



Light colored and coarse

**Granite**

Dark colored and fine

**Basalt**

**WHAT DO WE NEED TO EXPLAIN  
ABOUT IGNEOUS ROCKS?**



Light colored and coarse

## **Granite**

Well, for a start, why the great differences between two rocks like these?

Especially when we realize no other planets have granite.

Plus, we also want to know how two igneous rocks like granite and basalt could be related to each other –  
If they are.

Dark colored and fine

## **Basalt**

# ABRAHAM GOTTLOB WERNER

1714-1795



## NEPTUNISM

*Abraham Werner taught that all rocks with a crystalline texture, such as granite and basalt, were precipitated in an orderly sequence from a worldwide, primeval, ocean.*

It has not always been obvious that igneous rocks are the result of extremely high temperatures and volcanic activity.

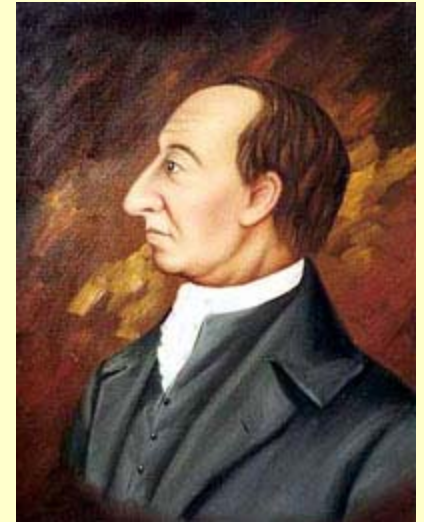
# JAMES HUTTON

1726-1797

“THEORY OF THE EARTH”

## VOLCANISM

*“That whatever be the materials in those two cases, Nature acts upon the same principle in her operations, in consolidating bodies by means of heat and fusion, and by moving great masses of fluid matter in the bowels of the Earth.”*



## James Hutton, Theory of the Earth, 1785

Engraving of *Map, Glen Tilt, Tayside, Scotland* by geologist James Hutton.



*This water color shows granite intruding into metamorphic layering. Hutton used this to argue that rocks like granite were of igneous origin, not water origin, and that not all of Werner's "primitive" rocks were primitive in age. Most Neptunists were not convinced.*

James Hutton, Theory of the Earth, 1785  
*isle of arran, scotland*



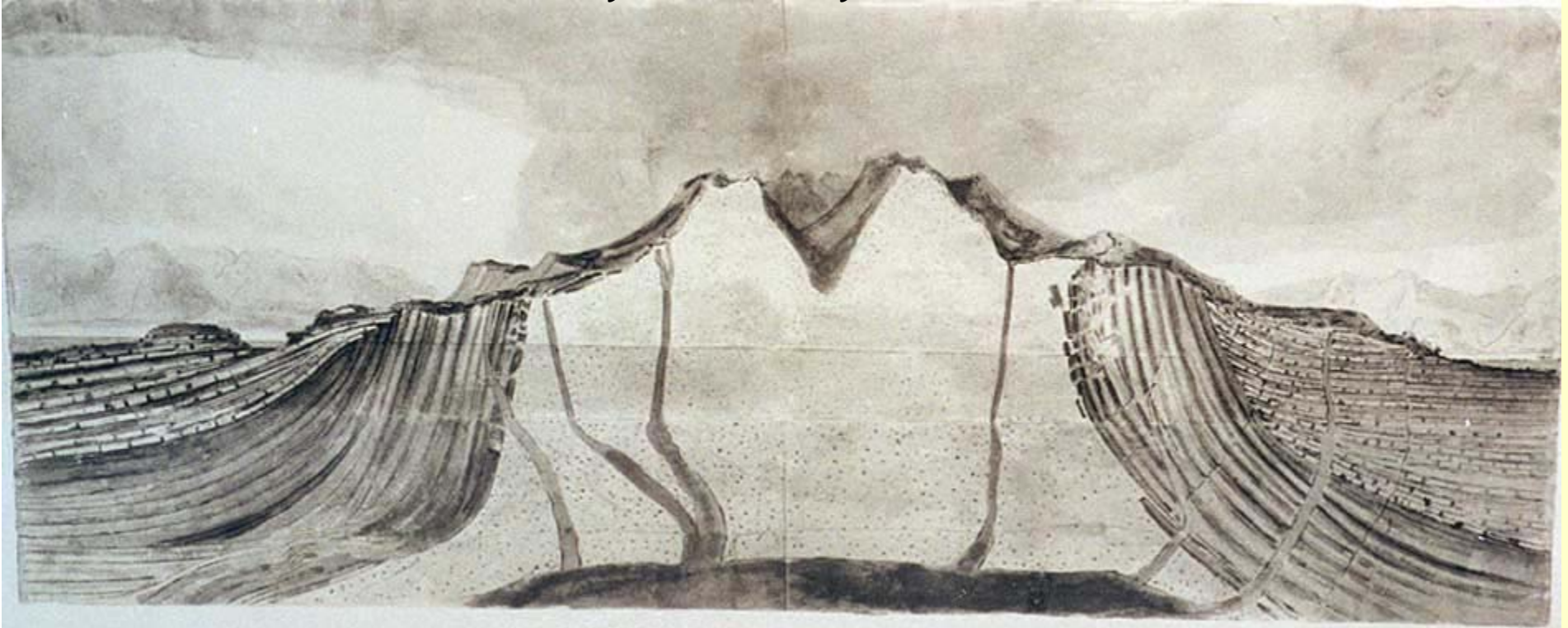
<http://www.worldofmore.com/walking/arran2003/thesaddlepan1.jpg>



<http://www.worldofmore.com/walking/arran2003/>

## James Hutton, Theory of the Earth, 1785

*Reproduction of a Watercolor print done by geologist James Hutton entitled, Detailed East-West Section, Northern Granite, Isle of Arran, Strathclyde or Theory of the Earth.*

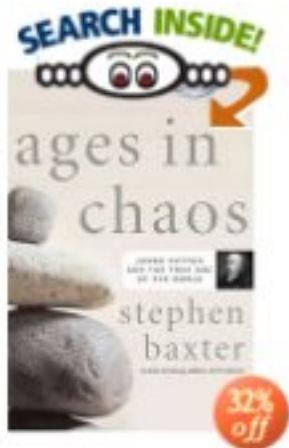


Detailed E-W section, Northern Granite, Isle of Arran, Strathclyde



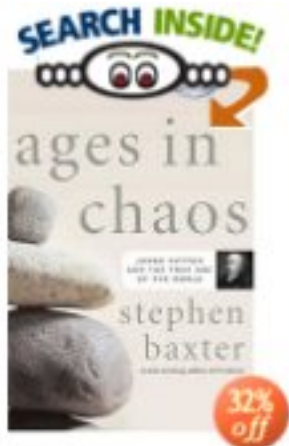
E-W section, Northern Granite, Isle of Arran, Strathclyde

## The Huttonian Theory of the Earth



*“The whole of his argument is an elegant interplay of three key metaphors: the Earth as an orderly Newtonian system, as orderly as the heavens; the Earth as a machine, like Watt’s steam engines; and the Earth as a body of cycles of renewal, like Harvey’s circulating blood.”*





