UNIT – 2

CLASSIFICATION OF IGNEOUS ROCKS

CLASSIFICATION OF IGNEOUS ROCKS

On the basis of

- **The Chemical Composition**
- **The Mineralogical Composition**
- **The Textural Characteristics**

Chemical Classification:

- Four American Geologists
- **C**ross, **I**ddings, **P**risson and **W**ashington (**CIPW Classification**)
- The relative abundance of **Normative Minerals** is taken as a basis for classification
- NORM – a standard set of Minerals divided into **Salic and Femic Minerals.**

Salic Minerals	**-**	**Quartz, Feldspar, (Orthoclase, Albite and Anorthosite), Laucite, Nephelite, Corundum, Zircon, Halite, etc.,**
Femic Minerals	-	**Acmite, Diopside, Hypersthene, Olivine, Magnetite, Chromite, Hematite, Pyrite, Rutile, etc.**

CIPW Classification

- Igneous rocks divided into **5 Classes**
- On the basis of Ratio – **Salic/Femic**
- Prefixes **“Per**” and **“Do”** are used – to denote **high and moderate dominance** of respective group (Salic / Femic)

Chemical Classification

Sl.No.	Salic/Femic Ration	Class Name
1.	**> 7.00**	**Per-salic**
2.	**7 – 1.66**	**Do-salic**
3.	**1.66 – 0.60**	**Sal-femic**
4.	**0.60 – 0.14**	**Do-femic**
5.	**< 0.14**	**Per-femic**

CIPW - Methodology

A] **Convert % oxides into molecular proportions**

wt% oxide ÷ formula wt = Molecular Proportion

Eg SiO_2 72.67 ÷ 60.09 = 1.211

B] **Allocate molecular proportions to minerals using the following rules:**

1. Apatite is one of the first minerals to precipitate. All P is in **apatite.**

2. Allocate Fe_2O_3, FeO to **magnetite**. The limiting factor is the total amount of Fe_2O_3. Molecular proportion of Fe_2O_3 = Molecular proportion of FeO.

3. Make pure Orthoclae, Albite and Anorthite.
   Eg: Orthoclase $1K_2O$ $1Al_2O_3$ $6SiO_2$

4. Use remaining Al_2O_3 making **Corundum**

5. Allocate remaining FeO, MgO to **hypersthene.**
   Molecular proportion of FeO+MgO = molecular proportion of SiO_2

6. Allocate the remaining SiO_2 to **quartz**.

C] Once the molecular fraction has been calculated for each mineral, multiply through by the atomic weight of that mineral.

Chemical Composition - refers to the amount of Silica (SiO2)

a. Acid Rocks - have greater than **63% SiO_2**
*(examples **granite and rhyolite**)*

b. Intermediate Rocks - have between **52 - 63% SiO_2**
*(example **andesite and dacite**)*

c. Basic Rocks - have between **45 - 52% SiO_2** and high iron-magnesium content
*(example **gabbro and basalt**)*

d. Ultrabasic Rocks - have less than **45% silica**.
*(examples **Dunite and peridotiite**)*

e. Alkalic Rocks - have 5 - 15% K_2O + Na_2O content or with a molar ratio of alkali to silica greater than 1:6.
*(examples **phonolite and trachyte**)*

Shand Classification

➢ On the basis of relative abundance of silica percentage (%)

1. Over saturated (Acidic rock) - > 66% of Silica

(oversaturated rocks, containing free silica of magamtic origin)

2. Saturated (Basic rock) - 45 – 66% of Silica

(saturated rocks, containing only saturated minerals)

3. Undersaturated (Ultrabasic rock) - < 45 % of Silica

(Unsaturated rocks, containing unsaturated minerals)

a. *Olivine bearing rocks*
b. Feldspathoid bearing rocks
c. Rocks with both olivine and feldspathoids

Mineralogical Classification

- On the basis of mineralogical assemblages – rock forming mineral assemblages

- The rock forming minerals are divided **into Felsic minerals and Mafic minerals**

- **Felsic** - **Light coloured, lower in density –** Quartz, Feldspar group and Feldspathoid group

- **Mafic** - **Dark coloured, heavier in density** and contain ferro magnesium minerals – Amphiboles, Pyroxenes, Micas, Olivines, Oxides of Iron etc

Classification by texture

Extrusive	*Intrusive*
Fine grained	*Coarse grained*
Basalt	gabbro
Andesite	diorite
Rhyolite	granite

Classification by composition

- magnesium (Mg) + iron (Fe) = mafic
- feldspar + quartz (Si) = felsic

Table 4.1 Common Minerals of Igneous Rocks

Compositional Group	Mineral	Chemical Composition	Silicate Structure
FELSIC	Quartz	SiO_2	Frameworks
	Potassium feldspar	$KAlSi_3O_8$	
	Plagioclase feldspar	$\left\{ \begin{array}{l} NaAlSi_3O_8 \\ CaAl_2Si_2O_8 \end{array} \right.$	
	Muscovite (mica)	$KAl_3Si_3O_{10}(OH)_2$	Sheets
MAFIC	Biotite (mica)	$\left. \begin{array}{l} K \\ Mg \\ Fe \\ Al \end{array} \right\} Si_3O_{10}(OH)_2$	
	Amphibole group	$\left. \begin{array}{l} Mg \\ Fe \\ Ca \\ Na \end{array} \right\} Si_8O_{22}(OH)_2$	Double chains
	Pyroxene group	$\left. \begin{array}{l} Mg \\ Fe \\ Ca \\ Al \end{array} \right\} SiO_3$	Single chains
	Olivine	$(Mg,Fe)_2SiO_4$	Isolated tetrahedra

Mineralogical Class - Colour Index

		% of Dark Minerals	
1.	**Lecocratic** Light-coloured because of a low content of ferromagnesian minerals	**1 – 30**	**Granite** Light Color rocks
2.	**Mesocratic** containing 30-60 % of ferromagnesian minerals. The moderately dark colour of the rock.	**31 – 60**	**Gabbro** Intermediate rocks
3.	**Melanocratic** Igneous rocks in which the quantity of dark-colored minerals (those rich in iron and magnesium)	**61 – 90**	**Peridodite** Dark Color rocks
4.	**Hypermelane**	**➢ 90**	**Pyroxinites, Picrite**

Textural Classification

Textures:

Aphanitic - crystals too small to see by eye

Phaneritic - can see the constituent minerals

Fine grained	-	**< 1 mm diameter**
Medium grained	-	**1-5 mm diameter**
Coarse grained	-	**5-50 mm diameter**
Very coarse grained	-	**> 50 mm diameter**

Porphyritic - bimodal grain size distribution

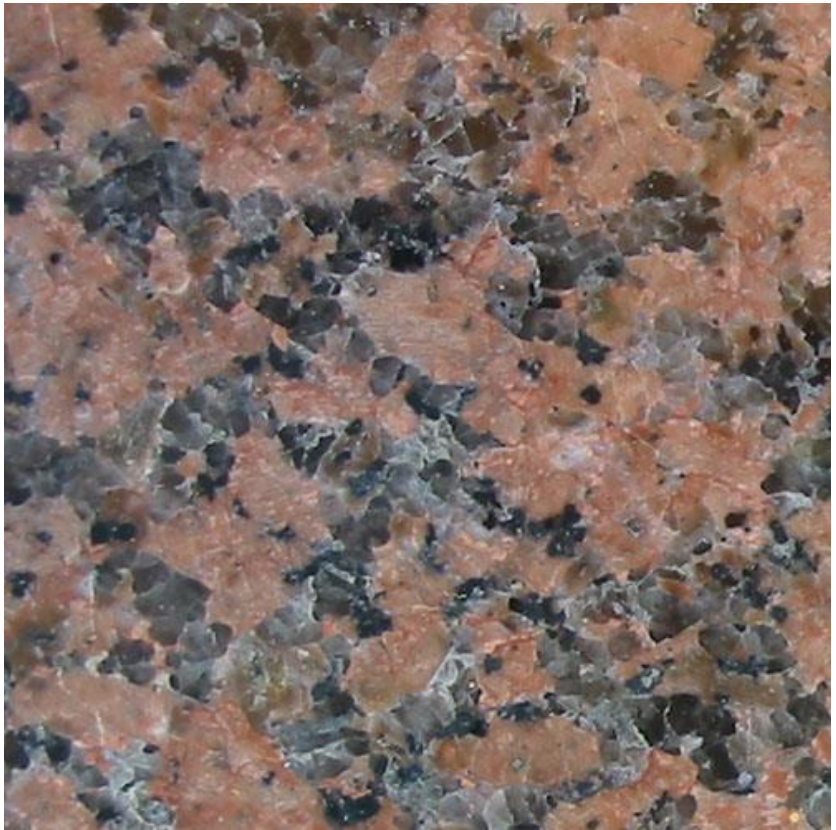
Glassy - no crystals formed

Aphanitic Texture.

- Aphanitic texture consists of extremely small crystals, and indicates that the rock cooled quickly enough to prevent the formation of large crystals.
- When examining such a texture, very few, if any, crystals will be visible to the naked eye.
- Viewing under a microscope, you should be able to see tiny crystals. The picture at right shows a rock with **aphanitic texture**.

Phaneritic Texture.

- A rock with phaneritic texture has crystal grains large enough to be distinguished with the eye.
- Granite is a typical **phaneritic textured rock**

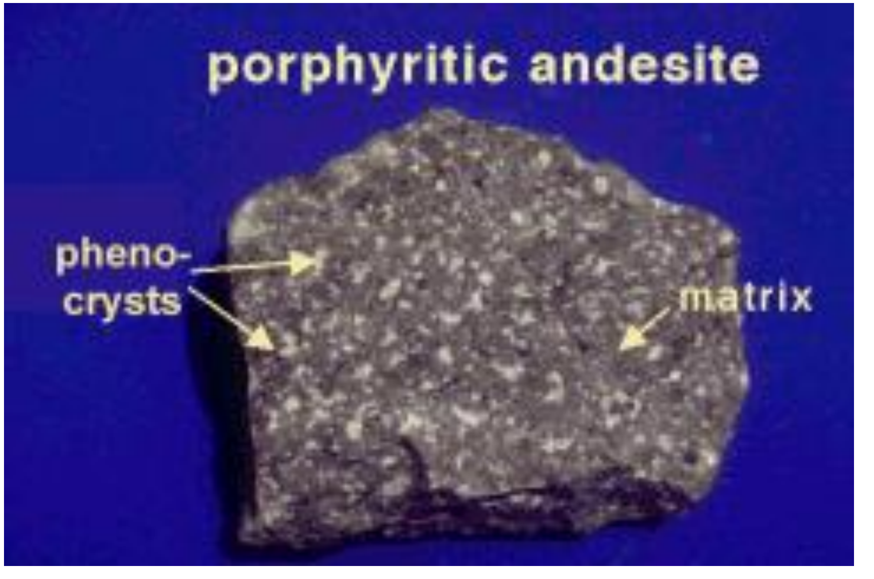


Porphyritic Texture.

- In some rocks, larger crystals are embedded in rocks that otherwise would appear to be aphanitic. The aphanitic portion of the rock is referred to as the "***matrix***" or "groundmass."
- The larger crystals are called ***phenocrysts***.

- Since a rock with aphanitic texture can contain some visible crystals, sometimes it is easy to confuse the two textures.

- The definition is in the eye of the beholder. Since both terms apply equally with some rocks, take your pick.



Glassy Texture.

- Glassy texture is typical of volcanic material that cools instantaneously.
- The rock displays conchoidal fracturing with sharp edges like broken glass.
- No individual crystals can be seen.
- The picture at right shows a rock known as **obsidian.**

COMMON IGNEOUS ROCKS
(Mineralogy and Composition)

1. **Felsic (sialic) igneous rocks**
2. **Intermediate igneous rocks**
3. **Mafic igneous rocks**
4. **Ultramafic igneous rocks**

1. Felsic (sialic) igneous rocks

- **Felsic (sialic) igneous rocks** are composed mainly of **potassic and sodic feldspars**

- *(light-colored minerals)* that formed under ***low-temperature and low- pressure conditions*** (Bowen's Reaction Series).

