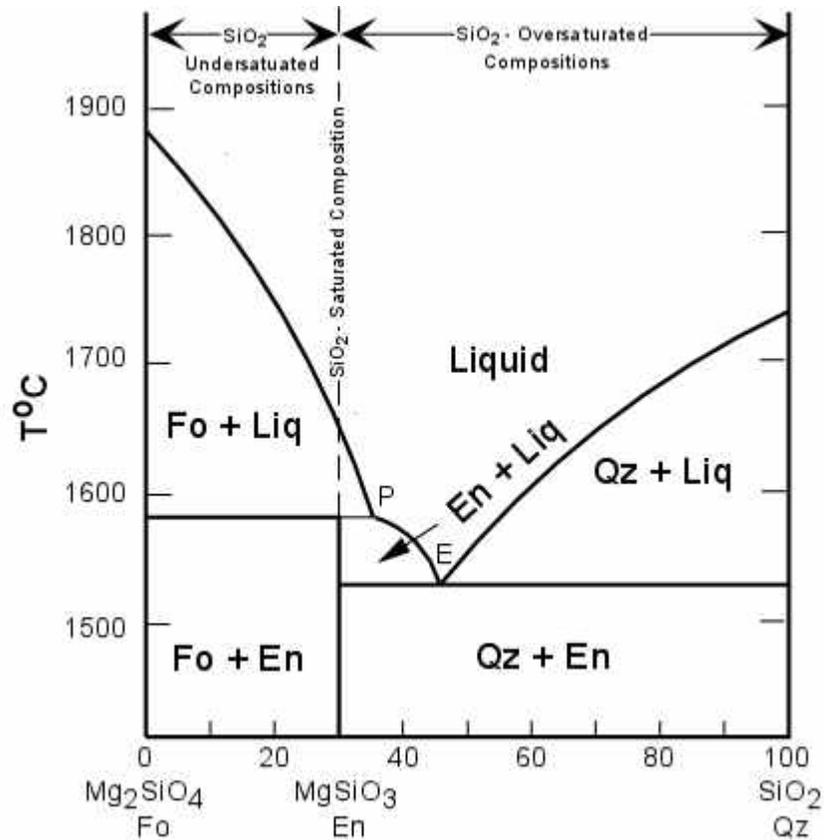
If we calculate a CIPW Norm, silica oversaturated rocks will contain normative quartz.

- 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 $\text{Mg}_2\text{SiO}_4 - \text{SiO}_2$

Note how compositions between Fo and En will end their crystallization with only Fo olivine and enstatite. These are SiO₂-undersaturated compositions. All compositions between En and SiO₂ will end their crystallization with quartz and enstatite. These are SiO₂-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.

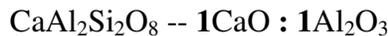
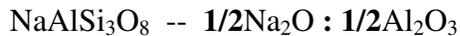


Applying the criteria above for identifying silica undersaturated rocks would tell us that this is a silica-undersaturated rock, which we know to be correct. Next, let's look at a silica oversaturated composition, such as one just to the left of the point labeled 'P' in the diagram. If this liquid is 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 (Al₂O₃) Saturation

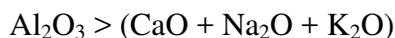
After silica, alumina is the second most abundant oxide constituent in igneous rocks. Feldspars are, in general, the most abundant minerals that occur in igneous rocks. Thus, the concept of alumina saturation is based on whether or not there is an excess or lack of Al to make up the

feldspars. Note that Al_2O_3 occurs in feldspars in a ratio of 1 Al to 1 Na, 1K, or 1 Ca:



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:



In peraluminous rocks we expect to find an Al_2O_3 -rich mineral present as a modal mineral - such as muscovite $[\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2]$, corundum $[\text{Al}_2\text{O}_3]$, topaz $[\text{Al}_2\text{SiO}_4(\text{OH},\text{F})_2]$, or an Al_2SiO_5 - mineral like kyanite, andalusite, or sillimanite.

Peraluminous rocks will have corundum $[\text{Al}_2\text{O}_3]$ in the CIPW norm and no diopside in the norm.

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



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 alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$), and thus undersaturated with respect to Al_2O_3 . On a molecular basis, these rocks show:



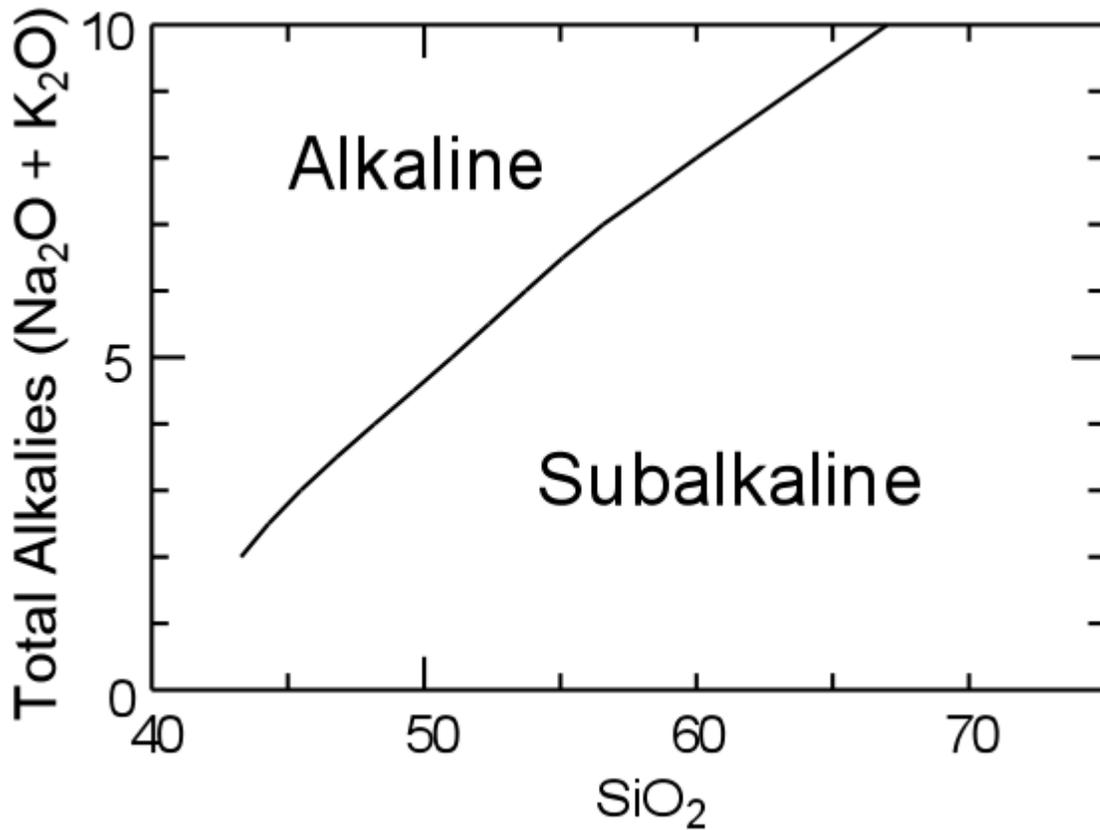
Peralkaline rocks are distinguished by the presence of Na-rich minerals like aegerine $[\text{NaFe}^{+3}\text{Si}_2\text{O}_6]$, riebeckite $[\text{Na}_2\text{Fe}_3^{+2}\text{Fe}_2^{+3}\text{Si}_8\text{O}_{22}(\text{OH})_2]$, arfvedsonite $[\text{Na}_3\text{Fe}_4^{+2}(\text{Al},\text{Fe}^{+3})\text{Si}_8\text{O}_{22}(\text{OH})_2]$, or aenigmatite $[\text{Na}_2\text{Fe}_5^{+2}\text{TiO}_2\text{Si}_6\text{O}_{18}]$ in the mode.

In the CIPW norm, acmite $[\text{NaFe}^{+3}\text{Si}_2\text{O}_6]$ 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.



Classification of Igneous Rocks

The most abundant elements in the crust are oxygen, silicon, aluminum, iron, magnesium, calcium, sodium and potassium. These eight elements account for 99 per cent of the crust. Since oxygen is by far the dominant anion, rock compositions are usually reported as oxides rather than as separate elements. Most minerals can be written as combinations of the oxides. For example, K-feldspar (KAlSi₃O₈) can be written as $\frac{1}{2}(\text{K}_2\text{O} + \text{Al}_2\text{O}_3 + 3\text{SiO}_2)$

The most abundant oxide by far is SiO₂, so the first question petrologists ask in classifying igneous rocks is **how much silica is present?** Is there so much that after all other minerals are accounted for, silica is left over to form quartz? Or is there so little that silica deficient minerals like olivine, leucite or nepheline are present?