## The Huttonian Theory of the Earth

# *The Earth is a System*

*On Hutton's Earth everything was in balance. Everything cycled; everything revolved. Hutton evoked a whole series of regenerations, of erosion being repaired by consolidation and uplift, as new lands were born from the wreckage of the old, over and over, using his heat-fuelled processes of lithification and uplift. And having no limit in time, a cycling, self-renewing Earth was surely a more perfect design than a world doomed to decay as soon as it was created.*

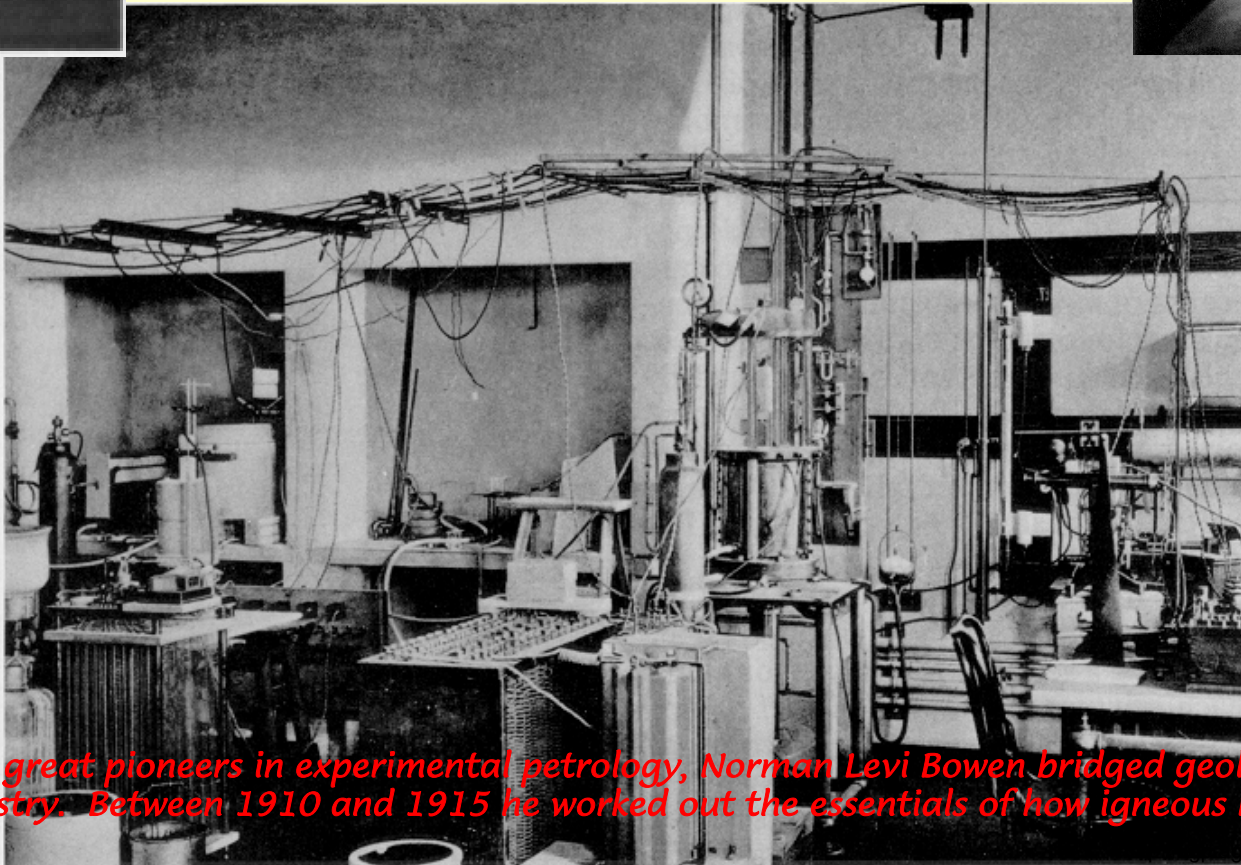


# NORMAN L. BOWEN

## 1887-1956

1928, The evolution of the igneous rocks: 334 p.  
Princeton University Press, Princeton.

# EXPERIMENTAL PETROLOGY



*One of the great pioneers in experimental petrology, Norman Levi Bowen bridged geology and physical chemistry. Between 1910 and 1915 he worked out the essentials of how igneous rocks evolve.*

NORMAN L. BOWEN

1928, The evolution of the  
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*One of the great pioneers in experimental petrology, Norman L. Bowen bridged geology and physical chemistry. Between 1910 and 1928 he worked out the essentials of how igneous rocks evolve.*

**The Evolution of  
Igneous Rocks  
By  
Fractionation**

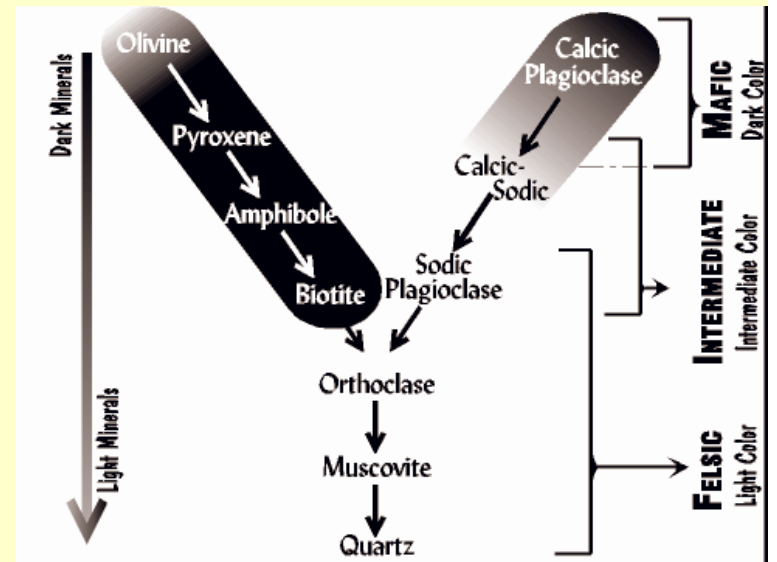
# FACTORS THAT CONTROL HOW AND WHICH IGNEOUS ROCKS FORM FROM A MAGMA

## Composition of the Magma

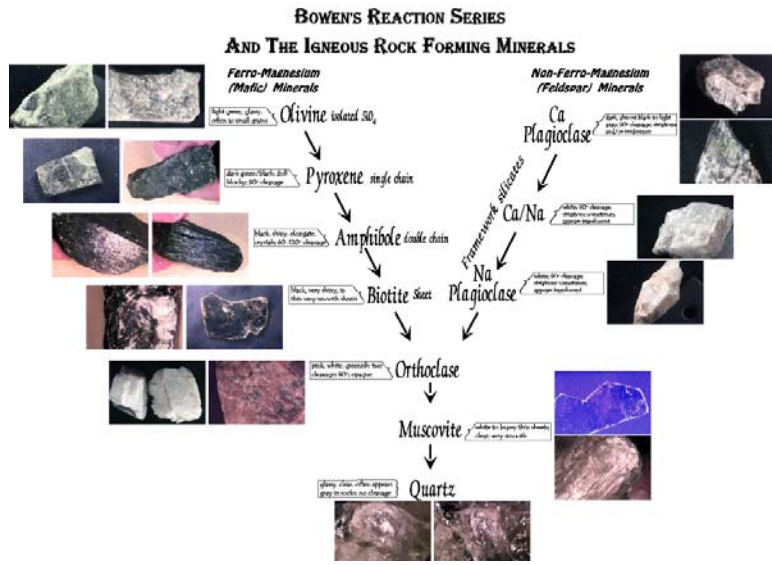
## The Reaction Principle

- *Minerals and rocks are stable only under the conditions at which they form; change the conditions and they must change also.*

