Crystallization of Magmas and Phase Diagrams

Igneous Rocks form by the Crystallization of Magmas at or beneath the Earth’s surface

Effects of cooling rate

- Magma cooled very suddenly freezes to glass (basalt must cool more quickly than rhyolite to form glass)
- Magma cooled pretty quickly has many small crystals (microscopic or sub-microscopic) - called aphanitic
- Magma cooled very slowly has big crystals - called phaneritic

How might a porphyritic texture develop?

Porphyritic means????

What happens to a magma as it cools?

- Pure liquids "freeze" (crystallize) at a single temperature (melting T = freezing T)
- Water to ice at 0°C
- SiO₂ liquid to cristobalite at 1740°C
- Impure liquids (like magmas) crystallize over a range of T, crystals are different composition than liquid
- Different minerals form at different temperatures as the magma cools

Sequence of mineral crystallization and T at which different minerals begin to crystallize depends on:
• Magma composition
• Pressure
• Water pressure
• Cooling rate
• and many other factors

Bowen’s Reaction Series (see handout) is a generalization about "typical" Crystallization order of basalts

To really understand igneous crystallization, we need to go beyond Bowen’s Reaction Series

• In the last 50+ years, geochemists have done laboratory experiments on many magma-like liquids
• One Method: Melt a rock, cool liquid to known T, "freeze" it, view it under the microscope, identify minerals - called "cook-and-look"
• Better Method: Start with simple systems, e.g., various proportions of pure Anorthite (Ca-plag, CaAl$_2$Si$_2$O$_8$) and pure Diopside, (pyroxene, CaMgSi$_2$O$_6$), examine results at different Ts

Results are displayed on phase diagrams

• What is a phase? - a homogeneous portion of a system that is physically distinct and mechanically separable from the other parts of the system (p = #phases)
• We also need to know about chemical composition
• components = the minimum number of chemical constituents necessary to describe the compositions of all solids, liquids and gases (phases) in a system (c = #components)

If the System of interest is:

• Quartz, Cristobalite, Tridymite, Stishovite, Coesite and liquid SiO$_2$
• All phases can be described with the single chemical formula SiO$_2$
• 1 component, SiO$_2$
• c=1
For more complex systems, finding the components is a trial-and-error process

- for Olivines and corresponding liquids: $\text{Mg}_2\text{SiO}_4$(Ol or liq.), $\text{Fe}_2\text{SiO}_4$(Ol or liq.), $\text{MgFeSiO}_4$(Ol or liq.), $\text{Mg}_{1.5}\text{Fe}_{0.5}\text{SiO}_4$(Ol or liq.), etc.
- try elements: Mg, Fe, Si, O 4
- try oxides: MgO, FeO, SiO$_2$ 3
- try mineral end-members: Mg$_2$SiO$_4$, Fe$_2$SiO$_4$ 2*
- 2 is the smallest number, therefore, Mg$_2$SiO$_4$ and Fe$_2$SiO$_4$ are the components, and c=2

For Olivines (Mg$_2$SiO$_4$ - Fe$_2$SiO$_4$) and Orthopyroxenes (MgSiO$_3$ - FeSiO$_3$) and corresponding liquids

- try mineral end-members: Mg$_2$SiO$_4$, Fe$_2$SiO$_4$, MgSiO$_3$, FeSiO$_3$ 4
- try oxides: MgO, FeO, SiO$_2$ 3*
- try elements: Mg, Fe, Si, O 4
- 3 is the smallest number, so MgO, FeO, and SiO$_2$ (oxides this time) are the components, and c=3

The Gibbs Phase Rule

- A generalization about phase diagrams
- by J. Willard Gibbs in the 1870s
- $f =$ degrees of freedom, the number of parameters that can be varied independently without changing the phases present
- $f = 2 + c - p$ (f = #degrees of freedom, c = #components, p = #phases)
- Examples will show what this means
- f=0 invariant (point)
- f=1 univariant (line)
- f=2 divariant (field or area)
- f=3 trivariant

One component system: SiO$_2$ (see handout)

Real Magmas have many components (8 or 9)

- We can’t draw diagrams that represent all those components
• Requires too many dimensions
• But we can learn a lot about crystallization of real magmas (like basalts) by examining several different 2-component systems!

2-component (Binary) Systems

• We’d need 3 dimensions to represent one phase fields (c=2, p=1, f=2+2-1=3; trivariant)
• But, we can only draw diagrams in 2 dimensions easily!
• Hold Pressure (P) constant, lose one degree of freedom, only need 2 dimensions
• Phase rule (at constant P) becomes
• \( f_P = 1 + c - p \)

Simple 2-component system: Diopside (CaMgSi$_2$O$_6$) - Anorthite (CaAl$_2$Si$_2$O$_8$)

Di - An (See handout)

This system is a pretty good simple model for basalts

How do we use this diagram to tell about crystallization of basalt? (follow on handout)

Crystallization of a Diopside (Di) -rich liquid

Crystallization of an Anorthite (An) -rich liquid

Tie-lines and the Lever Rule

View Animated Di-An Diagram

Professor Ken Windom
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Textures of rocks in Di-An System (See handout)
Plagioclase and Pyroxene in Diabase (slightly coarser-grained "basalt")

Plag and Pyroxene Phenocrysts in fine-grained groundmass - porphyritic basalt

Perfect Equilibrium Crystallization

- Crystals that have formed remain in contact with the liquid and continually equilibrate with it
- Constant bulk composition
- Makes little difference in Di-An system
- Contrasted with fractional crystallization, where crystals are physically separated from the liquid in which they were formed, unable to equilibrate

More Complex 2-component system

Forsterite (Mg$_2$SiO$_4$) - Enstatite (MgSiO$_3$) - Silica (SiO$_2$) System

Fo - En - SiO$_2$ (See handout)

Olivine in this Basalt reacted with Liquid to form Orthopyroxene

2-component system with Complete Solid Solution - Albite (NaAlSi$_3$O$_8$) - Anorthite (CaAl$_2$Si$_2$O$_8$) System

Ab-An (See handout)

See Windom Animated phase diagram

Zoned Plagioclase