- Felsic rocks include syenite, trachyte**,** **granite**, **rhyolite**, granodiorite, dacite, and some **obsidian.**

Igneous compositions

- **Naming igneous rocks – granitic rocks**
  - **Granite**

➢ **Phaneritic textures**

➢ **Over 25% quartz, about 65% or more feldspar**

➢ **Very abundant - often associated with mountain building**

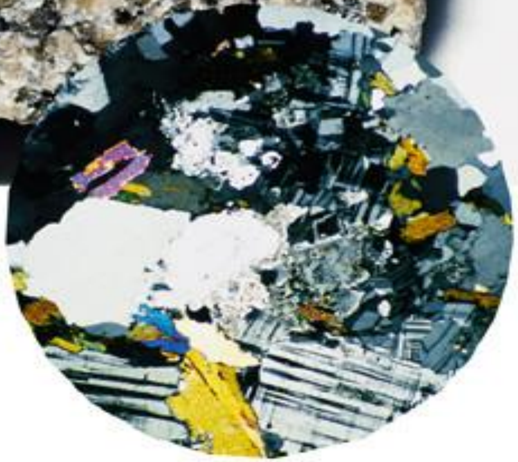
➢ **The term granite includes a wide range of mineral compositions**

Granite

A. Granite

Close up

Phaneritic texture



Coarse crystals cooled slowly
at great depth

Igneous compositions

- **Naming igneous rocks – granitic rocks**
  - **Rhyolite**
    - **Extrusive equivalent of granite**
    - **May contain glass fragments and vesicles**
    - **Aphanitic texture**
    - **Less common and less voluminous than granite**

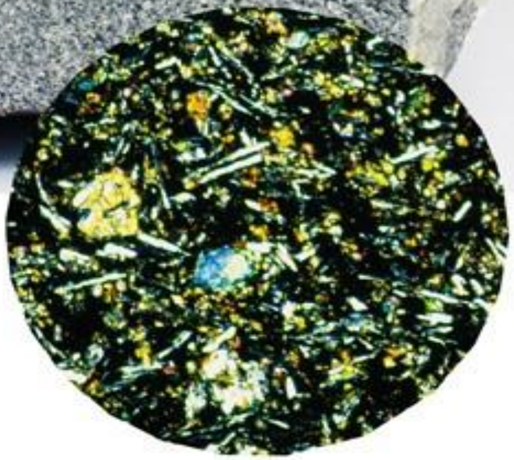
UMR

Rhyolite

B. Rhyolite

Close up

Aphanitic texture



Fine grained because it cooled
quickly at the surface

Igneous compositions

- **Naming igneous rocks – granitic rocks**
  - **Obsidian**
    - **Dark colored**
    - **Glassy texture**
  - **Pumice**
    - **Volcanic**
    - **Glassy texture**
    - **Frothy appearance with numerous voids**

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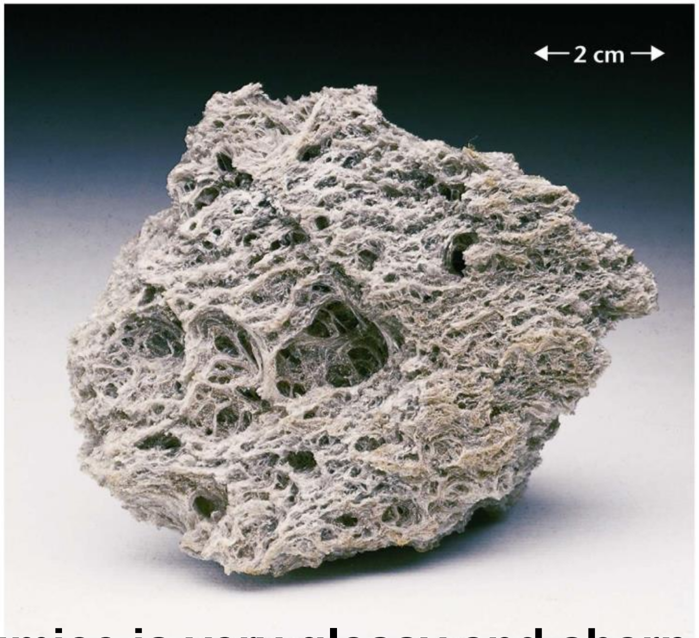
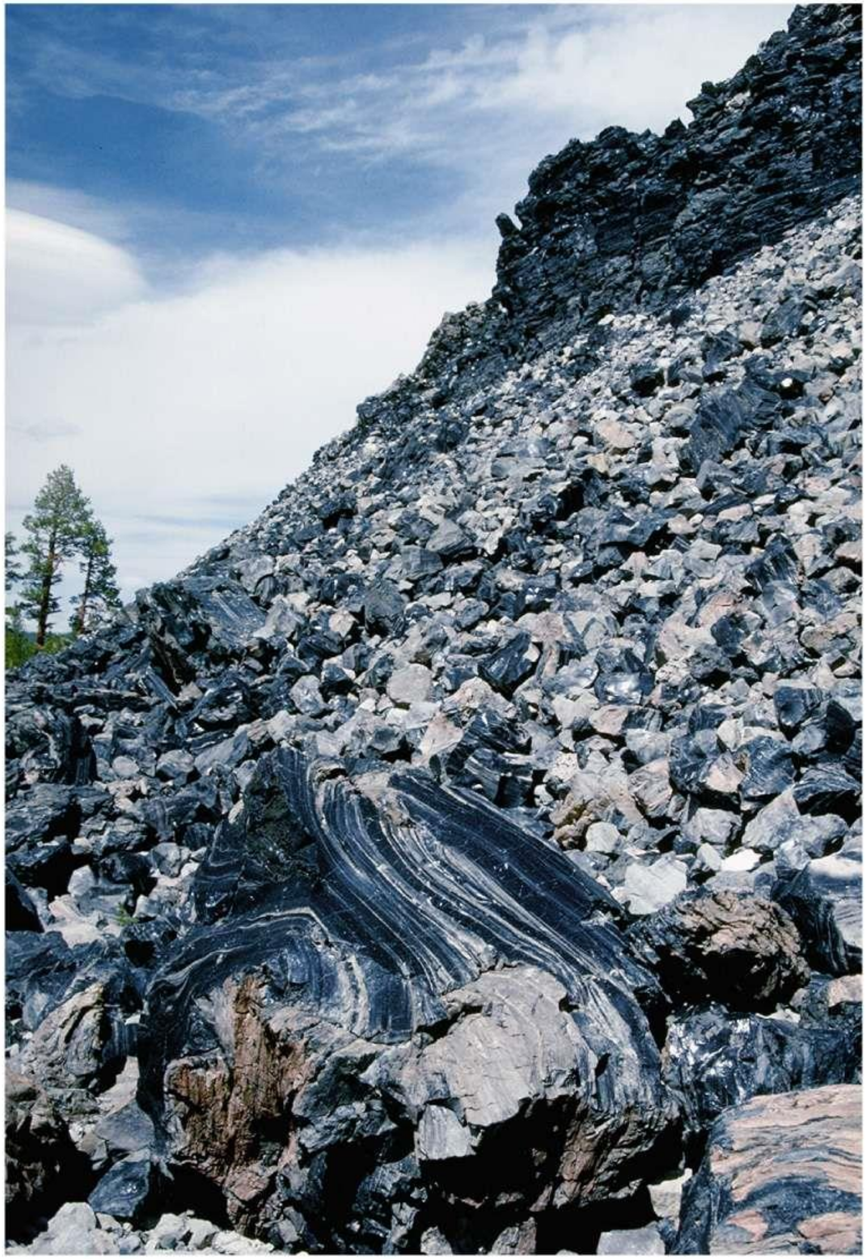


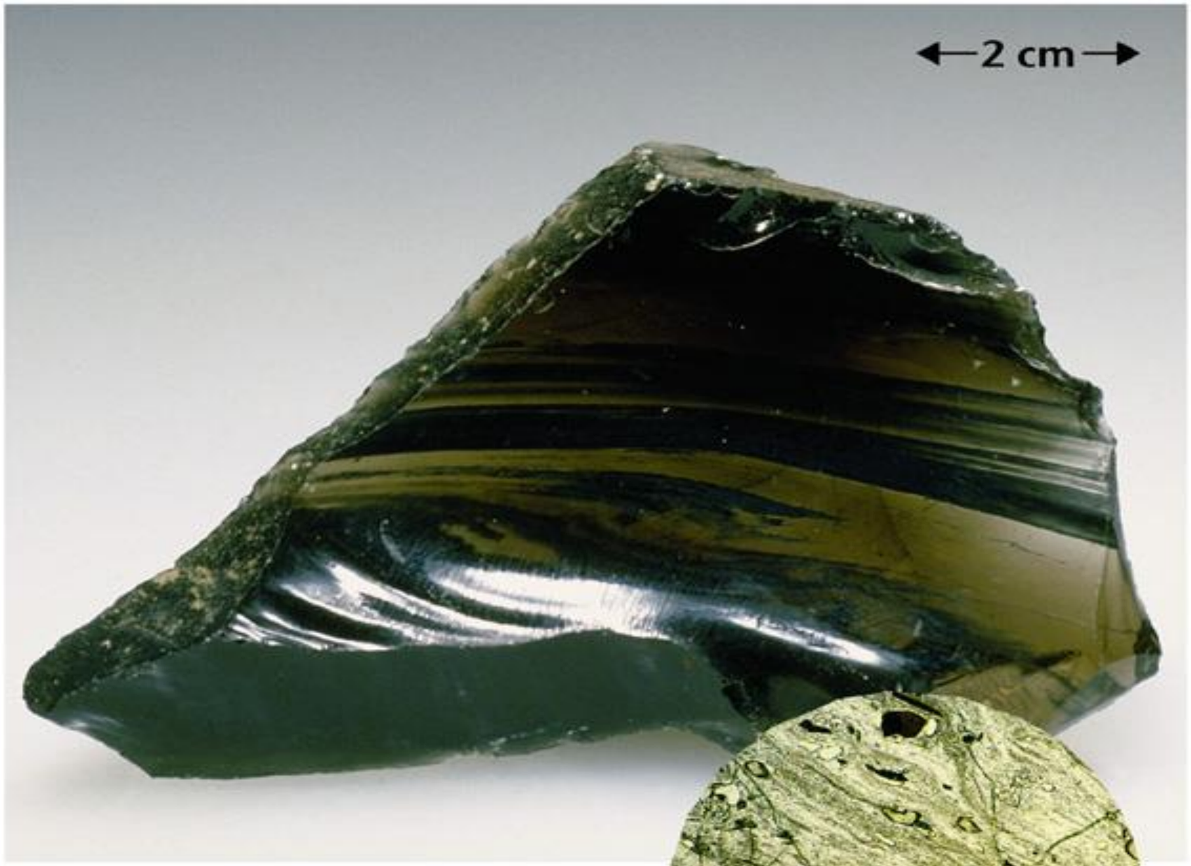
Pumice is very glassy and sharp, with countless vesicles.

B. Hand sample of obsidian.



A. Obsidian flow.

Glassy texture



D. Glassy

Obsidian

Fast cooling

2. Intermediate igneous rocks

- **Intermediate igneous rocks** have subequal amounts of **light and dark minerals**.