## The Fractionation Principle



# BOWEN'S REACTION PRINCIPLE P 84



*Minerals and rocks are stable only under the conditions at which they form; change the conditions and they must change also.*

**Olivine** Reacts with the magma to form **Pyroxene** Reacts with the magma to form **Amphibole**

**CaPlag** Reacts with the magma to form **Ca/NaPlag** Reacts with the magma to form **NaPlag**

*Reaction takes place best when cooling and crystallization is slow and all reactions have a chance to run to completion.*

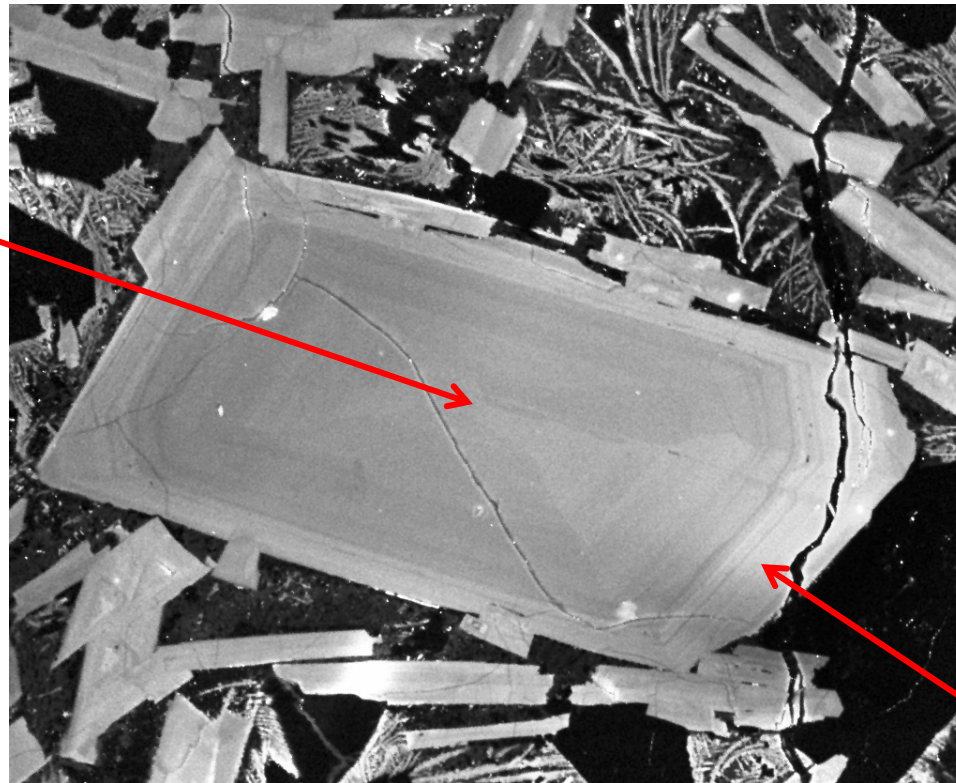
*Minerals keep adjusting to come into equilibrium with the conditions that exist.*

*But, if cooling is too fast, then  
fractionation may occur*

## Zoned crystal of plagioclase

Ca-rich in the center

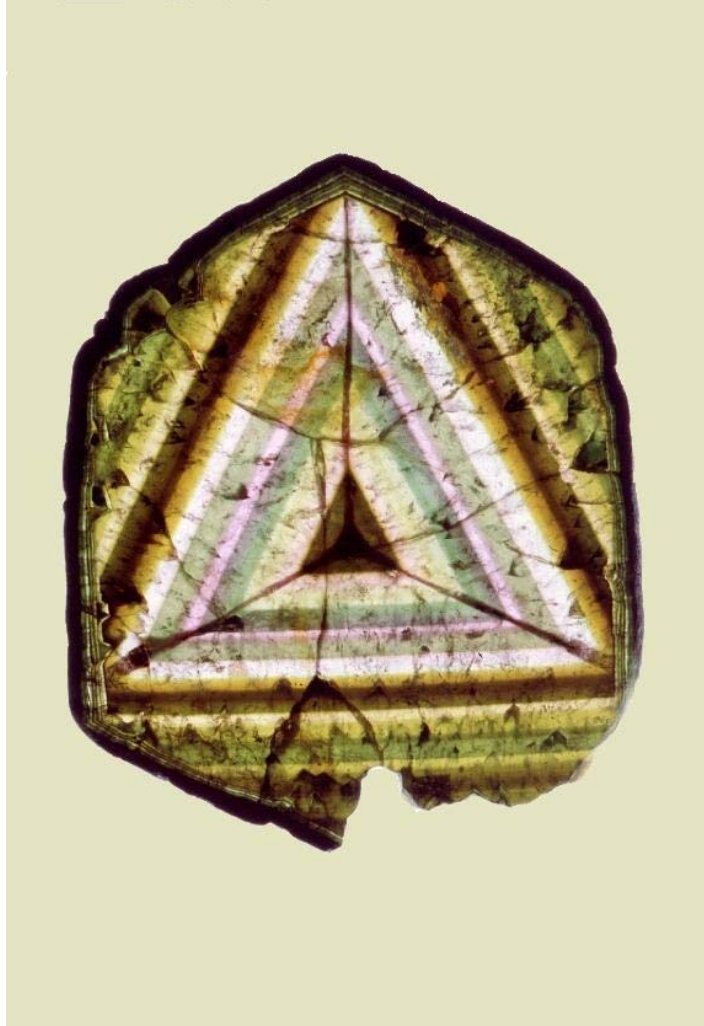
Because the center  
forms at a higher  
temperature, i.e.  
higher on Bowen's  
Reaction series,  
and is thus more  
calcium rich.