Next most abundant oxide is aluminum, which resides principally in feldspars. So the second question petrologists ask in classifying igneous rocks is **what feldspars are present?** The feldspars largely account not only for Al, but Ca, Na and K as well.

That leaves Mg, Fe and minor constituents. The third question petrologists ask in classifying igneous rocks is **what other minerals are present?**

As a student, I was puzzled and frustrated that the igneous rocks were classified on the basis of minerals that looked so much alike in thin section. However, to a practiced petrologist, quartz, K-feldspar and plagioclase are quite distinct and easily recognizable.

Apart from accounting for most of the major elements, there's another reason we define igneous rocks in terms of quartz and the feldspars. Relatively minor influences like water content can drastically change the ferromagnesian minerals in a rock. A very anhydrous magma might form the ferromagnesian pyroxene hypersthene. With a bit more water, the otherwise identical magma might form the amphibole actinolite or biotite mica.

Important Classes of Igneous Rocks

The silica and aluminum contents of igneous rocks can be placed in broad classes:

Silica content

- **Oversaturated rocks** are those with quartz.
- **Undersaturated rocks** are those with silica-deficient minerals that are incompatible with quartz. These minerals include corundum, olivine, leucite and nepheline.

Aluminum content

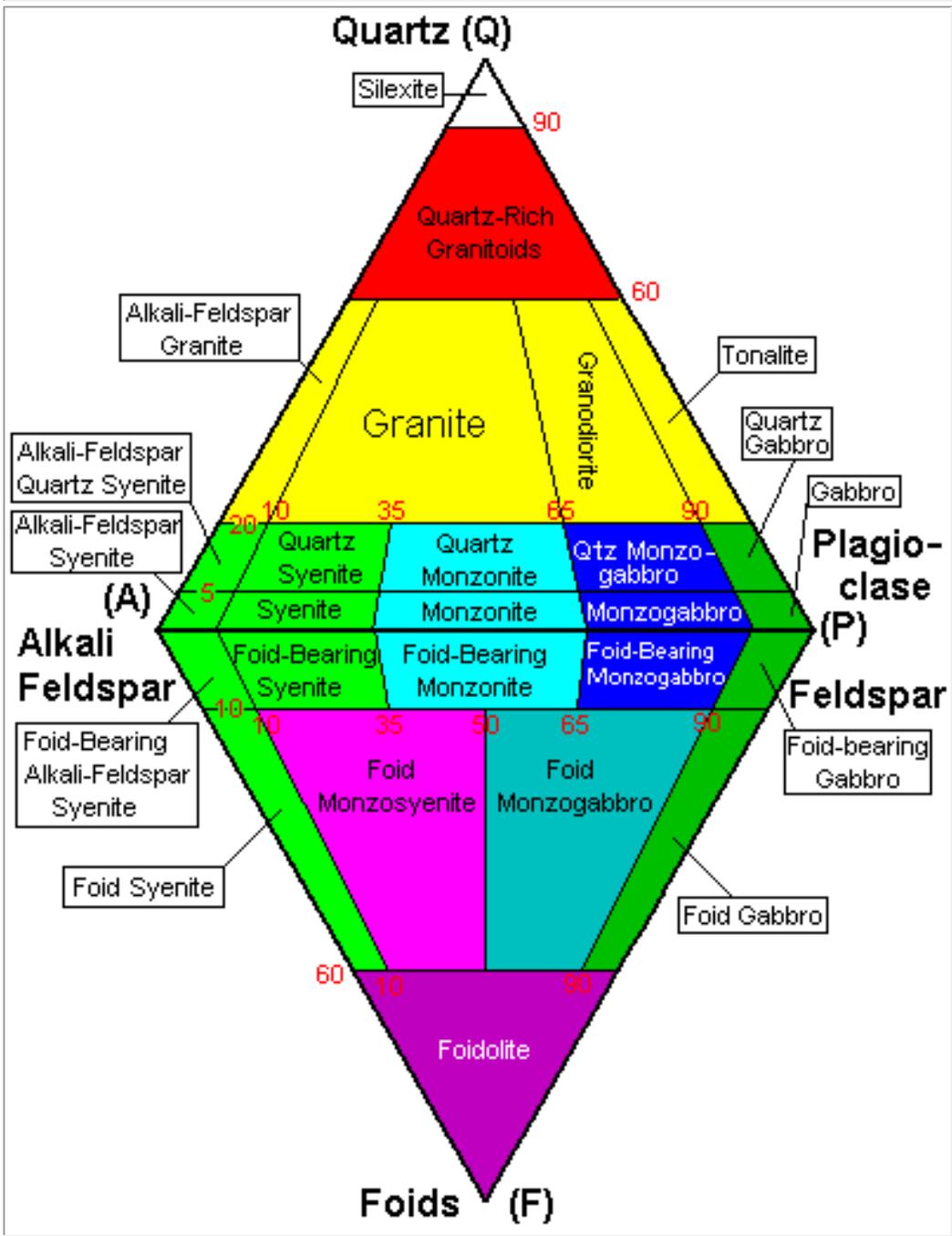
- **Peraluminous** rocks are those with an excess of aluminum, so that after the feldspars form, excess aluminum remains to form aluminum-rich minerals like corundum, andalusite, kyanite, sillimanite, or garnet.
- **Peralkaline** rocks are those with so little aluminum that sodium or potassium are left over after the feldspars form. The most common indications of peralkaline rocks are the sodium pyroxene aegerine (acmite) and the sodium amphibole riebeckite.

IUGS Igneous rock names

Oversaturated rocks can be plotted on a triangle diagram with its vertices occupied by quartz, alkali feldspar and plagioclase.

Undersaturated rocks can contain alkali feldspar and plagioclase, but not quartz. Instead they contain minerals like leucite or nepheline. These minerals were once called *feldspathoids*, a name that aptly describes their "ecological niche" since they perform the role of feldspars but form instead because of insufficient silica. In modern petrological classification, these minerals are termed "*foids*", a meaningless name that describes nothing. Undersaturated rocks can also be plotted on a triangle diagram with vertices

occupied by foids, alkali feldspar and plagioclase.



Since the two triangles have alkali feldspar and plagioclase in common, it is customary to join the two base to base with alkali feldspar and plagioclase along the common edge and quartz and foids at the top and bottom vertices. The two triangles are mutually exclusive.

In the diagram here, broad families of rocks (granitic rocks, syenite, gabbro) are shown by common colors.

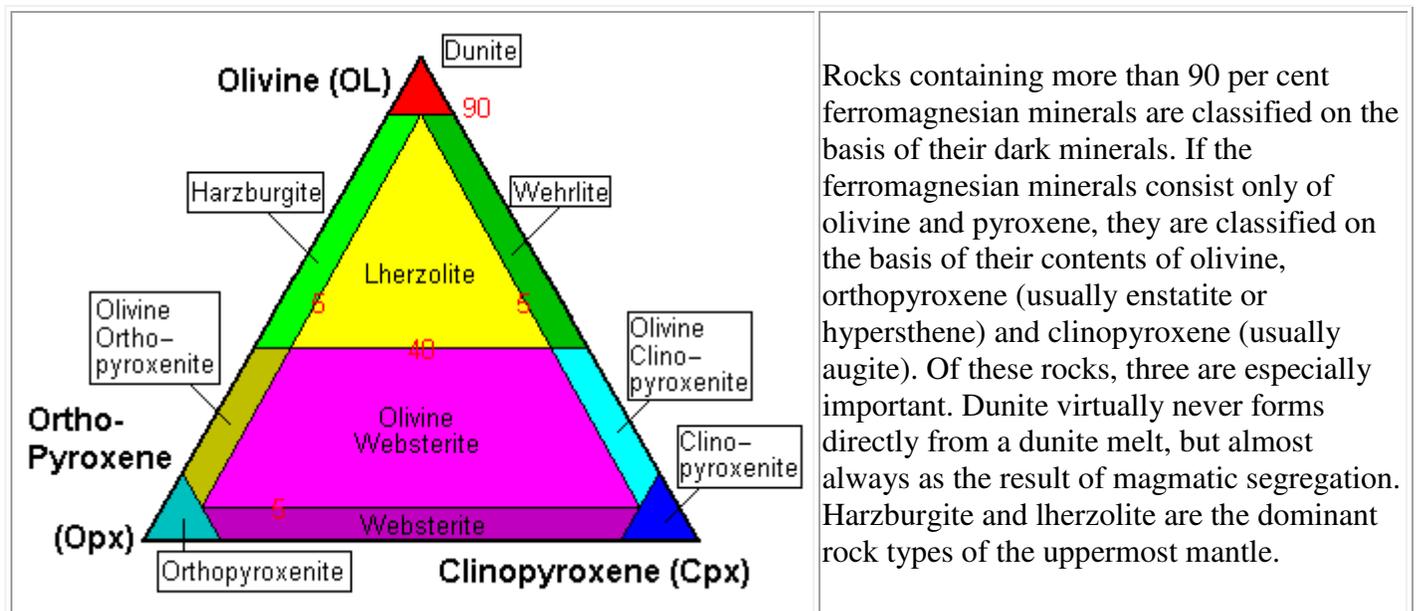
The term "alkali feldspar" refers to K-feldspar or albite (less than 10% anorthite). These feldspars form a fairly complete solid solution series. Any plagioclase richer than 10% anorthite is considered plagioclase.