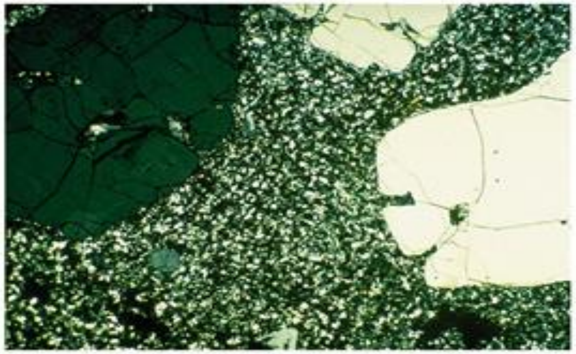
- Intermediate rocks include **andesite** (named for the Andes Mountains), and **diorite.**

Igneous compositions

- **Naming igneous rocks – intermediate rocks**
  - **Andesite**
    - **Volcanic origin**
    - **Aphanitic texture**
  - **Diorite**
    - **Plutonic equivalent of andesite**
    - **Coarse grained**

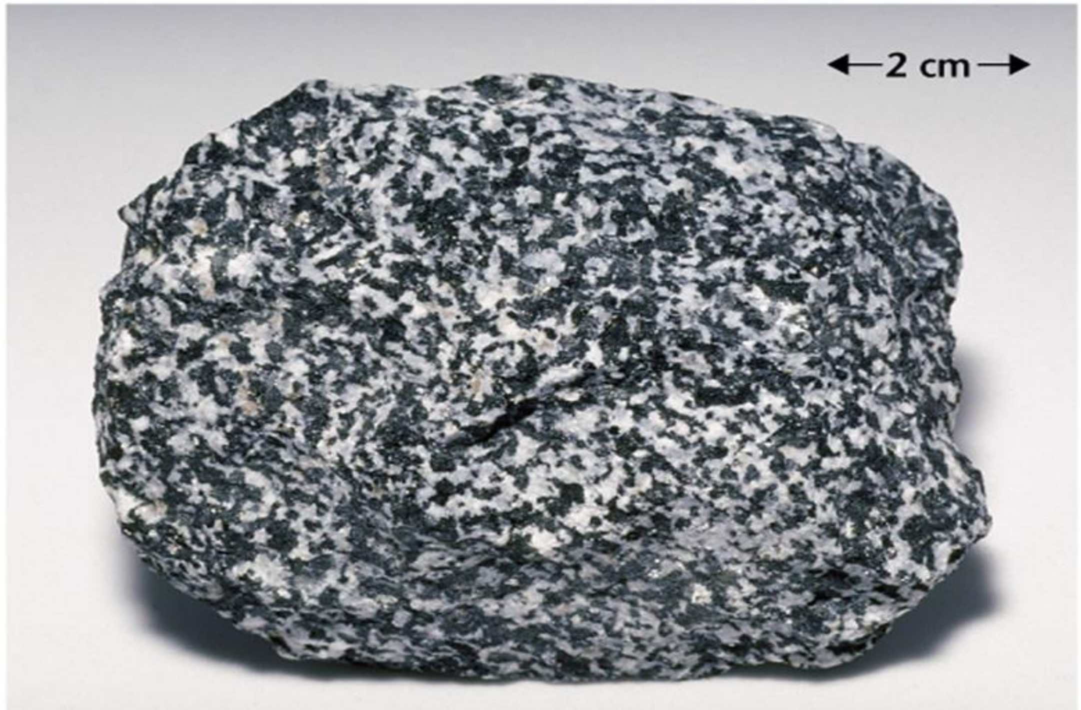
Andesite

A. Andesite porphyry



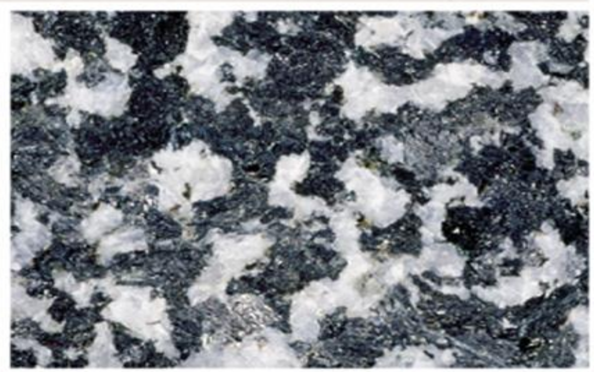
B. Close up

Diorite



Diorite

Close up



3. Mafic igneous rocks

- **Mafic igneous rocks** have a **large percentage of darker and strongly colored minerals.**

- **Rich in ferromagnesian components and calcic plagioclase feldspars**.

- These are minerals that form under *high-temperature and high-pressure conditions* (Bowens Reaction Series).

- Mafic rocks include **basalt** and **gabbro,** and some **obsidian.**

Igneous compositions

- Naming igneous rocks – basaltic rocks
  - Basalt
    - Volcanic origin
    - Aphanitic texture
    - Composed mainly of pyroxene and calcium-rich plagioclase feldspar
    - Most common extrusive igneous rock

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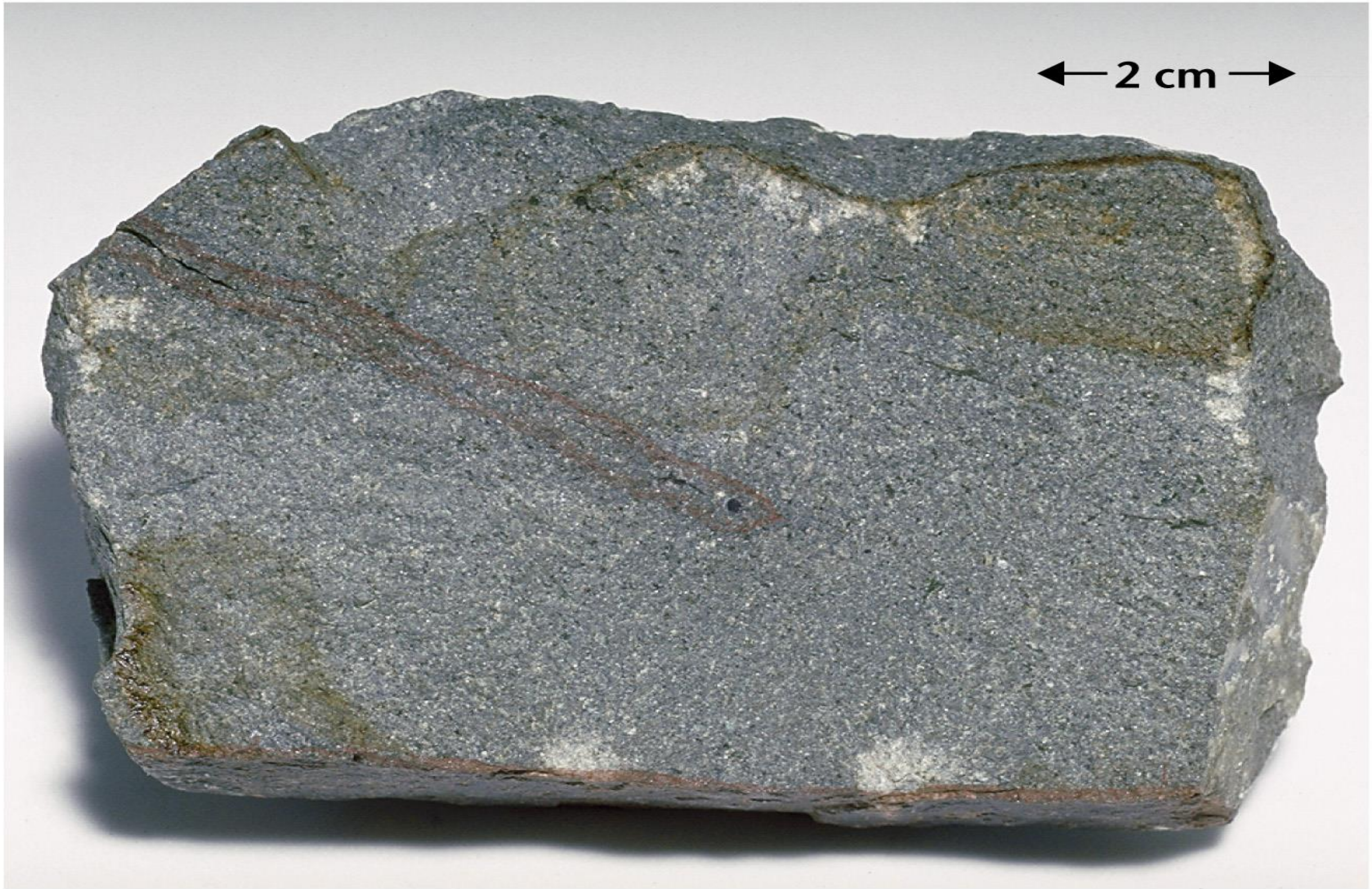
Basalt



A. Basalt

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Igneous compositions

- Naming igneous rocks – mafic rocks
  - Gabbro

    - Intrusive equivalent of basalt
    - Phaneritic texture consisting of pyroxene and calcium-rich plagioclase
    - Significant % of the oceanic crust

UMR

Gabbro

B. Gabbro

4. Ultramafic Igneous Rocks

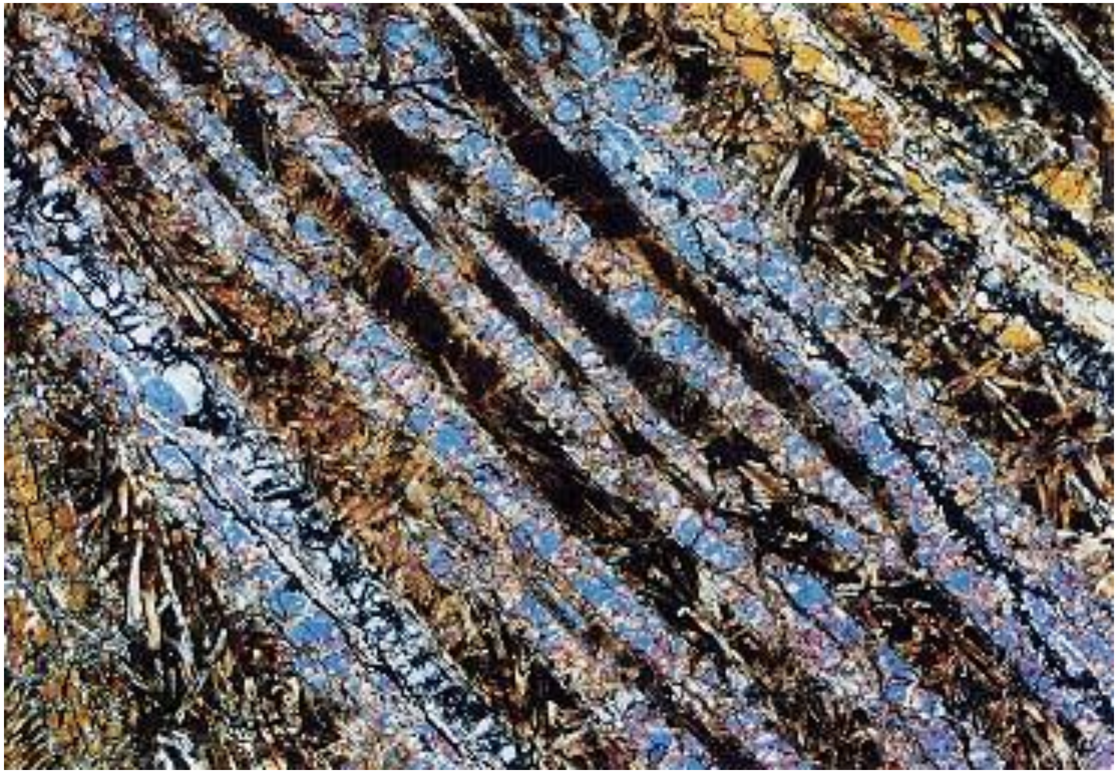
- **Ultramafic igneous rocks** often contain **70 to 90% olivine, other dark and strongly colored ferromagnesian minerals.**

- **The most calcic plagioclases,** and very minor, if any, percentages of silica.

- These minerals form under ***very high-temperature and high-pressure conditions*** (Bowen's Reaction Series).