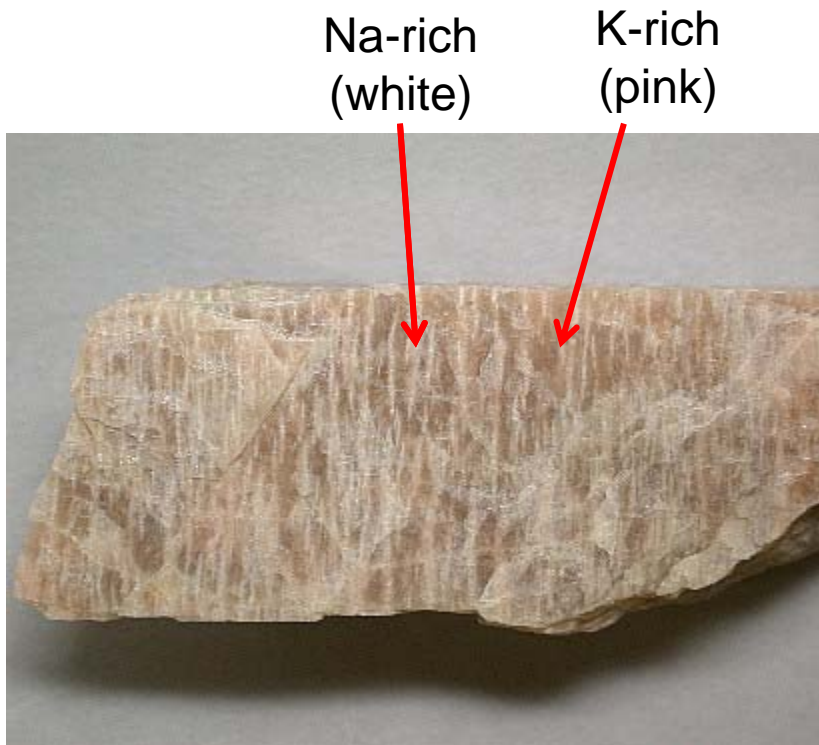
But, if the cooling is  
fast enough the Ca  
rich region does not  
have time to react,  
gets locked in Ca  
rich.

Which means the  
remaining melt is  
Ca depleted and  
Na rich so the later  
stages of mineral  
growth are Na rich

Na-rich







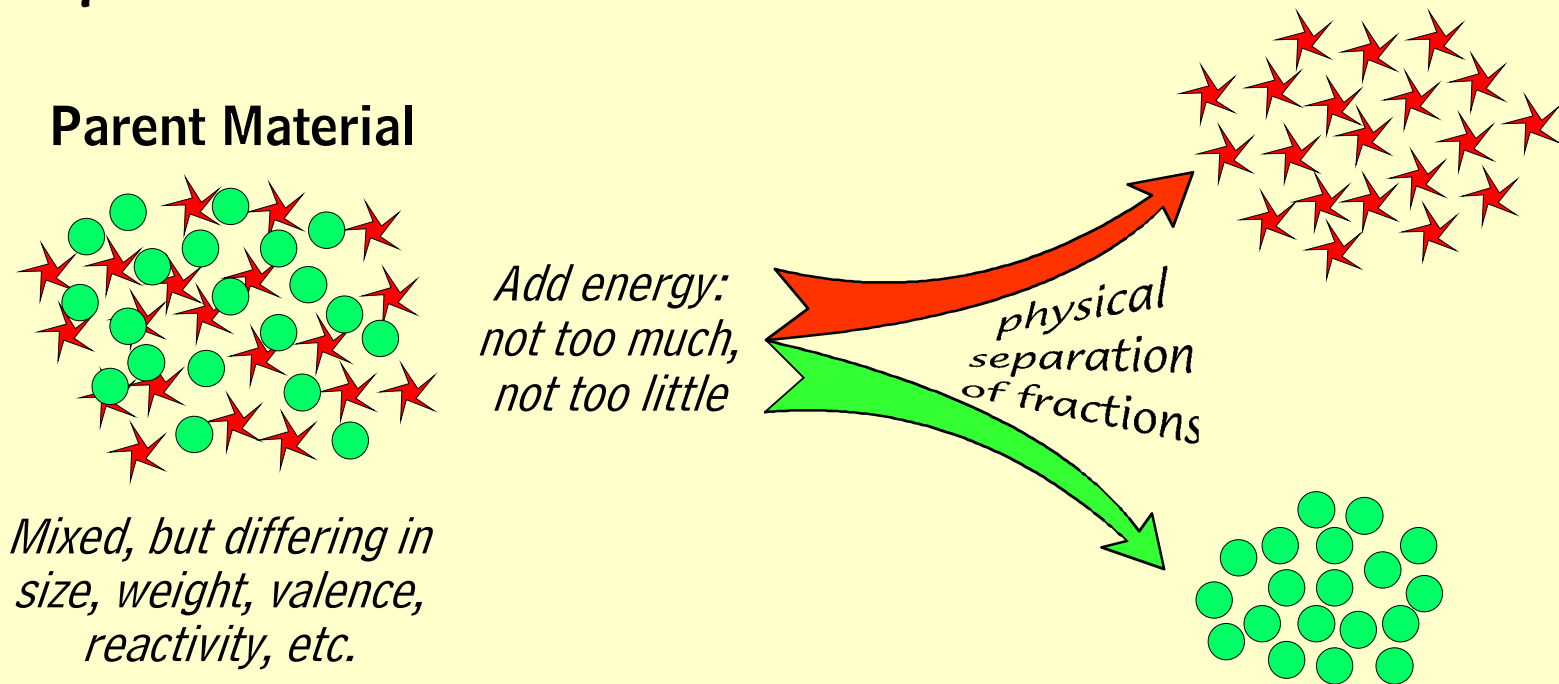
# PERTHITE

An intergrowth of Na rich plagioclase and orthoclase.

| Feldspar                   | Formula  | Cation Charge                      | Cation Size   | Substitutions   |
|----------------------------|--|------------------------------------|---------------|---|
| <b>Orthoclase</b>          | <b><math>\text{KAlSi}_3\text{O}_8</math></b>           | <b><math>\text{K}^{+1}</math></b>  | <b>1.33 A</b> | <i>Charges ok, but sizes differences too large for substitution</i><br><i>Sizes ok, but charges must be balanced from substitution. Done with Al and Si tetrahedra substitutions.</i> |
| <b>Sodium Plagioclase</b>  | <b><math>\text{NaAlSi}_3\text{O}_8</math></b>          | <b><math>\text{Na}^{+1}</math></b> | <b>0.95 A</b> |   |
| <b>Calcium Plagioclase</b> | <b><math>\text{CaAl}_2\text{Si}_2\text{O}_8</math></b> | <b><math>\text{Ca}^{+2}</math></b> | <b>0.99 A</b> |   |

# EVOLUTION BY FRACTIONATION

*Fractionation - also called differentiation - is the separation of components of a whole into fractions each of which has a different composition from the whole.*



*Occurs when heating and cooling is too fast for the system to come into equilibrium.*

# EVOLUTION BY FRACTIONATION

*Fractionation - also called differentiation - is the separation of components of a whole into fractions each of which has a different composition from the whole.*

Fractionation can occur by . . .

1. Beginning with a rock and slowly heating it until it begins to **partially** melt, and then separating the melt from the unmelted residue.
2. Beginning with a melt (magma) and cooling it until some crystals form, then separating them from the melt.

# FRACTIONATION IN BOWEN'S REACTION SERIES

**The unmelted fraction always goes up in composition**

This unmelted portion is higher in the reaction series because they require higher temperatures to melt.