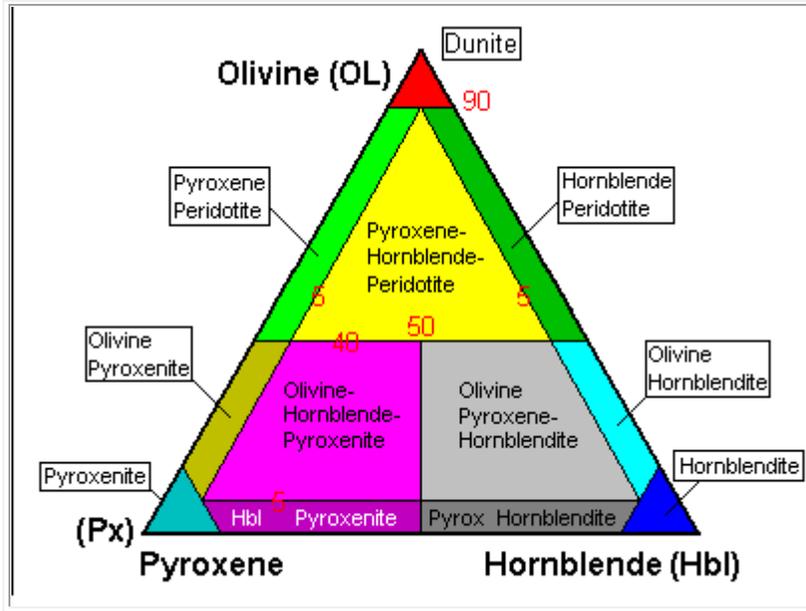
Gabbroic Rocks

Rocks with mostly plagioclase are termed *gabbro* or *diorite*. There are several subcategories of these rocks.

Rocks with less than 5 per cent ferromagnesian minerals (i.e. mostly made of plagioclase) are termed *anorthosite*. Rocks with over 40 % ferromagnesian minerals are generally termed *gabbro*. Rocks with 5-40 percent ferromagnesian minerals are termed *diorite* if their feldspar consists of less than 50 percent anorthite, or leucogabbro (*leuco-* is a Greek prefix meaning light or white) if their feldspar consists of more than 50 percent anorthite.

Ultramafic Rocks





If hornblende is present as well, the classification is based on the relative amounts of olivine, pyroxene and amphibole. Rocks consisting of more than 90 percent of any component are termed dunite, pyroxenite or hornblendite, respectively. Rocks consisting of mostly olivine are termed *peridotite*. (*Peridot* is the name of a gem variety of olivine.)

Volcanic Rocks

Volcanic rocks are classified in almost exactly the same way as plutonic rocks. The principal difference is that volcanic rock names are substituted for their plutonic equivalents:

Plutonic Rock	Volcanic Equivalent
Granite	Rhyolite
Granodiorite	Dacite
Tonalite	Quartz Andesite
Syenite	Trachyte
Monzonite	Latite
Diorite	Andesite
Gabbro	Basalt
Monzogabbro (or diorite)	Latite-basalt (or andesite)

Volcanic rocks of extreme foid or ultramafic composition are extremely rare.

The CIPW Norm

The CIPW norm is named for the four petrologists, Cross, Iddings, Pirsson and Washington, who devised it in 1931

What is a Norm and Why is it Needed?

A norm is a means of converting the chemical composition of an igneous rock to an ideal mineral composition. It often reveals similarities in rocks that have quite different *modes*, or observed mineral assemblages. Some of the factors that can cause such variations are:

- Disequilibrium (for example, zoned minerals or reaction rims isolating the interiors of grains)
 - Temperature
 - Pressure
 - Alteration
- Water content (otherwise identical rocks might contain biotite, amphibole, or pyroxene, depending on water content)
- Other minor constituents. For example, excess sulfur or chlorine might cause scapolite to form instead of feldspar. Boron typically causes tourmaline to form.

The CIPW norm calculates mineral composition as if the magma were anhydrous (water is simply treated as a separate phase) and at low pressure. Other more complex norms have been devised for high-pressure or very hydrous situations. In an ideal world, a norm would match the observed mineral phases perfectly. To create such a norm, we would have to understand magma crystallization perfectly (and we don't), and the norm would be extremely complex to calculate.

Logic of Calculation

The logic of calculating a norm is simple even if the steps are tedious. Deal with the simplest and most predictable minerals first, then apply corrections if the rock is silica-deficient.

- Allocate the most predictable elements
 - Allot Common Substitution Elements to Major Elements
Nickel and manganese are combined with ferrous iron, strontium and barium with calcium.

- Allot Minor Elements to Accessory Minerals. These include P (Apatite), S, (Pyrite), Cr (Chromite), F, (Fluorite), CO₂ (Calcite) and Zr (Zircon)
- Allot Titanium to ilmenite or sphene. Later on, Ti may need to be allotted to perovskite or rutile.
 - Allot Calcium and Aluminum to anorthite.
 - Provisionally form silica-saturated silicates
 - Provisionally Allot Alkalis and Aluminum
 - Begin Alloting Iron and Magnesium
 - Create Provisional Pyroxenes
 - Silica Excess forms Quartz
 - If there is no silica deficit, calculation is complete.
 - Convert Provisional Minerals to Remove Silica Deficit
 - Convert Hypersthene to Olivine
 - Convert Sphene to Perovskite
 - Convert Albite to Nepheline
 - Convert Orthoclase to Leucite
- Convert Wollastonite and Diopside to Calcium Orthosilicate (Rare)
 - Convert Orthoclase to Kaliophilite (Rare)

Calculating the Norm

Preliminary Comments

- **Convert all weight percentages to molecular percentages.**
- All quantities are running amounts; that is, use the quantity remaining after any previous calculations.
- Formulas follow common computer program syntax. For example, FeO = FeO + MnO + NiO means sum FeO, MnO and NiO, then replace the value of FeO with the calculated value.
- Provisional calculations are denoted by P*; for example, P*Albite means a provisional quantity for albite, which may be converted later on to nepheline. Any provisional amounts remaining at the end become final amounts.

Allot Common Substitution Elements to Major Elements

- FeO = FeO + MnO + NiO
- CaO = CaO + BaO + SrO

Allot Minor Elements to Accessory Minerals

- Apatite = P₂O₅, CaO = CaO - (10/3)P₂O₅, P₂O₅ = 0
 - Pyrite = S, FeO = FeO - S/2, S = 0
- Chromite = Cr₂O₃, FeO = FeO - Cr₂O₃, Cr₂O₃ = 0
 - Fluorite = F, CaO = CaO - F, F = 0
 - Calcite = CO₂, CaO = CaO - CO₂, CO₂ = 0
 - Zircon = ZrO₂, SiO₂ = SiO₂ - ZrO₂, ZrO₂ = 0

Allot Titanium

- If FeO exceeds Titanium then Ilmenite = TiO_2 , $FeO = FeO - TiO_2$, $TiO_2 = 0$
 - If TiO_2 exceeds FeO then:
P*Sphe = TiO_2 , $CaO = CaO - TiO_2$, $SiO_2 = SiO_2 - TiO_2$, $TiO_2 = 0$

Provisionally Allot Alkalis and Aluminum

- P*Orthoclase = K_2O , $Al_2O_3 = Al_2O_3 - K_2O$, $SiO_2 = SiO_2 - 6 K_2O$
 - If Al_2O_3 exceeds Na_2O then:
P*Albite = Na_2O , $Al_2O_3 = Al_2O_3 - Na_2O$, $SiO_2 = SiO_2 - 6 Na_2O$, $Na_2O = 0$
 - If Na_2O exceeds Al_2O_3 then:
 - Albite = Al_2O_3 , $Na_2O = Na_2O - Al_2O_3$, $SiO_2 = SiO_2 - 6 Na_2O$, $Al_2O_3 = 0$
 - Aegerine = Na_2O , $Fe_2O_3 = Fe_2O_3 - Na_2O$, $SiO_2 = SiO_2 - 4 Na_2O$
 - In the very rare case where Na_2O is left over due to insufficient Fe_2O_3 , allot it to sodium metasilicate. $SiO_2 = SiO_2 - Na_2O$.
 - If Al_2O_3 is left after allotting orthoclase and albite, then:
Anorthite = Al_2O_3 , $CaO = CaO - Al_2O_3$, $SiO_2 = SiO_2 - 2 Al_2O_3$, $Al_2O_3 = 0$
 - If Al_2O_3 exceeds CaO in the preceding calculation, then:
 - Anorthite = CaO , $Al_2O_3 = Al_2O_3 - CaO$, $SiO_2 = SiO_2 - 2 CaO$
 - Corundum = Al_2O_3 , $CaO = 0$, $Al_2O_3 = 0$

Begin Alloting Iron and Magnesium

- If FeO exceeds Fe_2O_3 then:
Magnetite = Fe_2O_3 , $FeO = FeO - Fe_2O_3$, $Fe_2O_3 = 0$
 - If Fe_2O_3 exceeds FeO then:
Magnetite = FeO , $Fe_2O_3 = Fe_2O_3 - FeO$, $FeO = 0$, Hematite = Fe_2O_3 , $Fe_2O_3 = 0$
- From here on, all FeO and MgO go to pyroxene plus olivine, but their relative proportions are maintained in all minerals. The sum of MgO plus FeO is designated FM in what follows.