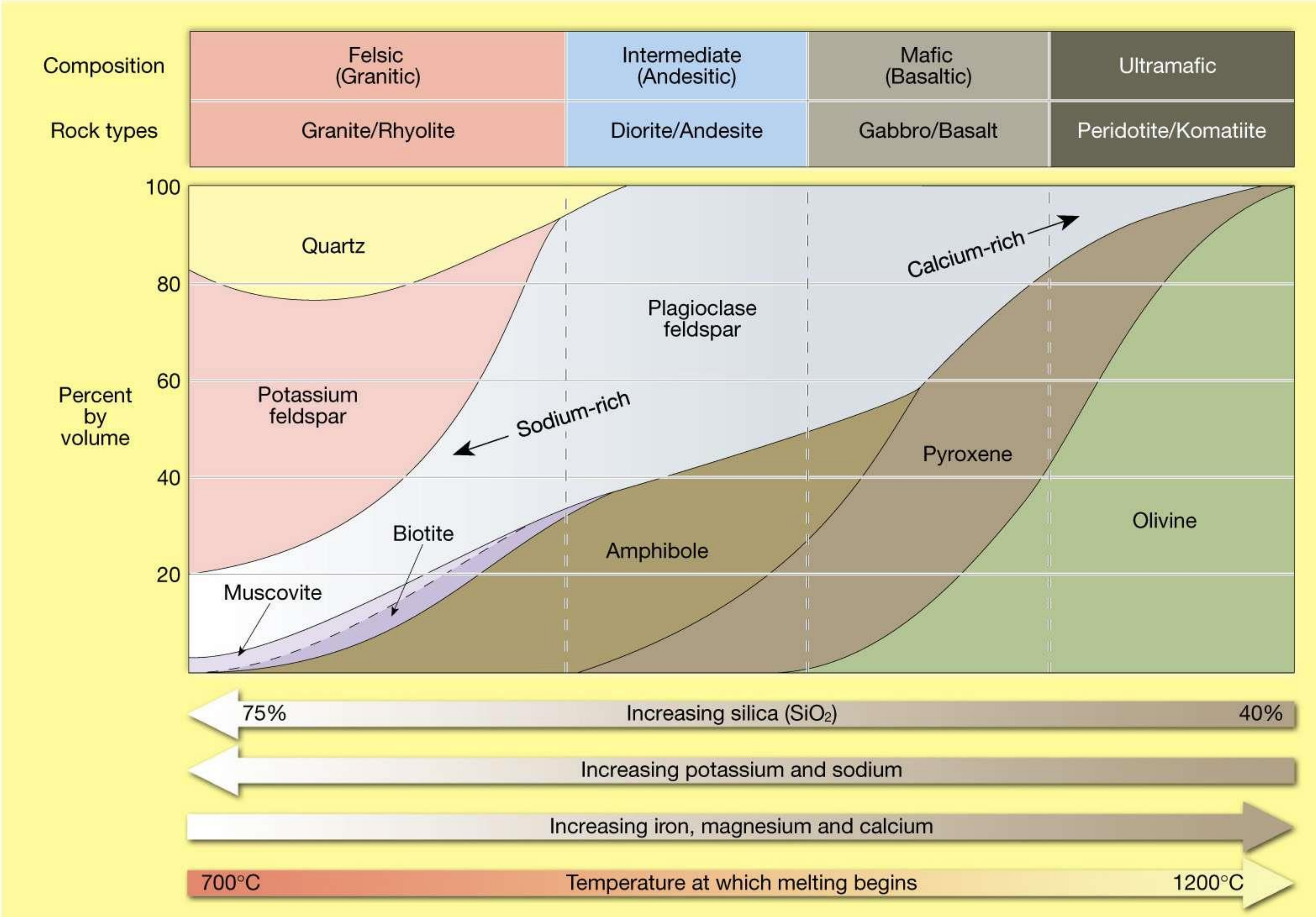
- Ultramafic rocks include **peridotite** and **komatite.** Ultramafic rocks are not common at or near the Earth's surface, but form in the asthenosphere and mantle.

Ultramafic igneous rocks - peridotite

Komatiites **are rare ultramafic volcanic rocks.**

This sample displays the characteristic **"spinifex texture"** defined by extremely acicular olivine phenocrysts--probably a sign of rapid crystallization from a significantly-undercooled magma.

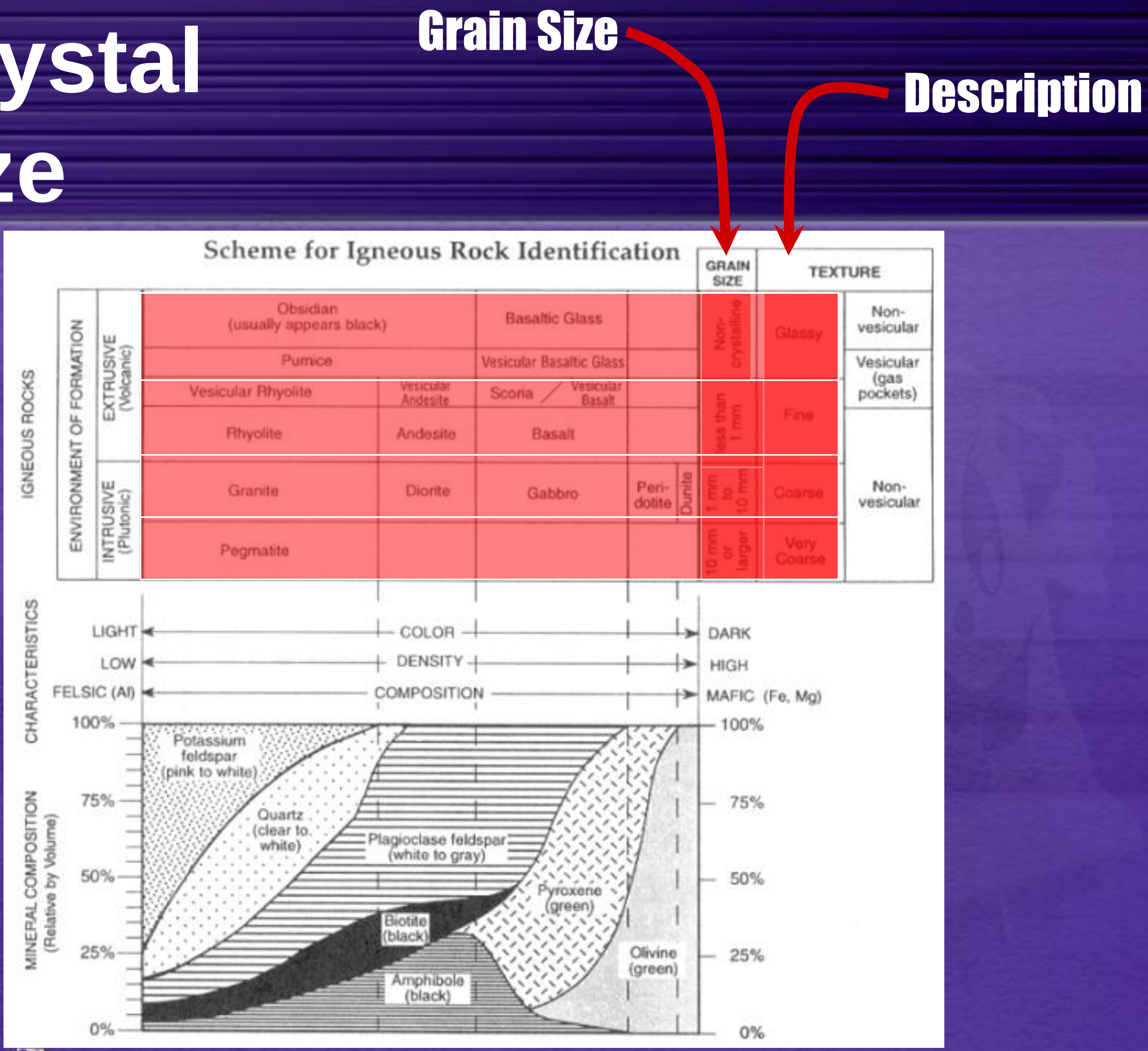


Composition
Felsic (Granitic)
Intermediate (Andesitic)
Mafic (Basaltic)
Ultramafic
Rock types
Granite/Rhyolite
Diorite/Andesite
Gabbro/Basalt
Peridotite/Komatiite
Percent by volume
100
80
60
40
20
Quartz
Plagioclase feldspar
Calcium-rich
Potassium feldspar
Sodium-rich
Pyroxene
Biotite
Amphibole
Olivine
Muscovite
75%
Increasing silica (SiO2)
40%
Increasing potassium and sodium
Increasing iron, magnesium and calcium
700°C
Temperature at which melting begins
1200°C

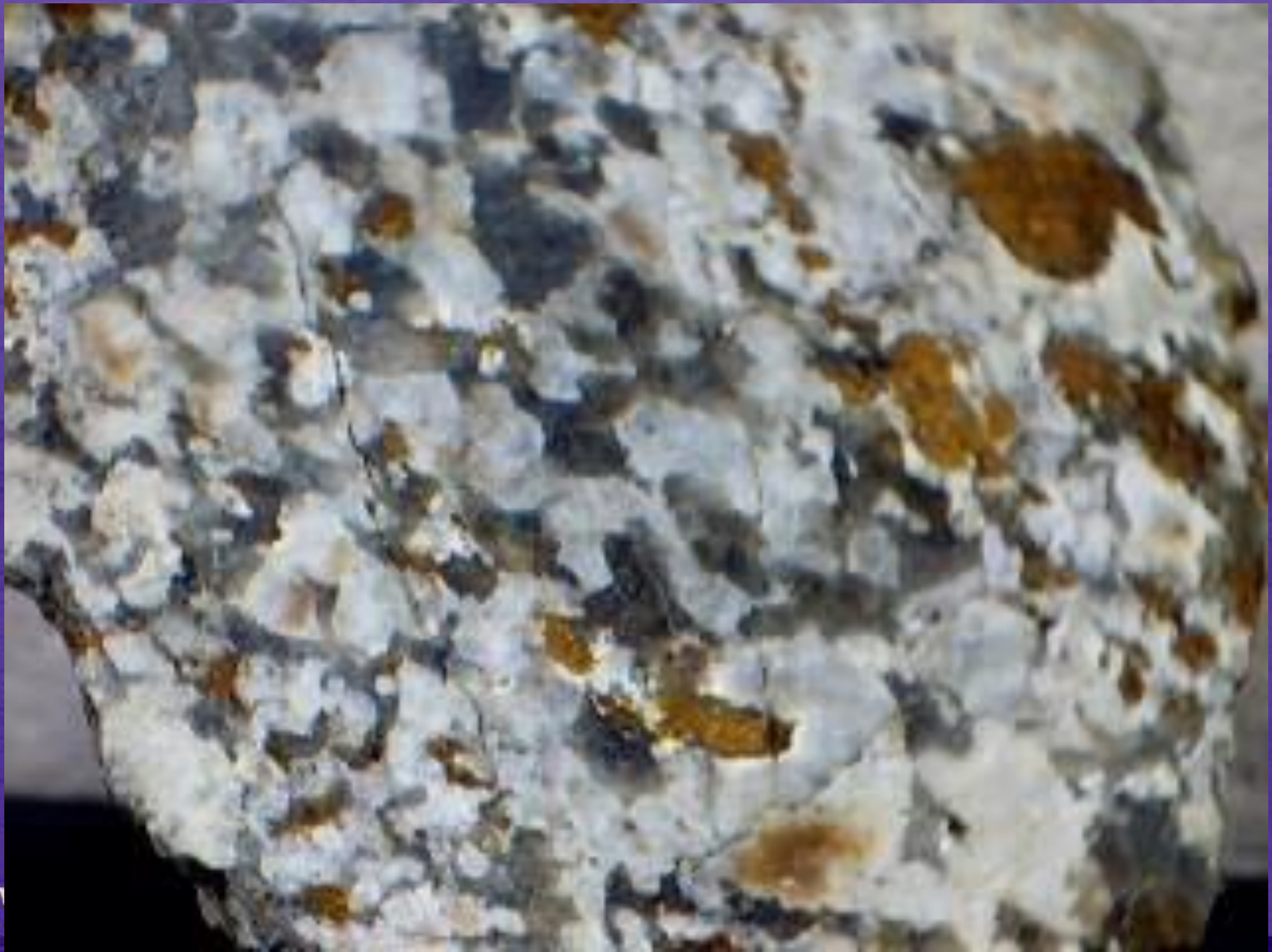
UMR

Chemical Composition	Granitic (Felsic)	Andesitic (Intermediate)	Basaltic (Mafic)	Ultramafic
Dominant Minerals	Quartz Potassium feldspar Sodium-rich plagioclase feldspar	Amphibole Sodium- and calcium-rich plagioclase feldspar	Pyroxene Calcium-rich plagioclase feldspar	Olivine Pyroxene
Accessory Minerals	Amphibole Muscovite Biotite	Pyroxene Biotite	Amphibole Olivine	Calcium-rich plagioclase feldspar
TEXTURE: Phaneritic (coarse-grained)	Granite	Diorite	Gabbro	Peridotite
TEXTURE: Aphanitic (fine-grained)	Rhyolite	Andesite	Basalt	Komatiite (rare)
TEXTURE: Porphyritic	"Porphyritic" precedes any of the above names whenever there are appreciable phenocrysts			Uncommon
TEXTURE: Glassy	Obsidian (compact glass) Pumice (frothy glass)			
TEXTURE: Pyroclastic (fragmental)	Tuff (fragments less than 2 mm) Volcanic Breccia (fragments greater than 2 mm)			
Rock Color (based on % of dark minerals)	0% to 25%	25% to 45%	45% to 85%	85% to 100%