**Ferro-Magnesium (Mafic) Minerals**

**Non-Ferro-Magnesium (Feldspar) Minerals**

**Olivine**

**Ca**

**Plagioclase**

**Pyroxene**

**Composition of Original Rock – Intermediate**

**Amphibole**

**Ca/Na**

**Biotite**

**Plagioclase**

**Orthoclase**

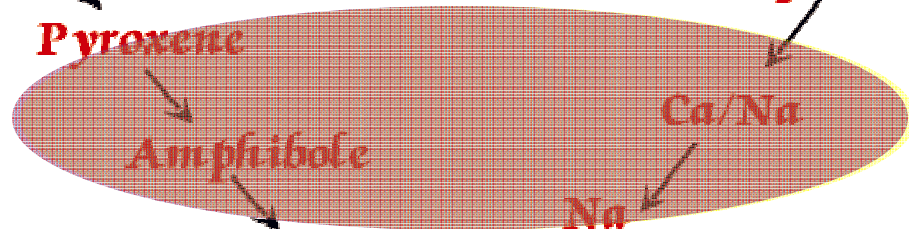
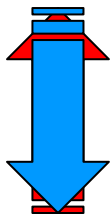
**We are going to heat it until it just begins to melt (fractionally melts)**

**Muscovite**

**Quartz**

**The melted fraction always goes down**

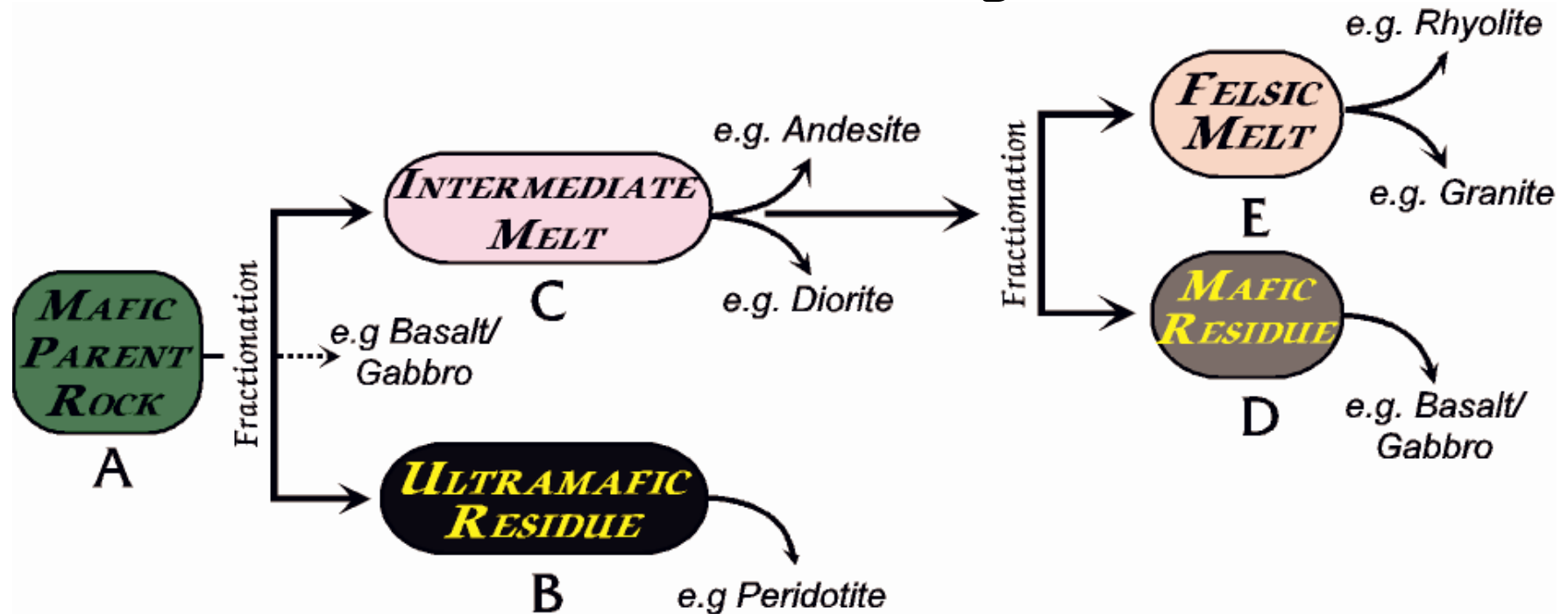
This melted portion is lower in the reaction series because minerals lower in the reaction series melt first.



# BOWEN'S HYPOTHESIS

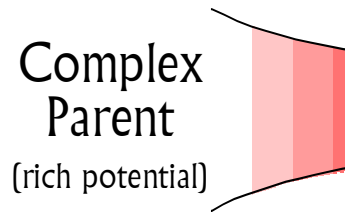
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## *The Simple Ideal Model For the Fractional Evolution of Igneous Rocks*



The core idea is that a silica rich mafic or ultramafic rock (the parent rock) gives rise to all other igneous rocks. The process occurs when the parent rock is fractionated, that is split into two fractions each with a composition different from the parent. During fractionation the mafic parent rock selectively melts producing two fractions. The first fraction is a melt whose composition is closer to the bottom of BRS than the original rock. This melt is intermediate in composition. The second fraction is the unmelted crystal residue with a composition more mafic than the original rock. That is, its composition is higher in Bowen's Reaction Series than the original rock. If time and conditions allow, the fractionation process can continue and the intermediate rock produced during the first fractionation can fractionate into a felsic magma, leaving behind a crystal residue more mafic than the intermediate rock. The diagram above shows the relationships among magma types.

# Fractionating Evolutionary<sup>P 120</sup> Attractors



- Begins with a complex parent and by removing more and more from it creates a large diversity of products.
- Always has a finite and predictable outcome because it follows chemical and physical laws.

# Igneous Rock Fractionation and Evolution

Fractionation means to divide a whole system into fractions. If a rock is heated slowly the minerals closer to the bottom of Bowen's Reaction Series will melt before the ones higher up, resulting in a magma, and a mush of unmelted crystals (the residue). If then, the melt and crystals are separated the system has been fractionated, with the melted fraction having a composition lower in the reaction series than what we began with, and a second fraction - the unmelted residue - having a composition higher in the reaction series than what we began with.