Create Provisional Pyroxenes

- If FM exceeds CaO then:
 - P*Diopside = CaO , $FM = FM - CaO$, $SiO_2 = SiO_2 - CaO$, $CaO = 0$
 - P*Hypersthene = FM , $SiO_2 = SiO_2 - FM$
 - If CaO exceeds FM then:
 - P*Diopside = FM , $CaO = CaO - FM$, $SiO_2 = SiO_2 - 2 CaO$, $FM = 0$
 - P*Wollastonite = CaO , $SiO_2 = SiO_2 - CaO$

Deal With Silica Excess or Deficit

- If SiO_2 is still positive then: Quartz = SiO_2 , $SiO_2 = 0$, **Calculation Finished**

- If SiO_2 is negative, then we must convert some of the P*minerals. Call the silica deficit D ($D = -\text{SiO}_2$) and proceed as follows. Whenever $D = 0$, the calculation is done.

Convert Provisional Minerals to Remove Silica Deficit

Form Olivine

- If D is less than $1/2$ of P*hypersthene, then:
Olivine = D, Hypersthene = P*Hypersthene - 2D, D = 0, **Calculation Finished**
- If D is greater than $1/2$ of P*hypersthene, then:
Olivine = P*Hypersthene, D = D - $1/2$ (P*Hypersthene), Hypersthene = 0,

Form Perovskite

- If D is less than P*Sphene, then:
Perovskite = D, Sphene = P*Sphene - D, D = 0, **Calculation Finished**
- If D is greater than P*Sphene, then:
Perovskite = P*Sphene, D = D - P*Sphene, Sphene = 0
- Any excess TiO_2 is accounted as Rutile

Form Nepheline

- If D is less than 4 (P*Albite) then:
Nepheline = D/4, Albite = P*Albite - D/4, P*Albite = 0, D = 0, **Calculation Finished**
- If D is greater than 4 (P*Albite) then:
Nepheline = P*Albite, D = D - 4 (P*Albite), Albite = 0

Form Leucite

- If D is less than 2 (P*Orthoclase) then:
Leucite = D/2, Orthoclase = P*Orthoclase - D/2, P*Orthoclase = 0, D = 0, **Calculation Finished**
- If D is greater than 2 (P*Orthoclase) then:
Leucite = P*Orthoclase, D = D - 2 (P*Orthoclase), Orthoclase = 0

Form Calcium Orthosilicate (Rare)

- If D is less than $(1/2)$ (P*Wollastonite) then: Calcium Orthosilicate = D, Wollastonite = P*Wollastonite - 2D, D = 0, **Calculation Finished**
- If D is greater than $(1/2)$ (P*Wollastonite) then: Calcium Orthosilicate = P*Wollastonite, D = P*Wollastonite/2, Wollastonite = 0
- If there is *still* a deficit, convert Diopside to Olivine + Calcium Orthosilicate as follows:

- If D is less than $P \cdot \text{Diopside}$ then:
 Additional Calcium Orthosilicate = $D/2$, Additional Olivine = $D/2$. Add these amounts to the previously-formed minerals. Diopside = $P \cdot \text{Diopside} - D$, $D = 0$, **Calculation Finished**
- If D is greater than $P \cdot \text{Diopside}$ then:
 Additional Calcium Orthosilicate = $P \cdot \text{Diopside}/2$, Additional Olivine = $P \cdot \text{Diopside}/2$. Add these amounts to the previously-formed minerals. $D = D - P \cdot \text{Diopside}$, Diopside = 0

Form Kaliophilite (Rare)

If there is *still* a deficit, convert Leucite to Kaliophilite: Kaliophilite = $D/2$, Leucite = Leucite - $D/2$, $D = 0$, **Calculation Finished**

Convert all remaining provisional minerals, if any, to final quantities.

(COMPILED BY GDC HANDWARA)

Lecture notes, 2nd semester unit-1

Petrology & Petrography

Petrology - The branch of geology dealing with the origin, occurrence, structure, and history of rocks.

Petrography - The branch of geology dealing with the description and systematic classification of rocks, especially by microscopic examination of thin sections. Petrography is a subfield of Petrology.

In this course, most of the lecture material falls under the field of Petrology, while much of the laboratory material falls in the field of Petrography.

Introduction to Igneous Rocks

An *igneous rock* is any crystalline or glassy rock that forms from cooling of a magma.

A *magma* consists mostly of liquid rock matter, but may contain crystals of various minerals, and may contain a gas phase that may be dissolved in the liquid or may be present as a separate gas phase.

Magma can cool to form an igneous rock either on the surface of the Earth - in which case it produces a *volcanic* or *extrusive igneous rock*, or beneath the surface of the Earth, - in which case it produces a *plutonic* or *intrusive igneous rock*.

Characteristics of Magma

Types of Magma

Types of magma are determined by chemical composition of the magma. Three general types are recognized, but we will look at other types later in the course:

1. *Basaltic magma* -- SiO₂ 45-55 wt%, high in Fe, Mg, Ca, low in K, Na
2. *Andesitic magma* -- SiO₂ 55-65 wt%, intermediate in Fe, Mg, Ca, Na, K
3. *Rhyolitic magma* -- SiO₂ 65-75%, low in Fe, Mg, Ca, high in K, Na

Gases in Magmas

At depth in the Earth nearly all magmas contain gas dissolved in the liquid, but the gas forms a separate vapor phase when pressure is decreased as magma rises toward the surface. This is similar to carbonated beverages which are bottled at high pressure. The high pressure keeps the gas in solution in the liquid, but when pressure is decreased, like when you open the can or bottle, the gas comes out of solution and forms a separate gas phase that you see as bubbles. Gas gives magmas their explosive character, because volume of gas expands as pressure is

reduced. The composition of the gases in magma are:

- Mostly H₂O (water vapor) with some CO₂ (carbon dioxide)
- Minor amounts of Sulfur, Chlorine, and Fluorine gases

The amount of gas in a magma is also related to the chemical composition of the magma. Rhyolitic magmas usually have higher dissolved gas contents than basaltic magmas.

Temperature of Magmas

Temperature of magmas is difficult to measure (due to the danger involved), but laboratory measurement and limited field observation indicate that the eruption temperature of various magmas is as follows:

- Basaltic magma - 1000 to 1200°C
- Andesitic magma - 800 to 1000°C
- Rhyolitic magma - 650 to 800°C.

Viscosity of Magmas

Viscosity is the resistance to flow (opposite of fluidity). Viscosity depends on primarily on the composition of the magma, and temperature.

- Higher SiO₂ (silica) content magmas have higher viscosity than lower SiO₂ content magmas (viscosity increases with increasing SiO₂ concentration in the magma).
- Lower temperature magmas have higher viscosity than higher temperature magmas (viscosity decreases with increasing temperature of the magma).

Thus, basaltic magmas tend to be fairly fluid (low viscosity), but their viscosity is still 10,000 to 100,000 times more viscous than water. Rhyolitic magmas tend to have even higher viscosity, ranging between 1 million and 100 million times more viscous than water. (Note that solids, even though they appear solid have a viscosity, but it is very high, measured as trillions time the viscosity of water). Viscosity is an important property in determining the eruptive behavior of magmas.