Crystal size



Intergrown



Intergrown

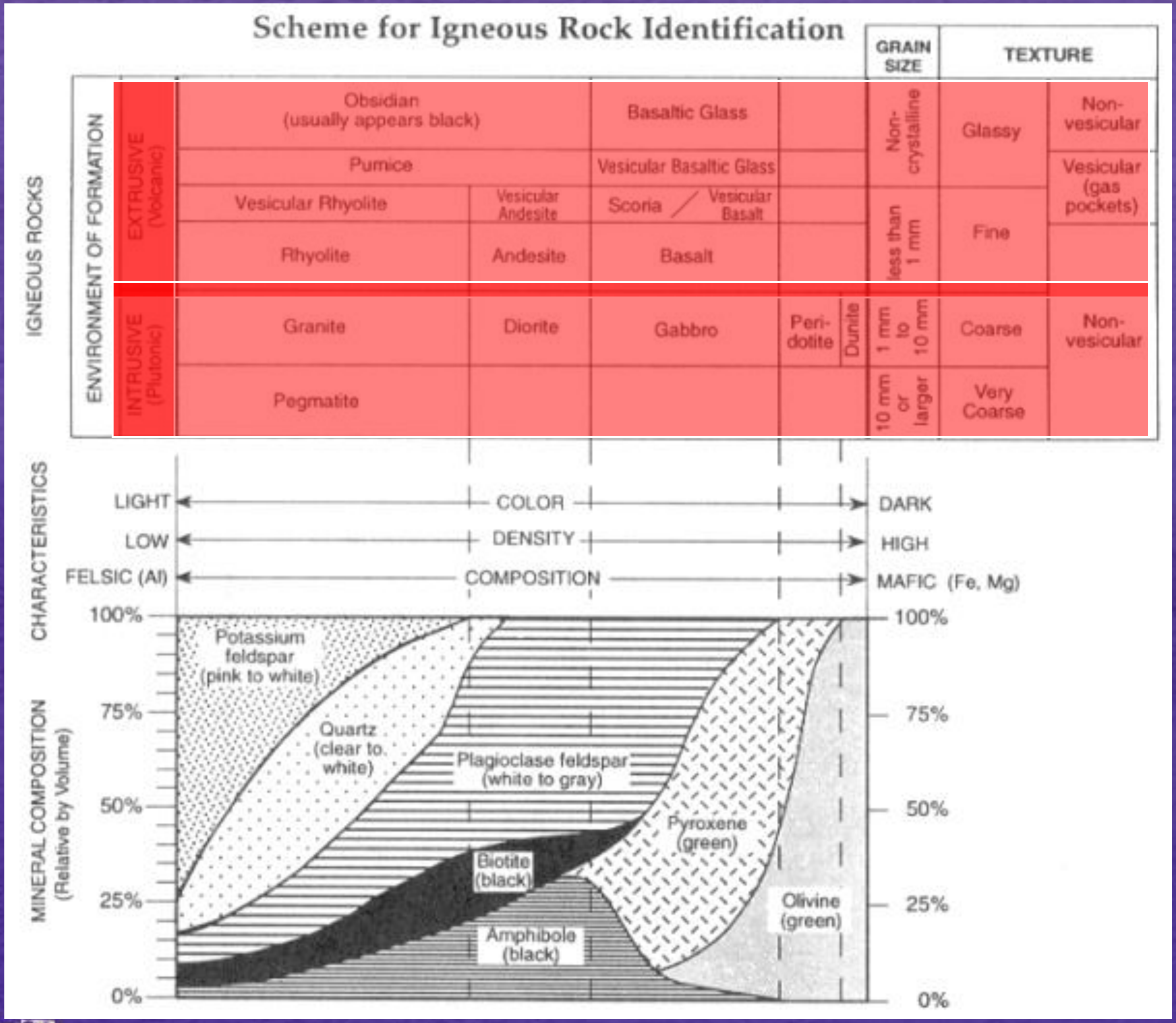
Intergrown

Not Intergrown

Inside the Earth: Intrusive

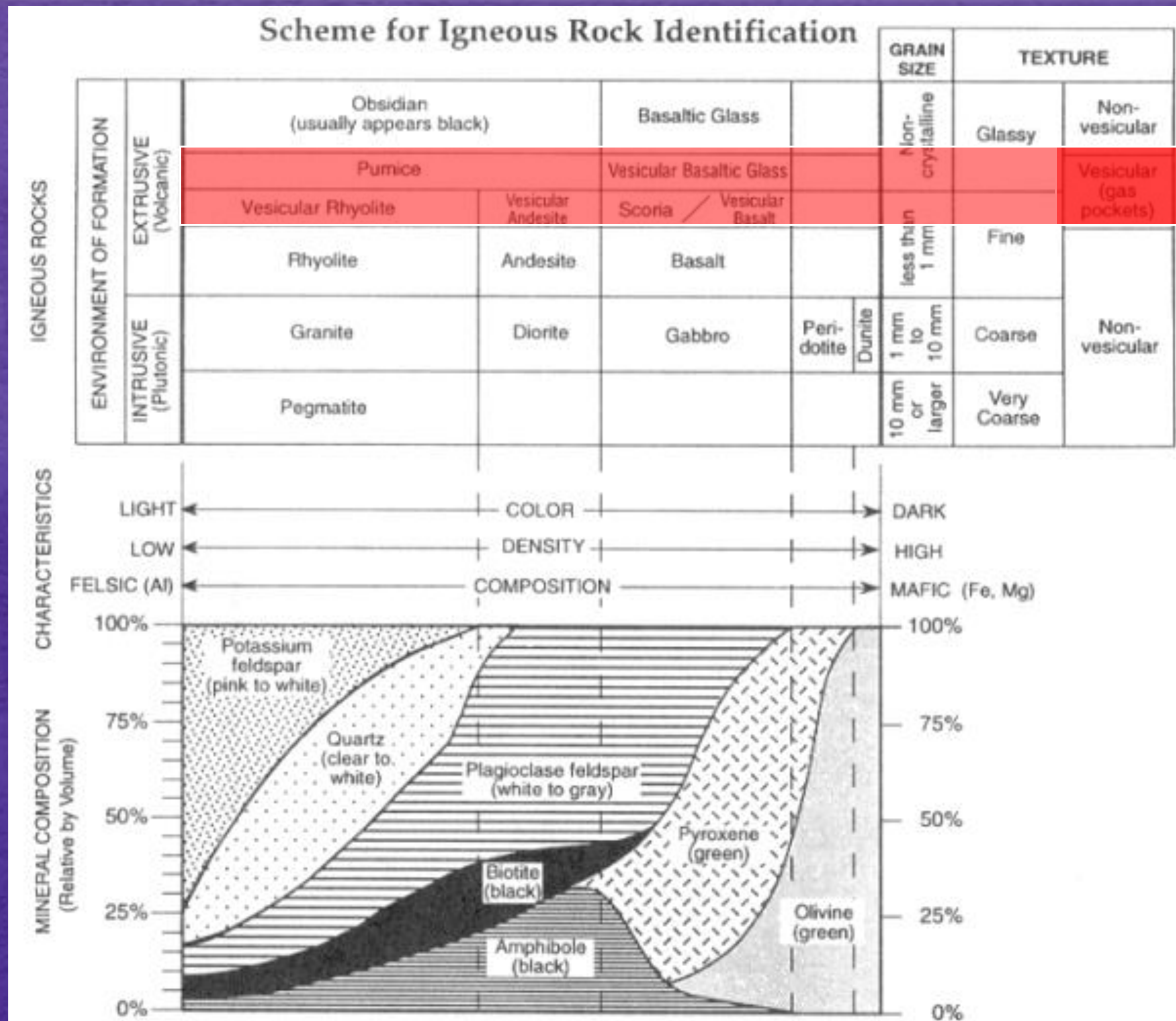
Outside the volcano: Extrusive

Where it was formed



Bubbles ?

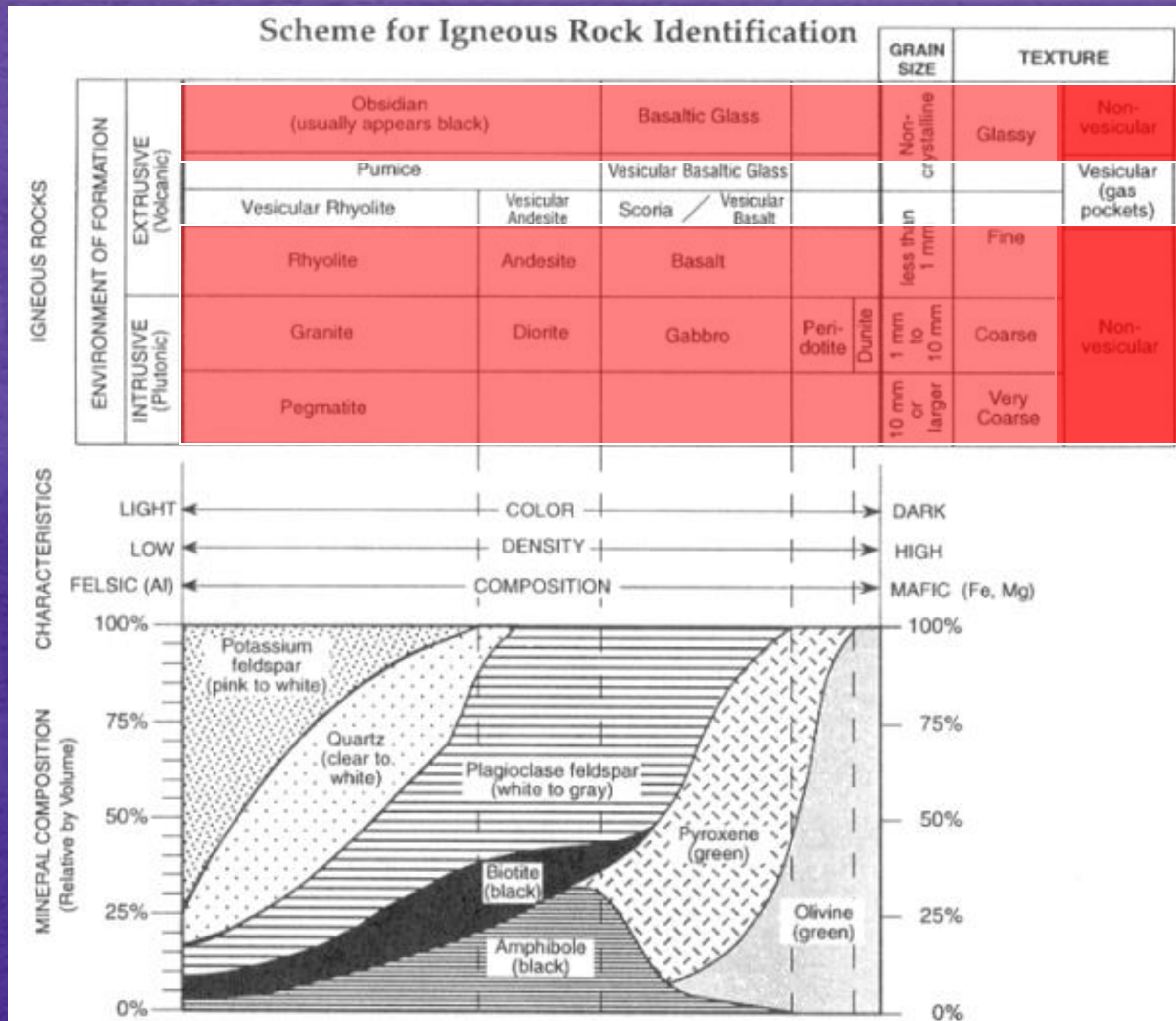
Yes= Vesicular



Trick or Treat

Bubbles ?