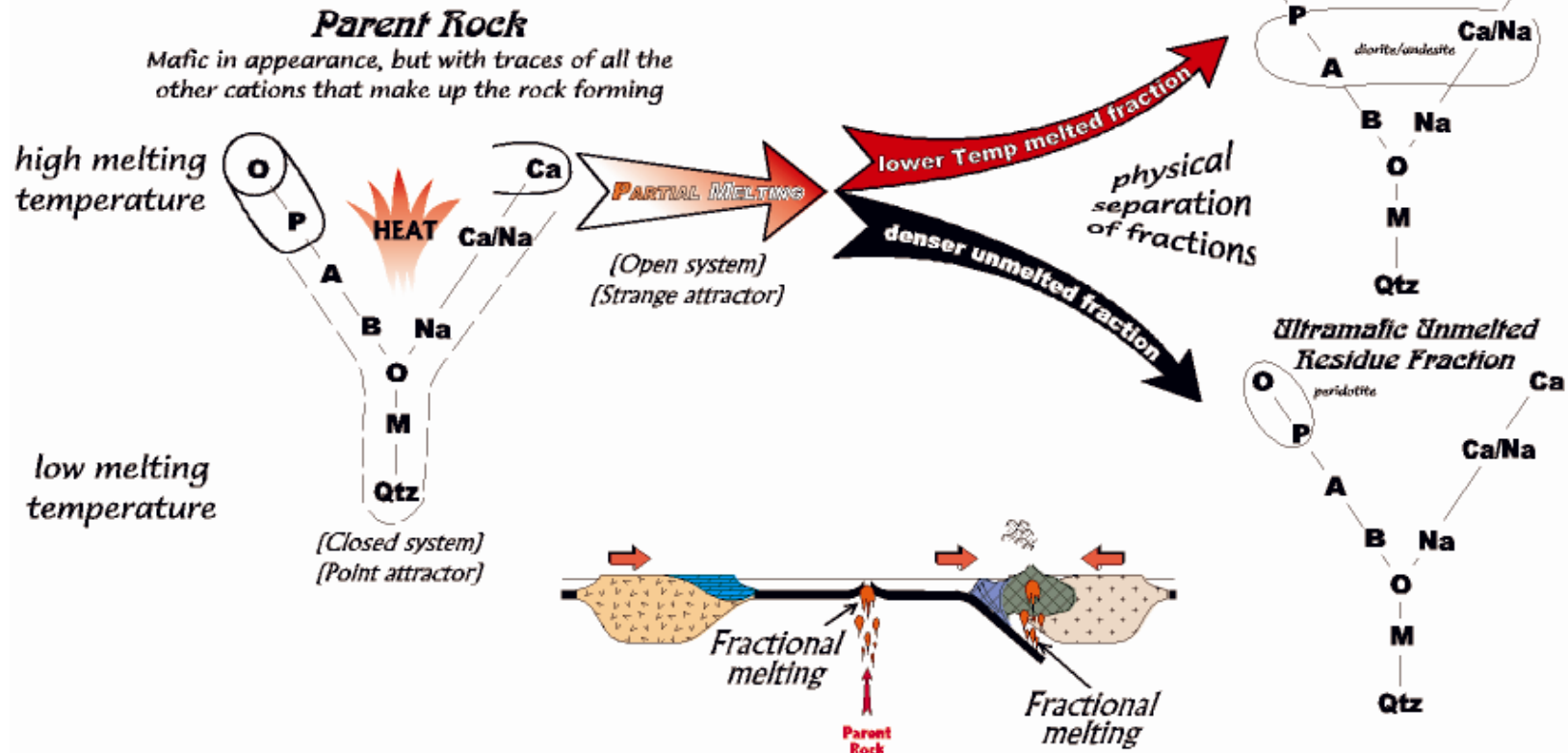
The fractionation just described occurs through partial melting, usually along subduction zones. Fractional crystallization, on the other hand, occurs through slow cooling of a complete magma. The first formed, higher temperature crystals are heavier and settle to the bottom of the magma chamber, dividing the system into two fractions.



**P 114**  
Migmatite is a partially melted rock. In the picture the light areas are the melted fractions; they are light because their composition is lower on the reaction series. The dark areas

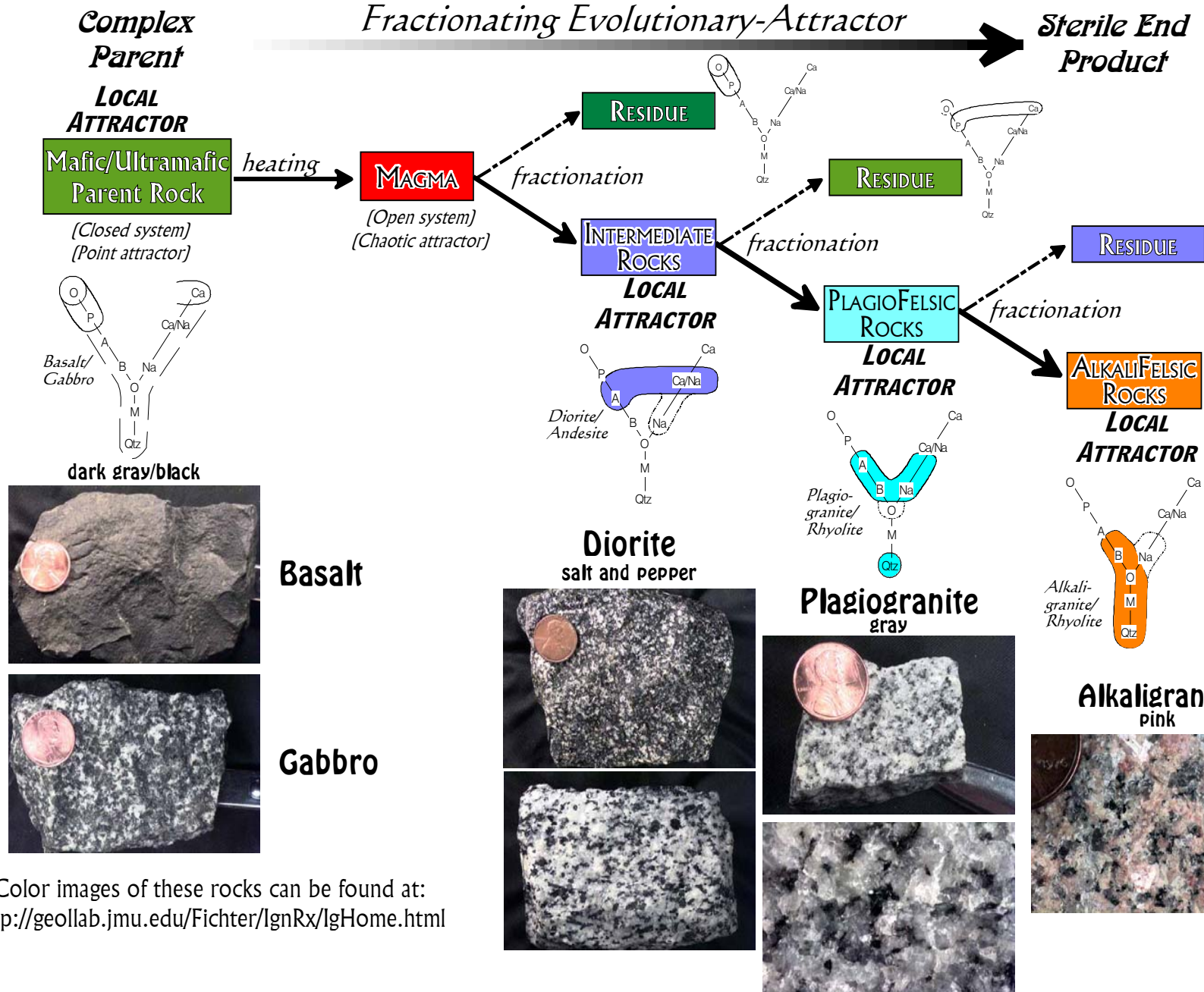
are the unmelted residues with a concentration of dark minerals from higher in the reaction series. If the rock were to completely melt the fractions would melt together and no fractionation would occur.