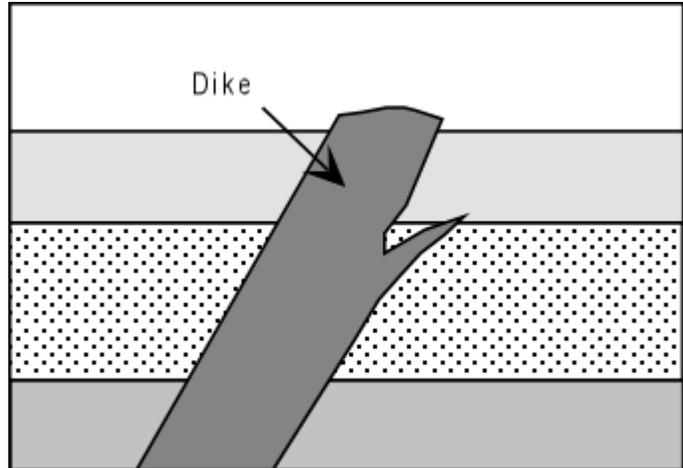
Magma Type	Solidified Rock	Chemical Composition	Temperature	Viscosity	Gas Content
Basaltic	Basalt	45-55 SiO ₂ %, high in Fe, Mg, Ca, low in K, Na	1000 - 1200 °C	10 - 10 ³ PaS	Low
Andesitic	Andesite	55-65 SiO ₂ %, intermediate in Fe, Mg, Ca, Na, K	800 - 1000 °C	10 ³ - 10 ⁵ PaS	Intermediate
Rhyolitic	Rhyolite	65-75 SiO ₂ %, low in Fe, Mg, Ca, high in K, Na.	650 - 800 °C	10 ⁵ - 10 ⁹ PaS	High

Plutonic (Intrusive) Igneous Rocks

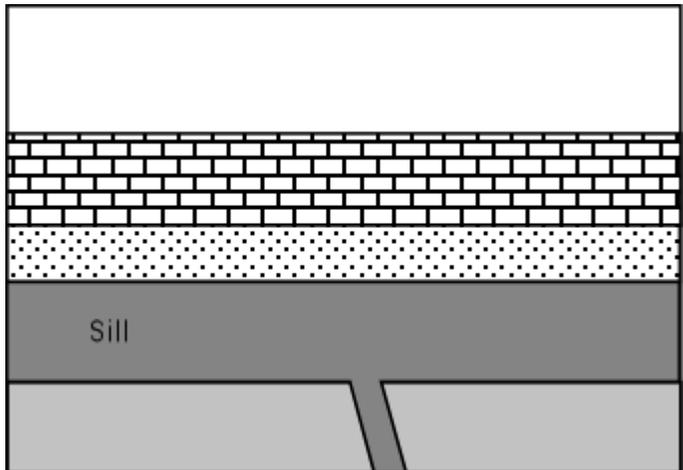
Hypabyssal Intrusions

Intrusions that intrude rocks at shallow levels of the crust are termed hypabyssal intrusions. Shallow generally refers to depths less than about 1 km. Hypabyssal intrusions always show sharp contact relations with the rocks that they intrude. Several types are found:

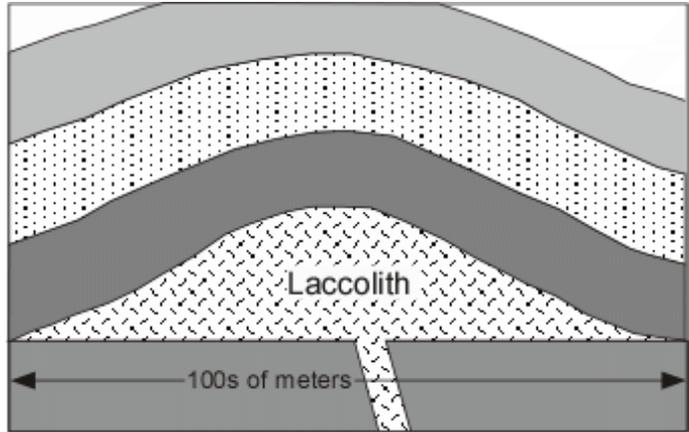
- **Dikes** are small (<20 m wide) shallow intrusions that show a discordant relationship to the rocks in which they intrude. Discordant means that they cut across preexisting structures. They may occur as isolated bodies or may occur as swarms of dikes emanating from a large intrusive body at depth.



- **Sills** are also small (<50 m thick) shallow intrusions that show a concordant relationship with the rocks that they intrude. Sills usually are fed by dikes, but these may not be exposed in the field.



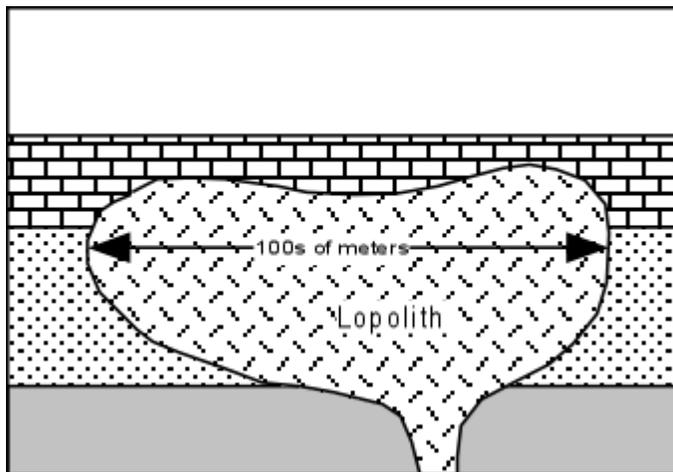
- **Laccoliths** are somewhat large intrusions that result in uplift and folding of the preexisting rocks above the intrusion. They are also concordant types of intrusions.



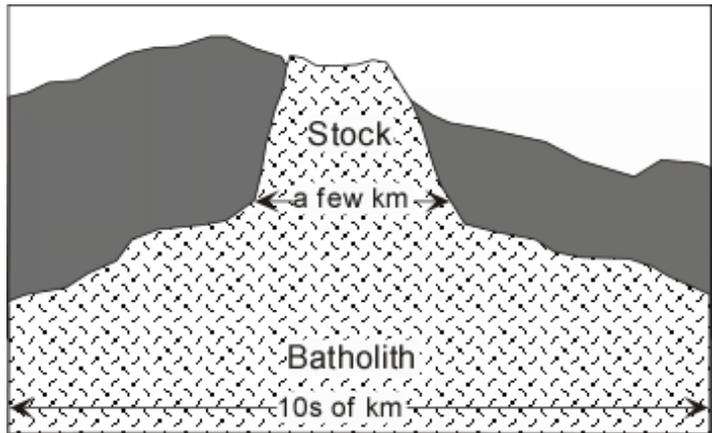
Plutons

Plutons are generally much larger intrusive bodies that have intruded much deeper in the crust. Although they may show sharp contacts with the surrounding rocks into which they intruded, at deeper levels in the crust the contacts are often gradational.

- **Lopoliths** are relatively small plutons that usually show a concave downward upper surface. This shape may have resulted from the reduction in volume that occurs when magmas crystallize, with the weight of the overlying rocks causing collapse of into the space once occupied by the magma when it had a larger volume as a liquid.



- **Batholiths** are very large intrusive bodies, usually so large that their bottoms are rarely exposed. Sometimes they are composed of several smaller intrusions.
- **Stocks** are smaller bodies that are likely fed from deeper level batholiths. Stocks may have been feeders for volcanic eruptions, but because large amounts of erosion are required to expose a stock or batholith, the associated volcanic rocks are rarely exposed.



Volcanic (Extrusive) Igneous Rocks

Volcanic Eruptions

- In general, magmas that are generated deep within the Earth begin to rise because they are less dense than the surrounding solid rocks.
- As they rise they may encounter a depth or pressure where the dissolved gas no longer can be held in solution in the magma, and the gas begins to form a separate phase (i.e. it makes bubbles just like in a bottle of carbonated beverage when the pressure is reduced).
- When a gas bubble forms, it will also continue to grow in size as pressure is reduced and more of the gas comes out of solution. In other words, the gas bubbles begin to expand.
- If the liquid part of the magma has a low viscosity, then the gas can expand relatively easily. When the magma reaches the surface, the gas bubble will simply burst, the gas will easily expand to atmospheric pressure, and a non-explosive eruption will occur, usually as a lava flow (*Lava* is the name we give to a magma on the surface of the Earth).
- If the liquid part of the magma has a high viscosity, then the gas will not be able to expand easily. Thus, pressure will build inside the gas bubble(s). When the magma reaches the surface, the gas bubbles will have a high pressure inside, which will cause them to burst explosively on reaching atmospheric pressure. This will cause an explosive volcanic eruption.