No=Non-vesicular



Trick or Treat

Color

Very Light

Neither Light nor Dark

NotVery Light

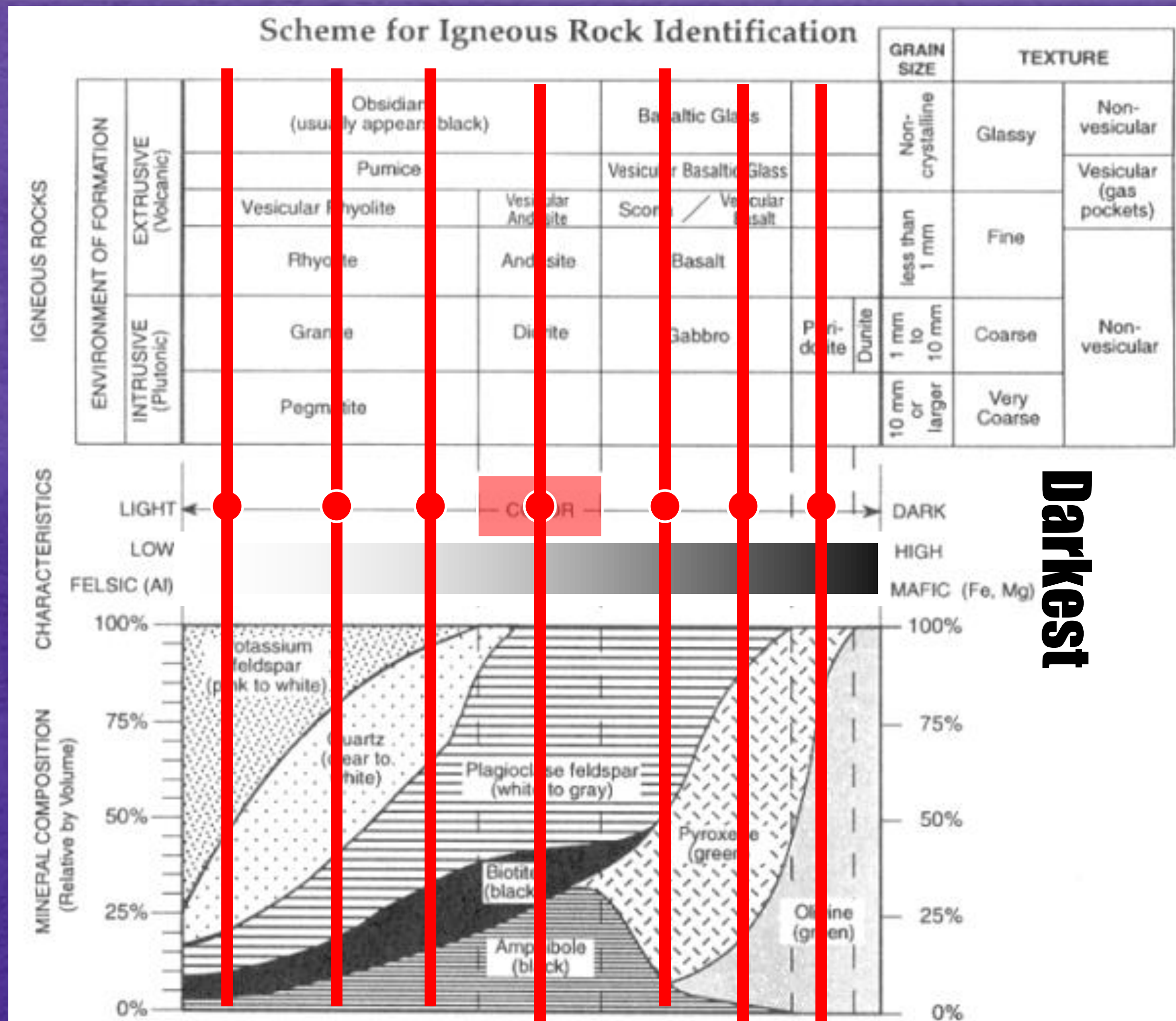
Not Very Dark

Very Dark

Light

Dark

Lightest



Darkest

Trick or Treat

Density

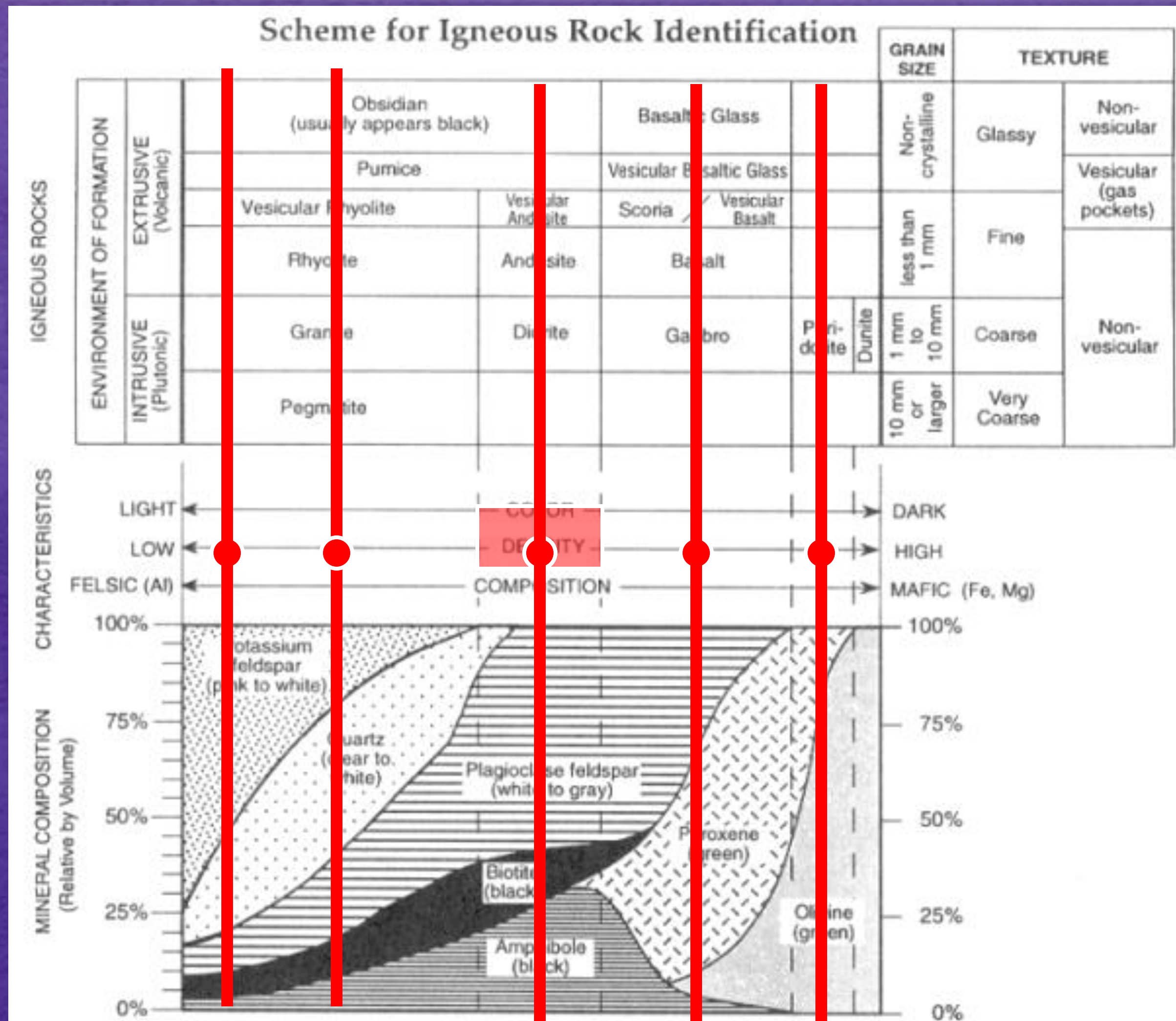
Very Light

Medium Density

Light

Dense

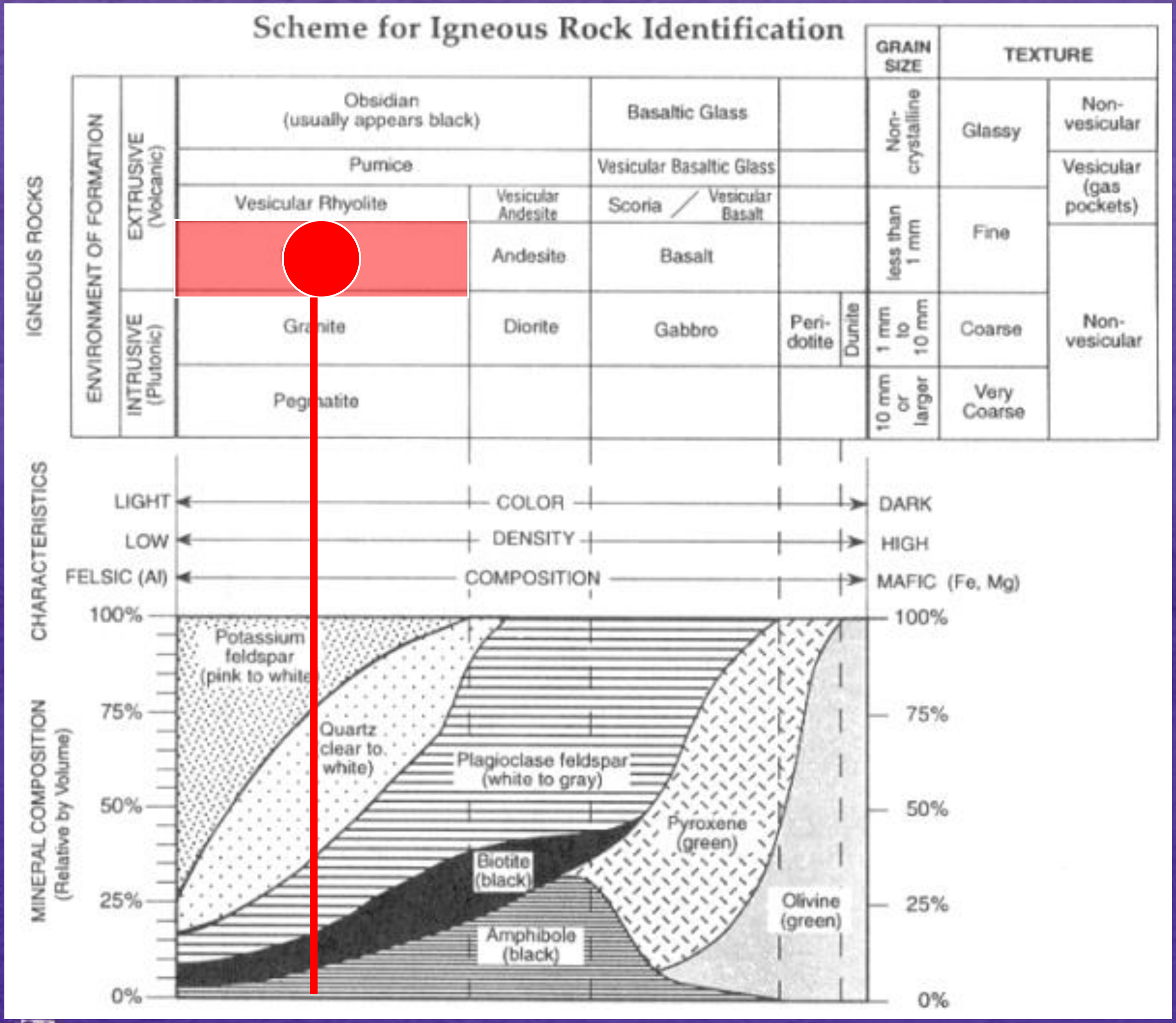
Very Dense



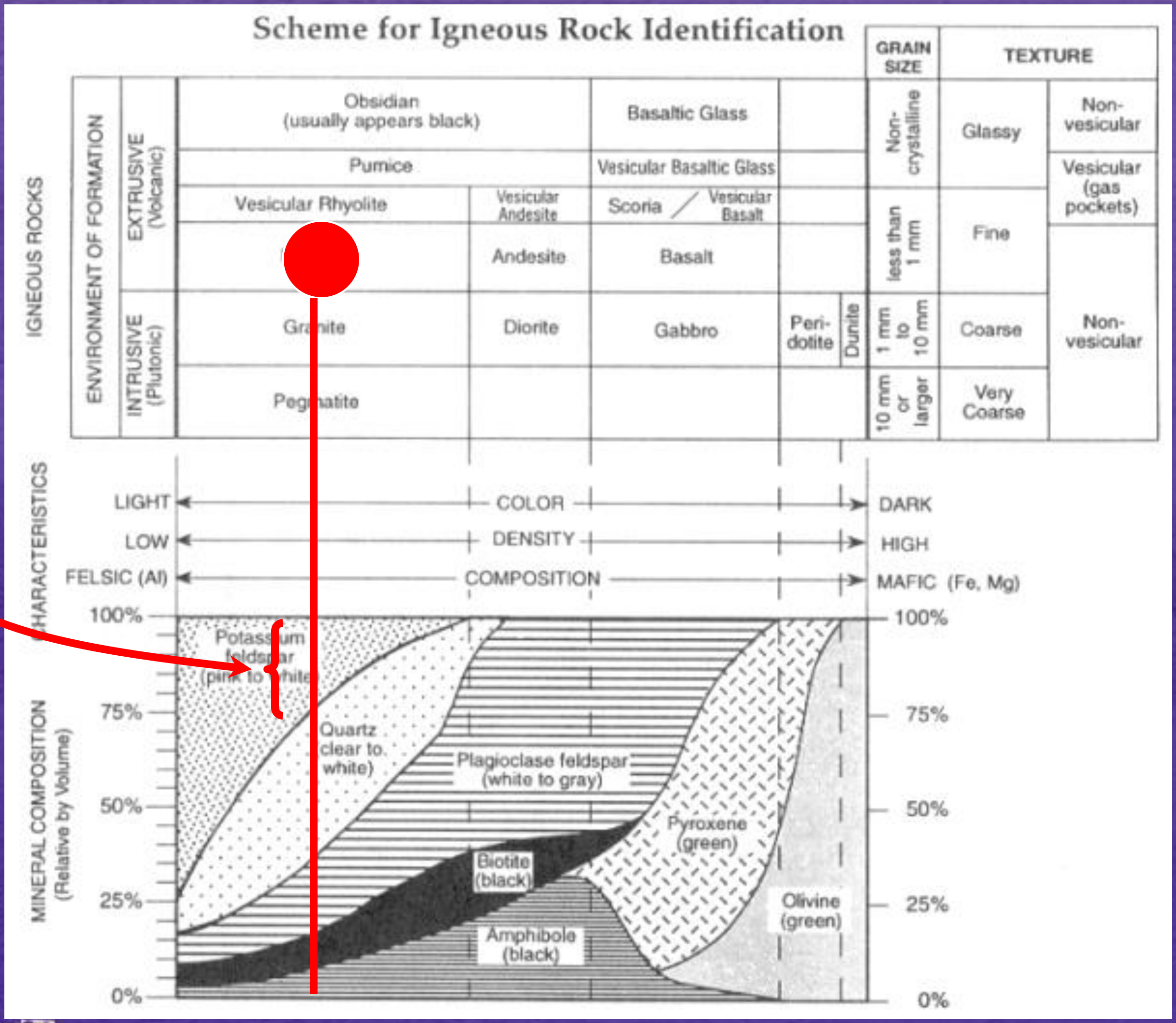
Trick or Treat

Finding The Minerals