## Fractional Melting



# Igneous Rock Evolution

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Color images of these rocks can be found at:  
<http://geollab.jmu.edu/Fichter/IgnRx/IgHome.html>



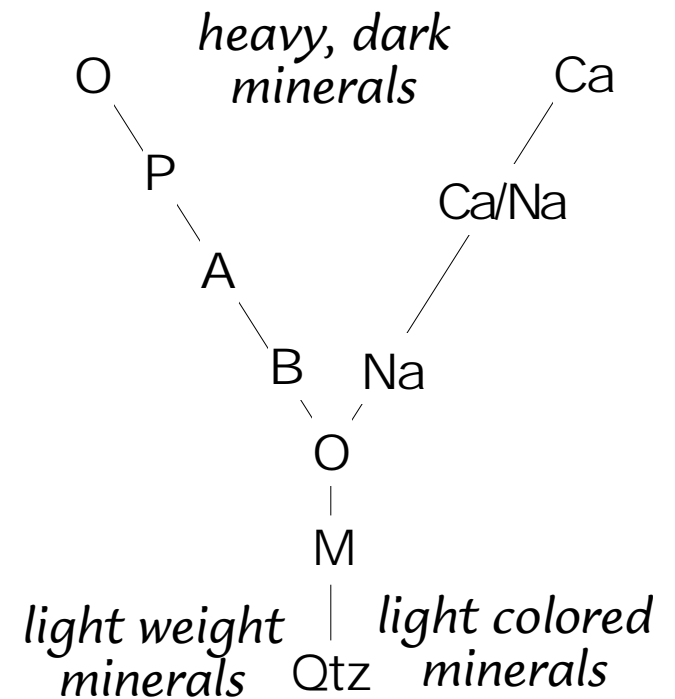
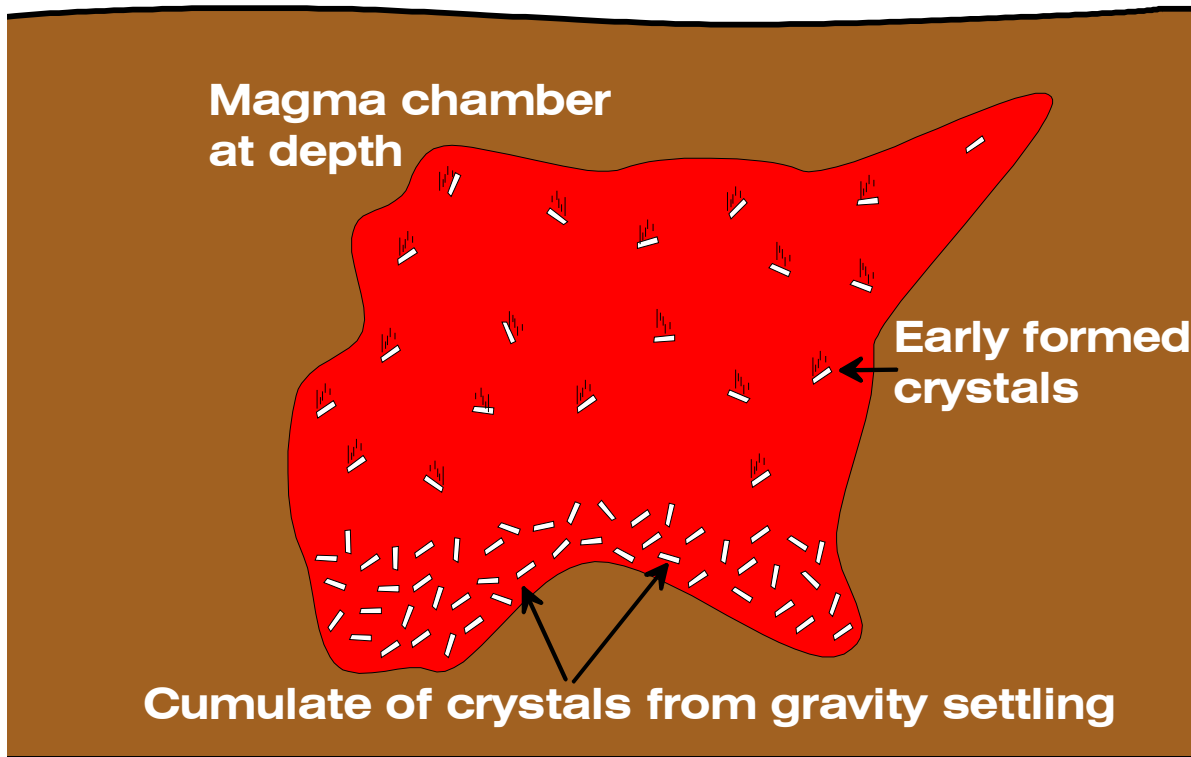
# Migmatite



Migmatite \_ a partially melted rock. In the picture the light areas are the melted fractions; they are light because their composition is lower on the reaction series. The dark areas are the unmelted residues with a concentration of dark minerals from higher in the reaction series. If the rock were to completely melt the fractions would melt together and no fractionation would occur.