Explosive Eruptions

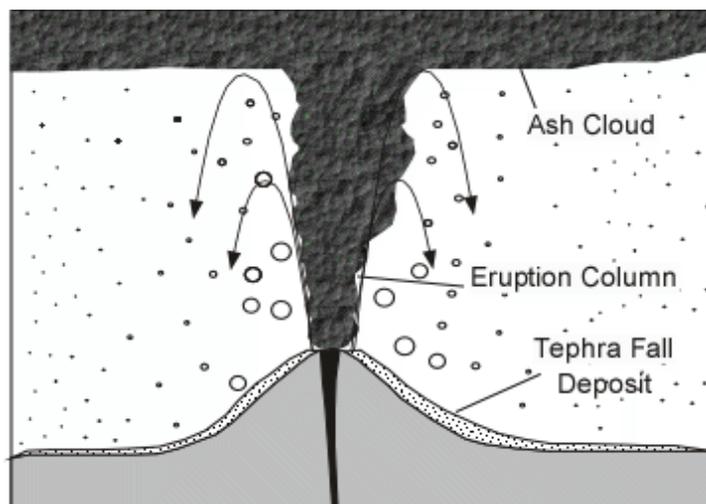
Explosive eruptions are favored by high gas content and high viscosity (andesitic to rhyolitic

magmas).

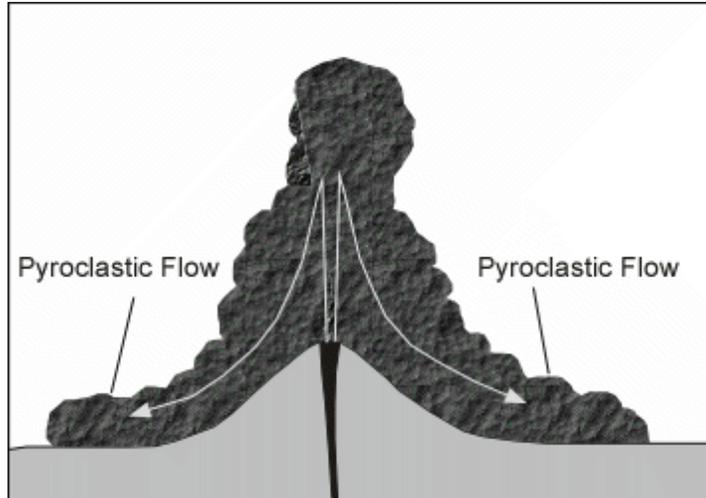
- Explosive bursting of bubbles will fragment the magma into clots of liquid that will cool as they fall through the air. These solid particles become *pyroclasts* (meaning - hot fragments) and *tephra* or *volcanic ash*, which refer to sand- sized or smaller fragments.

Tephra and Pyroclastic Rocks		
Average Particle Size (mm)	Unconsolidated Material (Tephra)	Pyroclastic Rock
>64	Bombs or Blocks	Agglomerate
2 - 64	Lapilli	Lapilli Tuff
<2	Ash	Ash Tuff

- Blocks** are angular fragments that were solid when ejected.
 - Bombs** have an aerodynamic shape indicating they were liquid when ejected.
 - Bombs and lapilli that consist mostly of gas bubbles (*vesicles*) result in a low density highly vesicular rock fragment called *pumice*.
- Clouds of gas and tephra that rise above a volcano produce an *eruption column* that can rise up to 45 km into the atmosphere. Eventually the tephra in the eruption column will be picked up by the wind, carried for some distance, and then fall back to the surface as a *tephra fall* or *ash fall*.



- If the eruption column collapses a **pyroclastic flow** will occur, wherein gas and tephra rush down the flanks of the volcano at high speed. This is the most dangerous type of volcanic eruption. The deposits that are produced are called **ignimbrites** if they contain pumice or **pyroclastic flow deposits** if they contain non-vesicular blocks.



Nonexplosive Eruptions

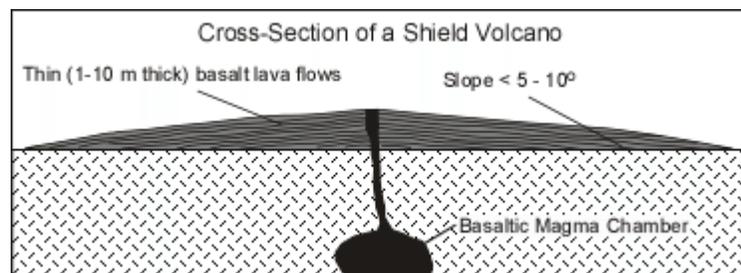
Non explosive eruptions are favored by low gas content and low viscosity magmas (basaltic to andesitic magmas).

- If the viscosity is low, nonexplosive eruptions usually begin with fire fountains due to release of dissolved gases.
- Lava flows are produced on the surface, and these run like liquids down slope, along the lowest areas they can find.
- Lava flows produced by eruptions under water are called **pillow lavas**.
- If the viscosity is high, but the gas content is low, then the lava will pile up over the vent to produce a **lava dome** or **volcanic dome**.

Volcanic Landforms

Shield Volcanoes

- A shield volcano is characterized by gentle upper slopes (about 5°) and somewhat steeper lower slopes (about 10°).

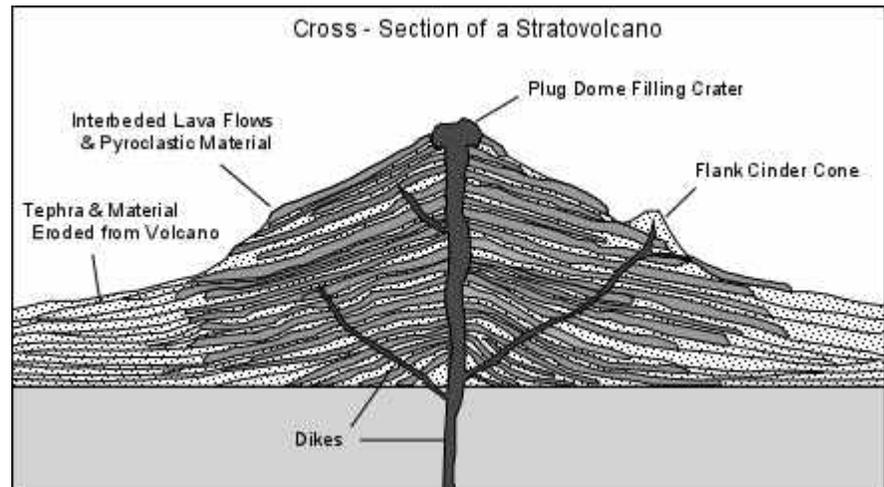


- Shield volcanoes are composed almost entirely of thin lava flows built up over a central vent.
- Most shields are formed by low viscosity basaltic magma that flows easily down slope away from a summit vent.
- The low viscosity of the magma allows the lava to travel down slope on a gentle slope, but as it cools and its viscosity increases, its thickness builds up on the lower slopes giving a somewhat steeper lower slope.
- Most shield volcanoes have a roughly circular or oval shape in map view.

- Very little pyroclastic material is found within a shield volcano, except near the eruptive vents, where small amounts of pyroclastic material accumulate as a result of fire fountaining events.

Stratovolcanoes (also called **Composite Volcanoes**)

- Have steeper slopes than shields, with slopes of $6 - 10^\circ$ low on the flanks to 30° near the summit.
- Steep slope near the summit result from thick, short viscous lava flows that don't travel far from the vent.

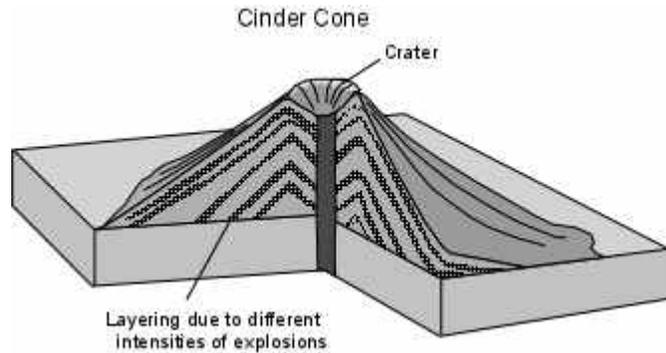


- The gentler slopes near the base are due to accumulations of material eroded from the volcano and to the accumulation of pyroclastic material.
- Stratovolcanoes show inter-layering of lava flows and pyroclastic material, which is why they are sometimes called composite volcanoes. Pyroclastic material can make up over 50% of the volume of a stratovolcano.
- Lavas and pyroclastics are usually andesitic to rhyolitic in composition.
- Due to the higher viscosity of magmas erupted from these volcanoes, they are usually more explosive than shield volcanoes.
- Stratovolcanoes sometimes have a crater at the summit, that is formed by explosive ejection of material from a central vent. Sometimes the craters have been filled in by lava flows or lava domes, sometimes they are filled with glacial ice, and less commonly they are filled with water.
- Long periods of repose (times of inactivity) lasting for hundreds to thousands of years, make this type of volcano particularly dangerous, since many times they have shown no historic activity, and people are reluctant to heed warnings about possible eruptions.