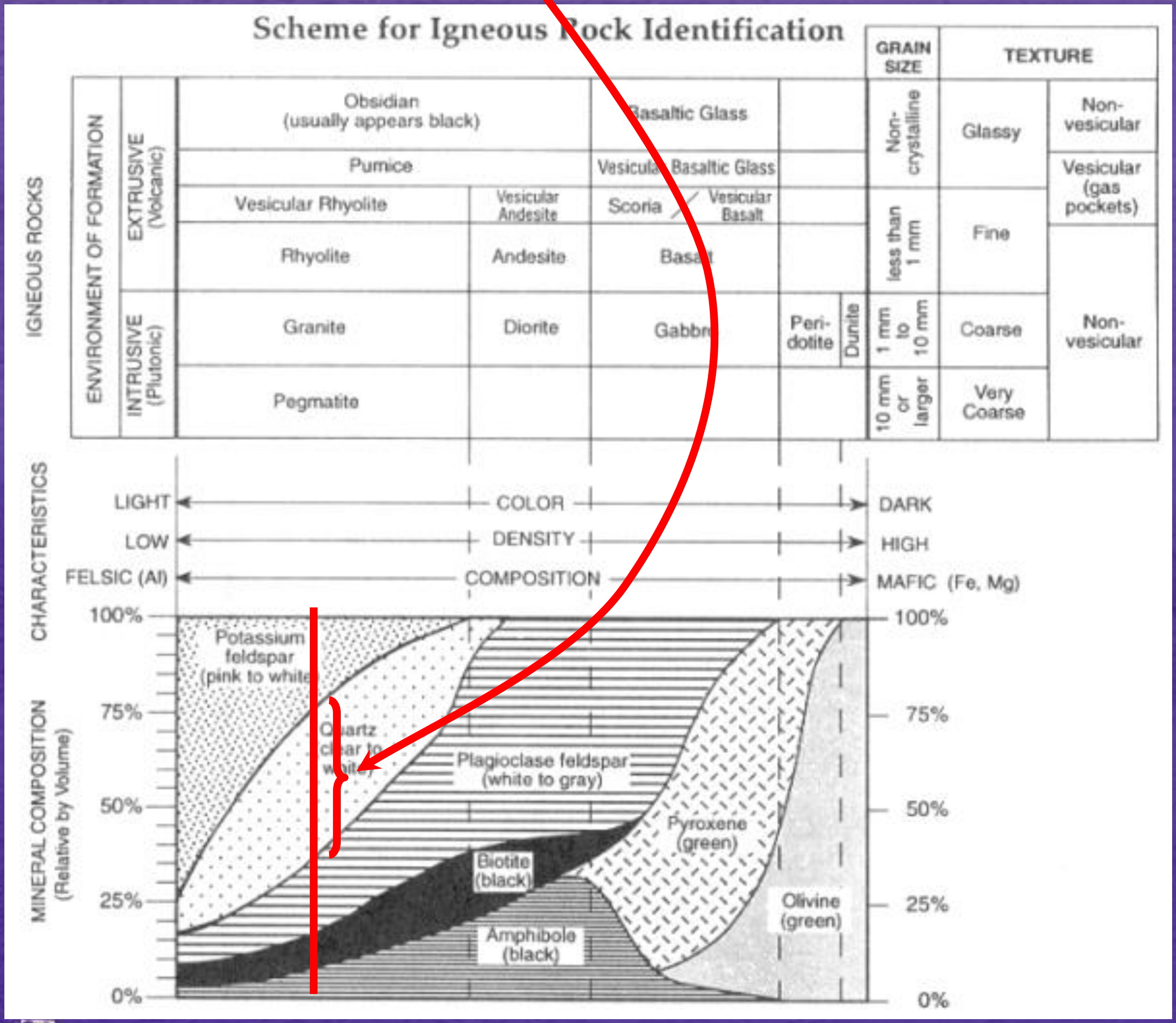
Identify the rock. **Unless you have other information, work in the middle of the rock's box.**



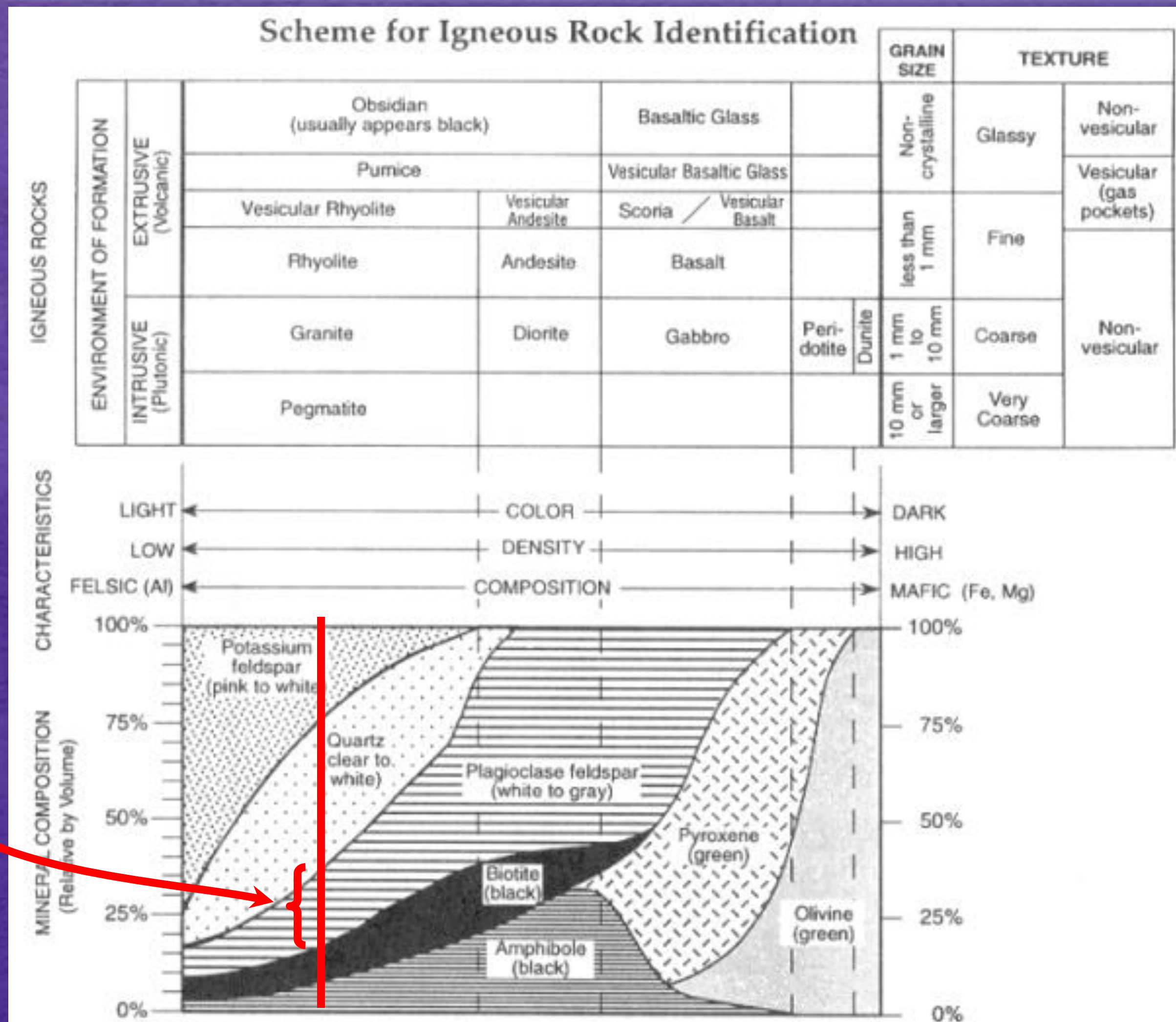
This is the amount of Potassium Feldspar in the rock.



This is the amount of Quartz in the rock.



This is the amount of Plagioclase Feldspar in the rock.

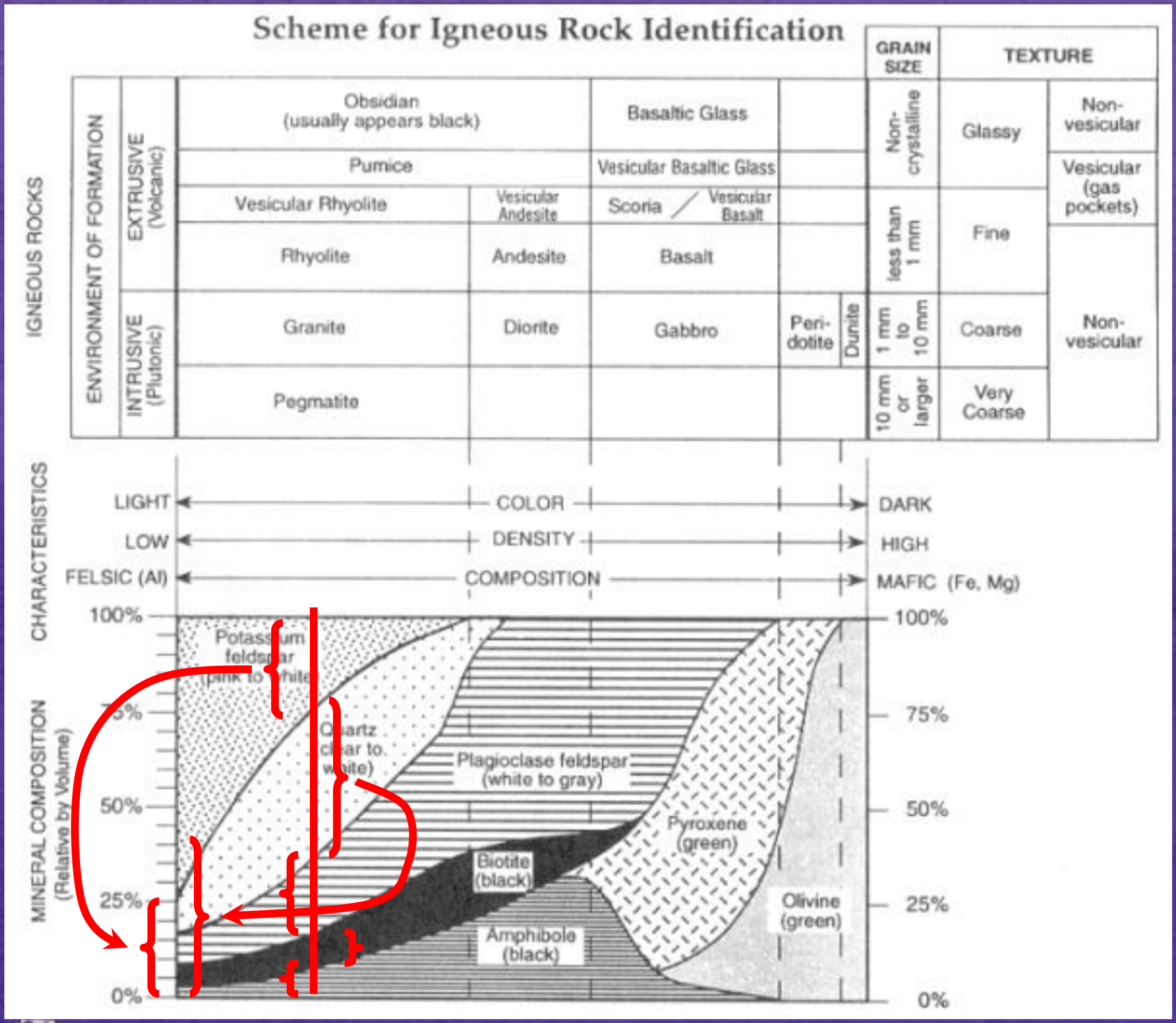


Trick or Treat

Use tick marks on a scrap paper to measure the percentage.