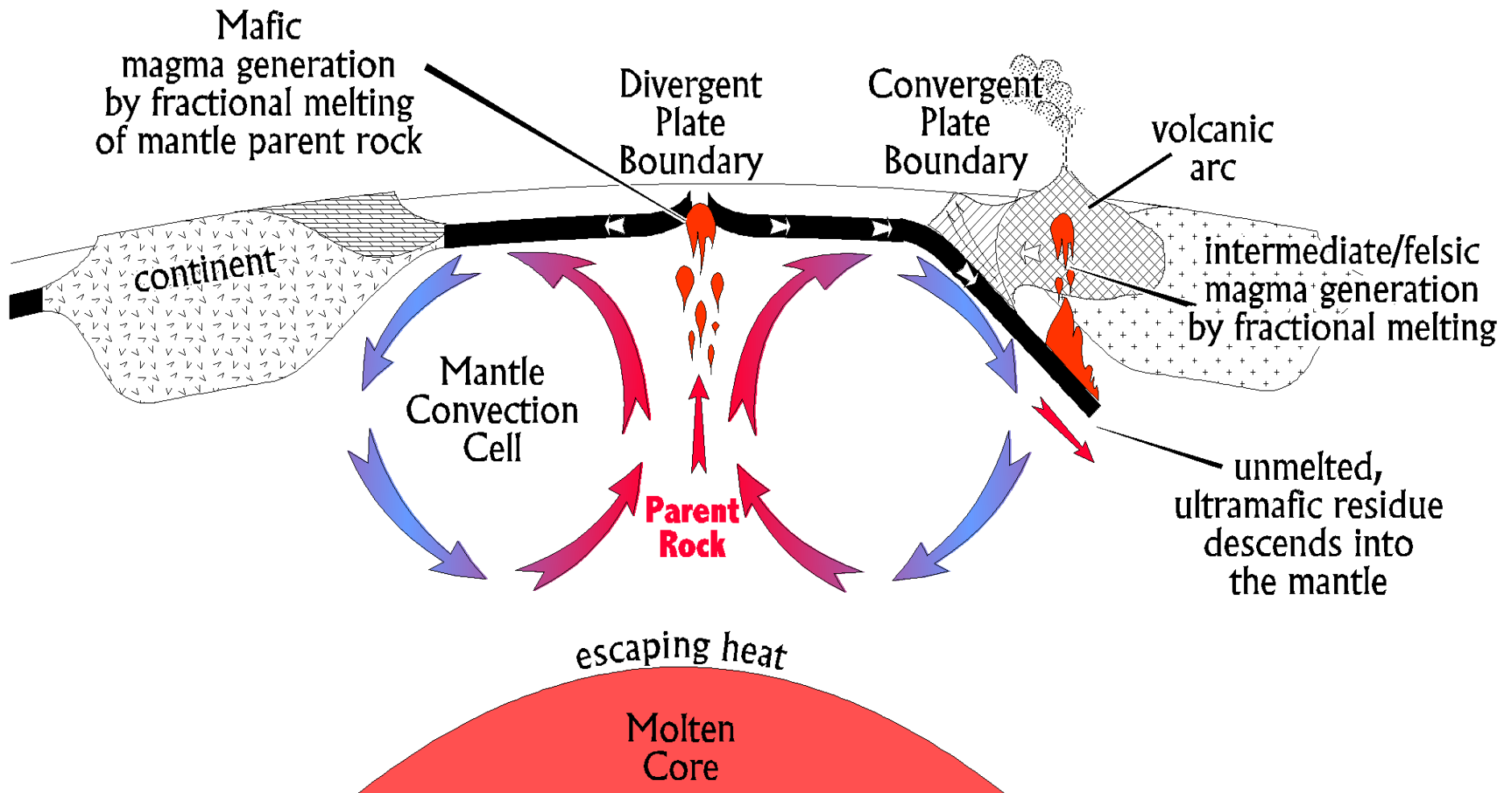
# CONDITIONS UNDER WHICH FRACTIONATION OCCURS

## Fractional Crystallization **P 115**

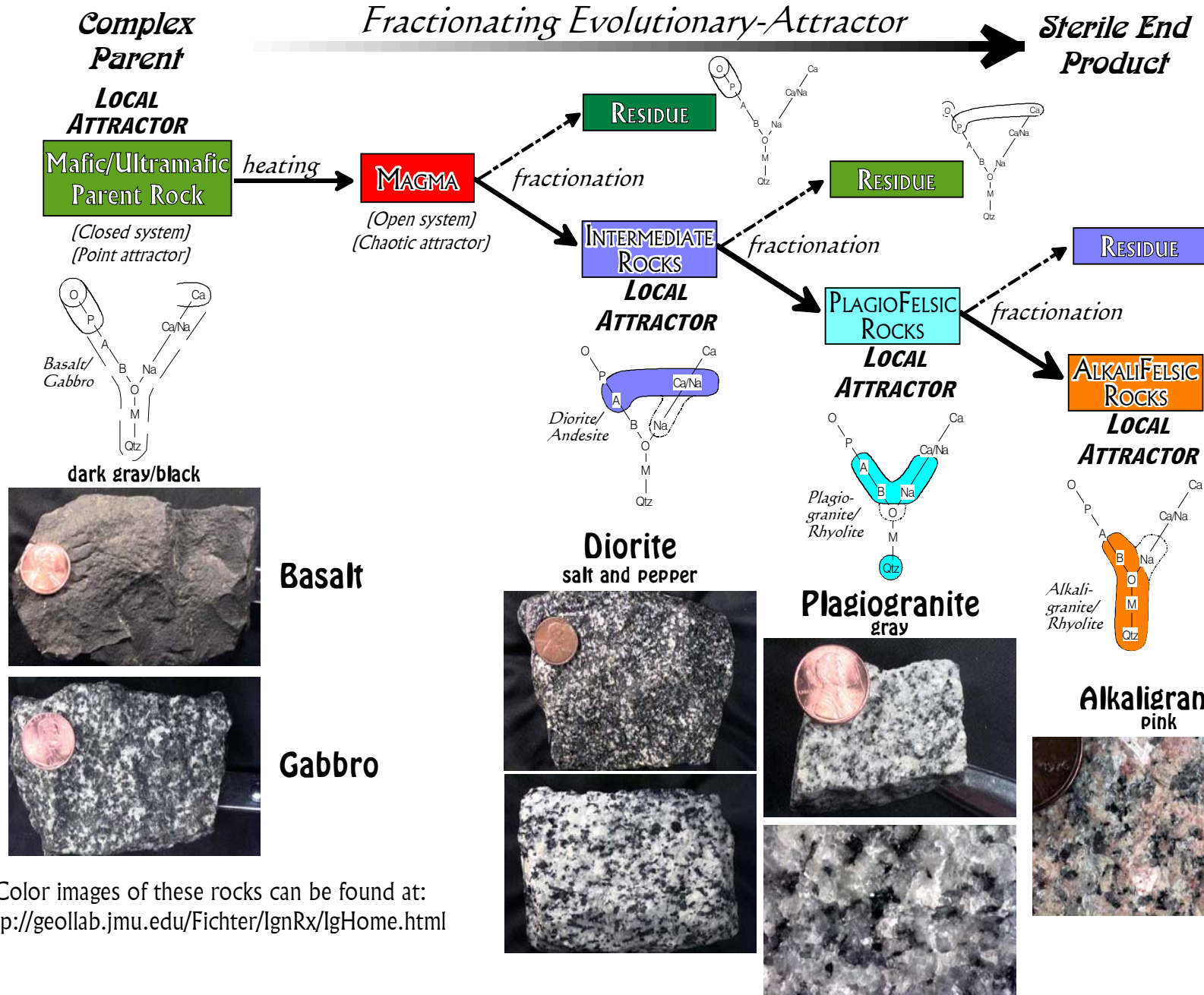


# Mechanisms of Igneous Fractionation **P 115**

## Fractional Melting



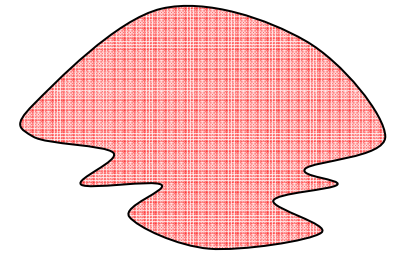
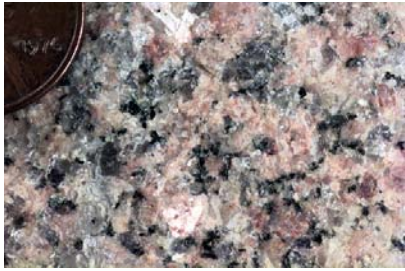
# Igneous Rock Evolution



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<http://geollab.jmu.edu/Fichter/IgnRx/IgHome.html>

# P 210

*Mafic*  
(Basalt/Gabbro)  
**RIFTING CENTER**



# Mechanisms of Igneous Fractionation **P 115**

## Fractional Melting