Tephra Cones (also called **Cinder Cones**)

- Tephra cones are small volume cones consisting predominantly of tephra that result from strombolian eruptions. They usually consist of basaltic to andesitic material.
- They are actually fall deposits that are built surrounding the eruptive vent.

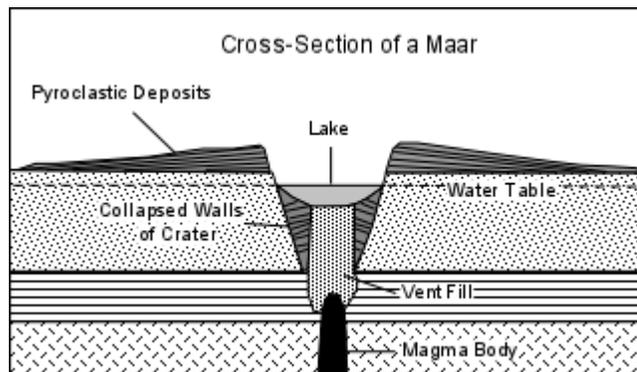
- Slopes of the cones are controlled by the angle of repose (angle of stable slope for loose unconsolidated material) and are usually between about 25 and 35°.
- They show an internal layered structure due to varying intensities of the explosions that deposit different sizes of pyroclastics.



- On young cones, a depression at the top of the cone, called a crater, is evident, and represents the area above the vent from which material was explosively ejected. Craters are usually eroded away on older cones.
- If lava flows are emitted from tephra cones, they are usually emitted from vents on the flank or near the base of the cone during the later stages of eruption.
- Cinder and tephra cones usually occur around summit vents and flank vents of stratovolcanoes.
- An excellent example of cinder cone is Parícutin Volcano in Mexico. This volcano was born in a farmers corn field in 1943 and erupted for the next 9 years. Lava flows erupted from the base of the cone eventually covered two towns.
- Cinder cones often occur in groups, where tens to hundreds of cones are found in one area

Maars

- Maars result from phreatic or phreatomagmatic activity, wherein magma heats up water in the groundwater system, pressure builds as the water turns to steam, and then the water and preexisting rock (and some new magma if the eruption is phreatomagmatic) are blasted out of the ground to form a tephra cone with gentle slopes.



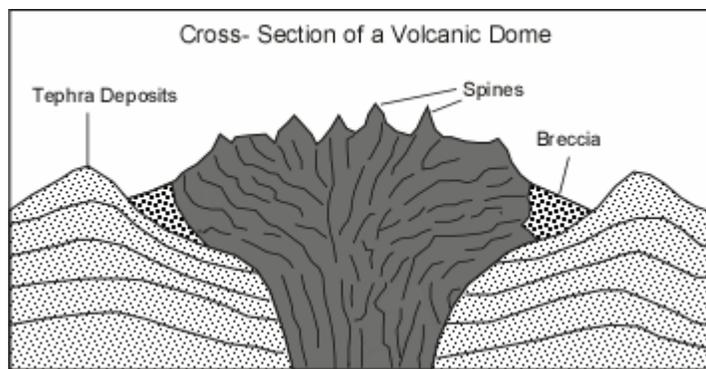
Parts of the crater walls eventually collapse back into the crater, the vent is filled with loose material, and, if the crater still is deeper than the water table, the crater fills with

water to form a lake, the lake level coinciding with the water table.

Lava Domes (also called Volcanic Domes)

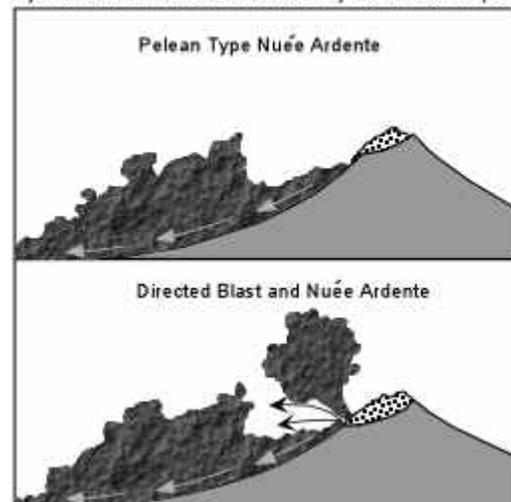
- Volcanic Domes result from the extrusion of highly viscous, gas poor andesitic and rhyolitic lava. Since the viscosity is so high, the lava does not flow away from the vent, but instead piles up over the vent.

- Blocks of nearly solid lava break off the outer surface of the dome and roll down its flanks to form a breccia around the margins of domes.
- The surface of volcanic domes are generally very rough, with numerous spines that have been pushed up by the magma from below.



- Most dome eruptions are preceded by explosive eruptions of more gas rich magma, producing a tephra cone into which the dome is extruded.
- Volcanic domes can be extremely dangerous. because they form unstable slopes that may collapse to expose gas-rich viscous magma to atmospheric pressure. This can result in lateral blasts or Pelean type pyroclastic flow (nuee ardent) eruptions.

Pyroclastic Flows Generated by Dome Collapse



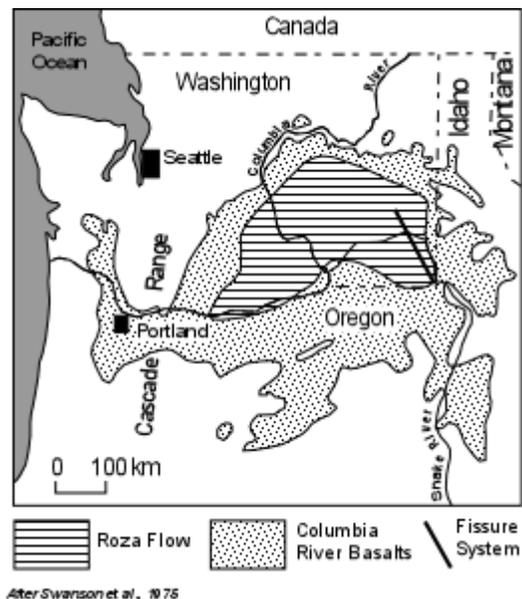
Craters and Calderas

- Craters are circular depressions, usually less than 1 km in diameter, that form as a result of explosions that emit gases and tephra.

- Calderas are much larger depressions, circular to elliptical in shape, with diameters ranging from 1 km to 50 km. Calderas form as a result of collapse of a volcanic structure. The collapse results from evacuation of the underlying magma chamber.
- In shield volcanoes, like in Hawaii, the evacuation of the magma chamber is a slow drawn out processes, wherein magma is withdrawn to erupt on from the rift zones on the flanks.
- In stratovolcanoes the collapse and formation of a caldera results from rapid evacuation of the underlying magma chamber by voluminous explosive eruptions that form extensive fall deposits and pyroclastic flows.
- Calderas are often enclosed depressions that collect rain water and snow melt, and thus lakes often form within a caldera.

Plateau Basalts or Flood Basalts

- Plateau or Flood basalts are extremely large volume outpourings of low viscosity basaltic magma from fissure vents. The basalts spread huge areas of relatively low slope and build up plateaus.
- The only historic example occurred in Iceland in 1783, where the Laki basalt erupted from a 32 km long fissure and covered an area of 588 km² with 12 km³ of lava. As a result of this eruption, homes were destroyed, livestock were killed, and crops were destroyed, resulting in a famine that killed 9336 people.
- In Oregon and Washington of the northwestern U.S., the Columbia River Basalts represent a series of lava flows all erupted within about 1 million years 12 million years ago. One of the basalt flows, the Roza flow, was erupted over a period of a few weeks traveled about 300 km and has a volume of about 1500 km³.



Textures of Igneous Rocks

The main factor that determines the texture of an igneous rock is the **cooling rate** (dT/dt)

Other factors involved are:

- The diffusion rate - the rate at which atoms or molecules can move (diffuse) through the

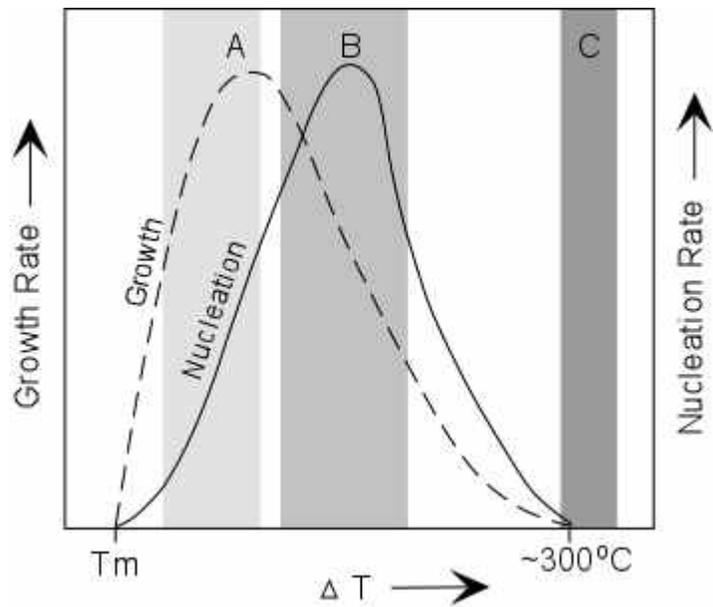
liquid.

- The rate of nucleation of new crystals - the rate at which enough of the chemical constituents of a crystal can come together in one place without dissolving.
- The rate of growth of crystals - the rate at which new constituents can arrive at the surface of the growing crystal. This depends largely on the diffusion rate of the molecules of concern.

In order for a crystal to form in a magma enough of the chemical constituents that will make up the crystal must be at the same place at the same time to form a **nucleus** of the crystal. Once a nucleus forms, the chemical constituents must diffuse through the liquid to arrive at the surface of the growing crystal. The crystal can then grow until it runs into other crystals or the supply of chemical constituents is cut off.

All of these rates are strongly dependent on the temperature of the system. First, nucleation and growth cannot occur until temperatures are below the temperature at which equilibrium crystallization begins. Shown below are hypothetical nucleation and growth rate curves based on experiments in simple systems. Note that the rate of crystal growth and nucleation depends on how long the magma resides at a specified degree of undercooling ($\Delta T = T_m - T$), and thus the rate at which temperature is lowered below the crystallization temperature. Three cases are shown.

1. For small degrees of undercooling (region A in the figure to the right) the nucleation rate will be low and the growth rate moderate. A few crystals will form and grow at a moderate rate until they run into each other. Because there are few nuclei, the crystals will be able to grow to relatively large size, and a coarse grained texture will result. This would be called a **phaneritic texture**.



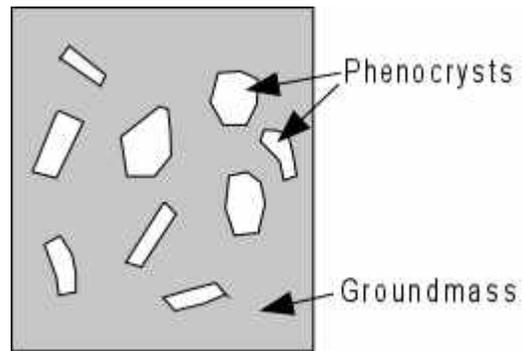
Aphanitic Texture

Phaneritic Texture



- At larger degrees of undercooling, the nucleation rate will be high and the growth rate also high. This will result in many crystals all growing rapidly, but because there are so many crystals, they will run into each other before they have time to grow and the resulting texture will be a fine grained texture. If the size of the grains are so small that crystals cannot be distinguished with a handlens, the texture is said to be **aphanitic**.
- At high degrees of undercooling, both the growth rate and nucleation rate will be low. Thus few crystals will form and they will not grow to any large size. The resulting texture will be glassy, with a few tiny crystals called microlites. A completely glassy texture is called **holohyaline texture**.

Two stages of cooling, i.e. slow cooling to grow a few large crystals, followed by rapid cooling to grow many smaller crystals could result in a **porphyritic texture**, a texture with two or more distinct sizes of grains. Single stage cooling can also produce a porphyritic texture. In a porphyritic texture, the larger grains are called **phenocrysts** and the material surrounding the the phenocrysts is called **groundmass** or **matrix**



In a rock with a phaneritic texture, where all grains are about the same size, we use the grain size ranges shown to the right to describe the texture:

<1 mm	fine grained
1 - 5 mm	medium grained
5 - 3 cm	coarse grained
> 3 cm	very coarse grained

In a rock with a porphyritic texture, we use the above table to define the grain size of the groundmass or matrix, and this table to describe the phenocrysts:

0.03 - 0.3 mm	microphenocrysts
0.3 - 5 mm	phenocrysts
> 5 mm	megaphenocrysts

Another aspect of texture, particularly in medium to coarse grained rocks is referred to as fabric. **Fabric** refers to the mutual relationship between the grains. Three types of fabric are commonly referred to:

- If most of the grains are **euhedral** - that is they are bounded by well-formed crystal faces. The fabric is said to be **idomorphic granular**.
- If most of the grains are **subhedral** - that is they are bounded by only a few well-formed crystal faces, the fabric is said to be **hypidiomorphic granular**.
- If most of the grains are **anhedral** - that is they are generally not bounded by crystal faces, the fabric is said to be **allotriomorphic granular**.

If the grains have particularly descriptive shapes, then it is essential to describe the individual grains. Some common grain shapes are:

- *Tabular* - a term used to describe grains with rectangular tablet shapes.
- *Equant* - a term used to describe grains that have all of their boundaries of approximately equal length.
- *Fibrous* - a term used to describe grains that occur as long fibers.
- *Acicular* - a term used to describe grains that occur as long, slender crystals.
- *Prismatic* - a term used to describe grains that show an abundance of prism faces.

Other terms may apply to certain situations and should be noted if found in a rock.

- *Vesicular* - if the rock contains numerous holes that were once occupied by a gas phase, then this term is added to the textural description of the rock.
- *Glomeroporphyritic* - if phenocrysts are found to occur as clusters of crystals, then the rock should be described as glomeroporphyritic instead of porphyritic.
- *Amygdular* - if vesicles have been filled with material (usually calcite, chalcedony, or quartz, then the term amygdular should be added to the textural description of the rock. An amygdule is defined as a refilled vesicle.
- *Pumiceous* - if vesicles are so abundant that they make up over 50% of the rock and the rock has a density less than 1 (i.e. it would float in water), then the rock is pumiceous.
- *Scoraceous* - if vesicles are so abundant that they make up over 50% of the rock and the rock has a density greater than 1, then the rock is said to be scoraceous.
- *Graphic* - a texture consisting of intergrowths of quartz and alkali feldspar wherein the orientation of the quartz grains resembles cuneiform writing. This texture is most commonly observed in pegmatites.
- *Spherulitic* - a texture commonly found in glassy rhyolites wherein spherical intergrowths of radiating quartz and feldspar replace glass as a result of devitrification.
- *Obicular* - a texture usually restricted to coarser grained rocks that consists of concentrically banded spheres wherein the bands consist of alternating light colored and dark colored minerals.

Other textures that may be evident on microscopic examination of igneous rocks are as follows:

- *Myrmekitic texture* - an intergrowth of quartz and plagioclase that shows small wormlike bodies of quartz enclosed in plagioclase. This texture is found in granites.
- *Ophitic texture* - laths of plagioclase in a coarse grained matrix of pyroxene crystals,

wherein the plagioclase is totally surrounded by pyroxene grains. This texture is common in diabases and gabbros.

- *Subophitic texture* - similar to ophitic texture wherein the plagioclase grains are not completely enclosed in a matrix of pyroxene grains.
- *Poikilitic texture* - smaller grains of one mineral are completely enclosed in large, optically continuous grains of another mineral.
- *Intergranular texture* - a texture in which the angular interstices between plagioclase grains are occupied by grains of ferromagnesium minerals such as olivine, pyroxene, or iron titanium oxides.
- *Intersertal texture* - a texture similar to intergranular texture except that the interstices between plagioclase grains are occupied by glass or cryptocrystalline material.
- *Hyalophitic texture* - a texture similar to ophitic texture except that glass completely surrounds the plagioclase laths.
- *Hyalopilitic texture* - a texture wherein microlites of plagioclase are more abundant than groundmass, and the groundmass consists of glass which occupies the tiny interstices between plagioclase grains.
- *Trachytic texture* - a texture wherein plagioclase grains show a preferred orientation due to flowage, and the interstices between plagioclase grains are occupied by glass or cryptocrystalline material.
- *Coronas or reaction rims* - often times reaction rims or coronas surround individual crystals as a result of the crystal becoming unstable and reacting with its surrounding crystals or melt. If such rims are present on crystals they should be noted in the textural description.
- *Patchy zoning* - This sometimes occurs in plagioclase crystals where irregularly shaped patches of the crystal show different compositions as evidenced by going extinct at angles different from other zones in the crystal.
- *Oscillatory zoning* - This sometimes occurs in plagioclase grains wherein concentric zones around the grain show thin zones of different composition as evidenced by extinction phenomena.
- *Moth eaten texture* (also called *sieve texture*)- This sometimes occurs in plagioclase wherein individual plagioclase grains show an abundance of glassy inclusions.
- *Perthitic texture* - Exsolution lamellae of albite occurring in orthoclase or microc

(COMPILED BY GDC HANDWARA)