Potassium Feldspar 25%

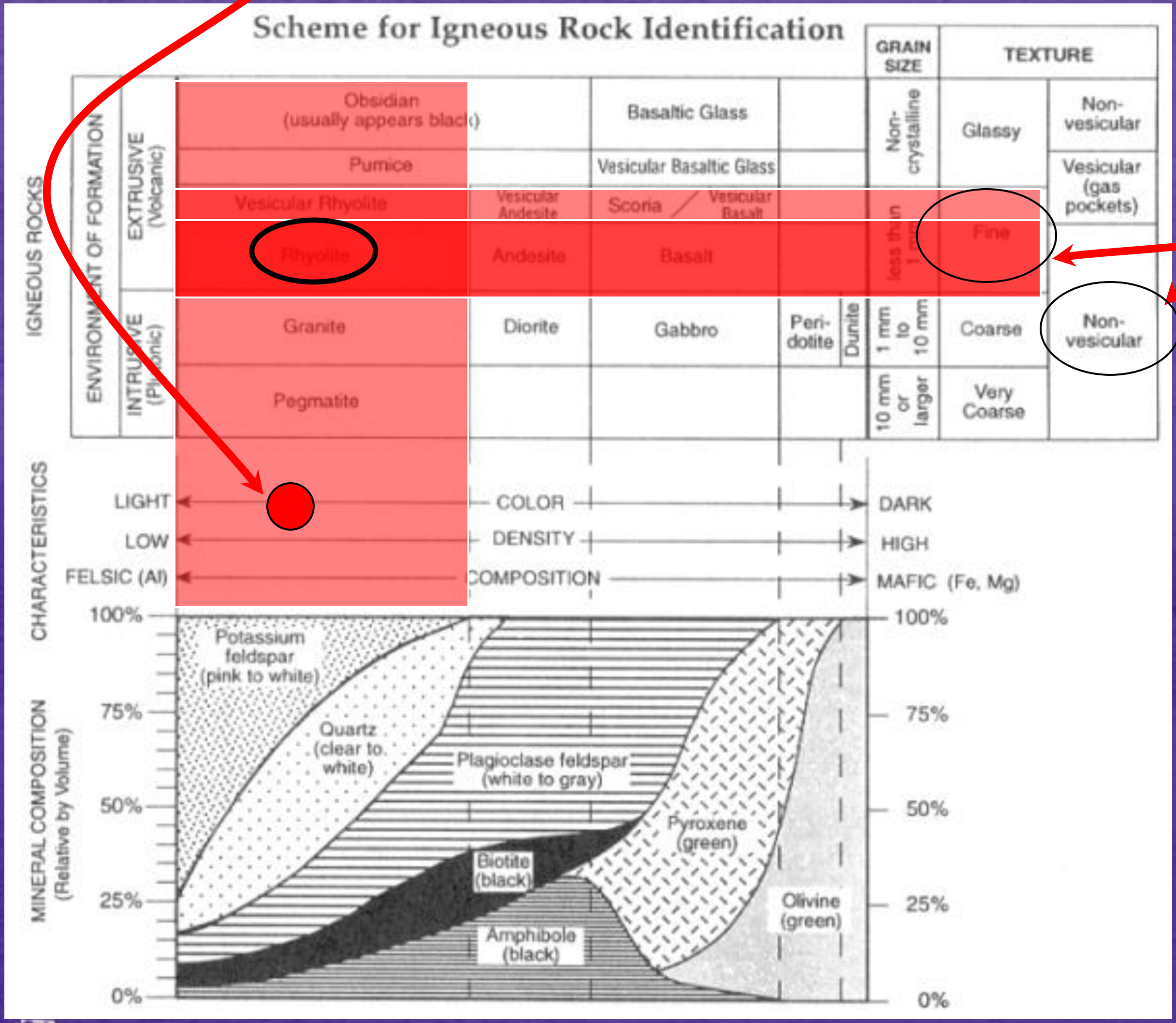
Quartz 40%



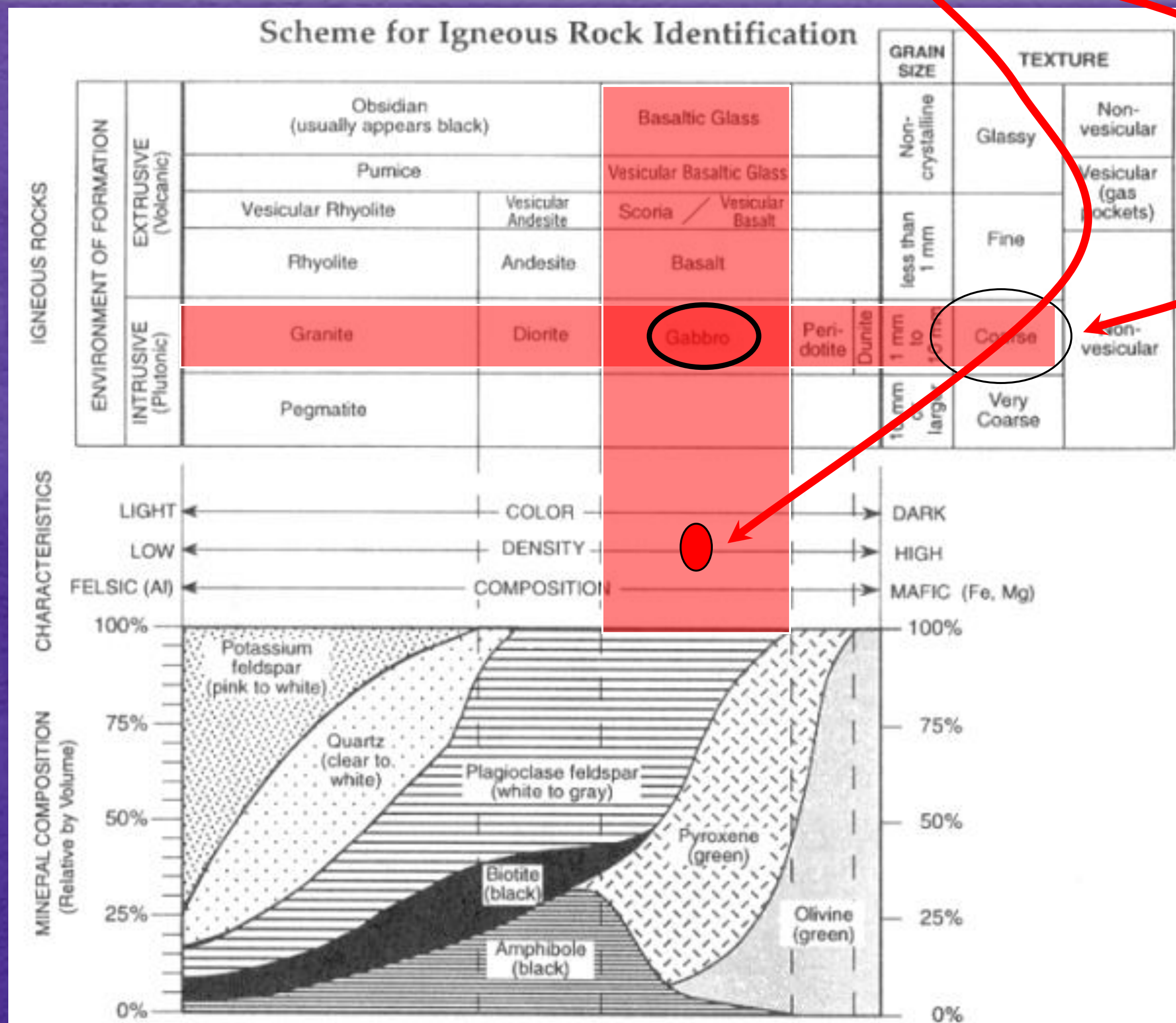
Trick or Treat

Practice

Name a light-colored, fine-grained rock with no bubbles.



Name a coarse-grained, dense rock.



Trick or Treat

Bowen's Reaction Series

Experiments that determined the sequence of crystallization of minerals from a gradually cooling mafic (basaltic) magma

Conducted by Norman L. Bowen prior to 1916

These experiments totally rewrote our understanding of igneous rock formation

- **Continuous (atomic structures of new minerals are same with minor constituent change)**
- **Discontinuous (New minerals with different atomic structure and chemical composition)**

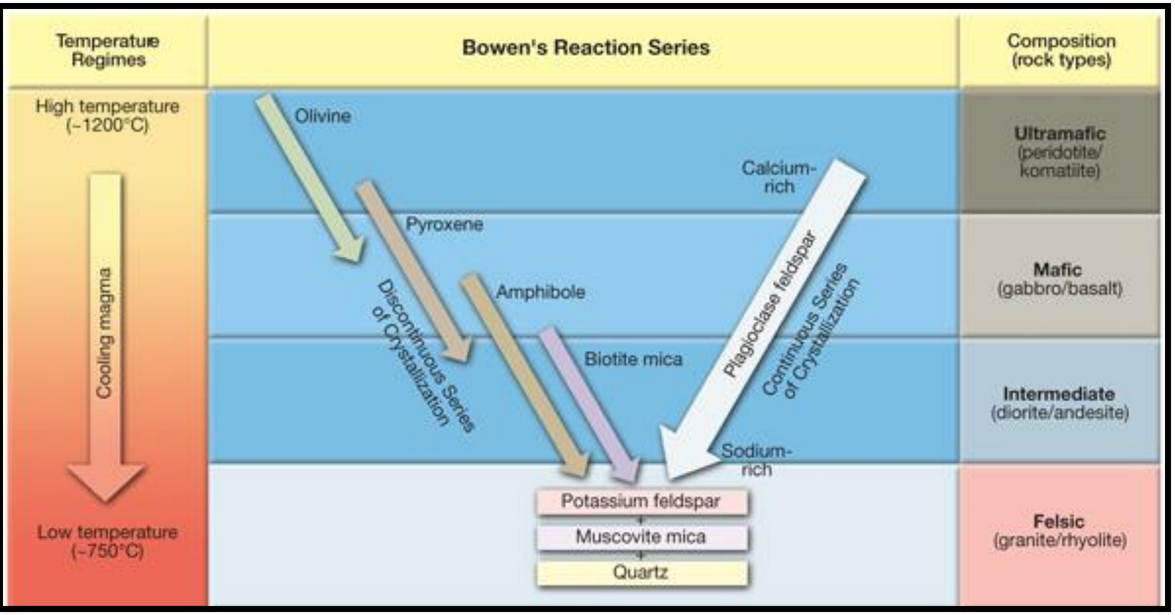
Bowen's Reaction Series

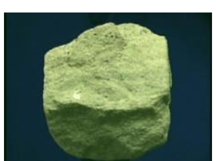
What is Bowen's Reaction Series?

Bowen's Reaction Series helps us understand why certain types of minerals tend to be found together while others are almost never found together.

How Does It Work?

- Different minerals form from magma at different temperatures.
- Some minerals crystallize when magma is at a higher temperature, while others only crystallize when magma is at a lower temperature.
- Minerals that form at high temperatures are listed at the top and minerals that form at lower temperatures are listed at the bottom.
- Rocks that form from magma at high temperatures are called <u>mafic</u> and tend to be dominated by dark colored minerals such as olivine and pyroxene.
- Rocks that form from magma at lower temperatures are called <u>felsic</u> and tend to be dominated by light colored minerals such as potassium feldspar and quartz.




Olivine


Pyroxene


Amphibole


Biotite

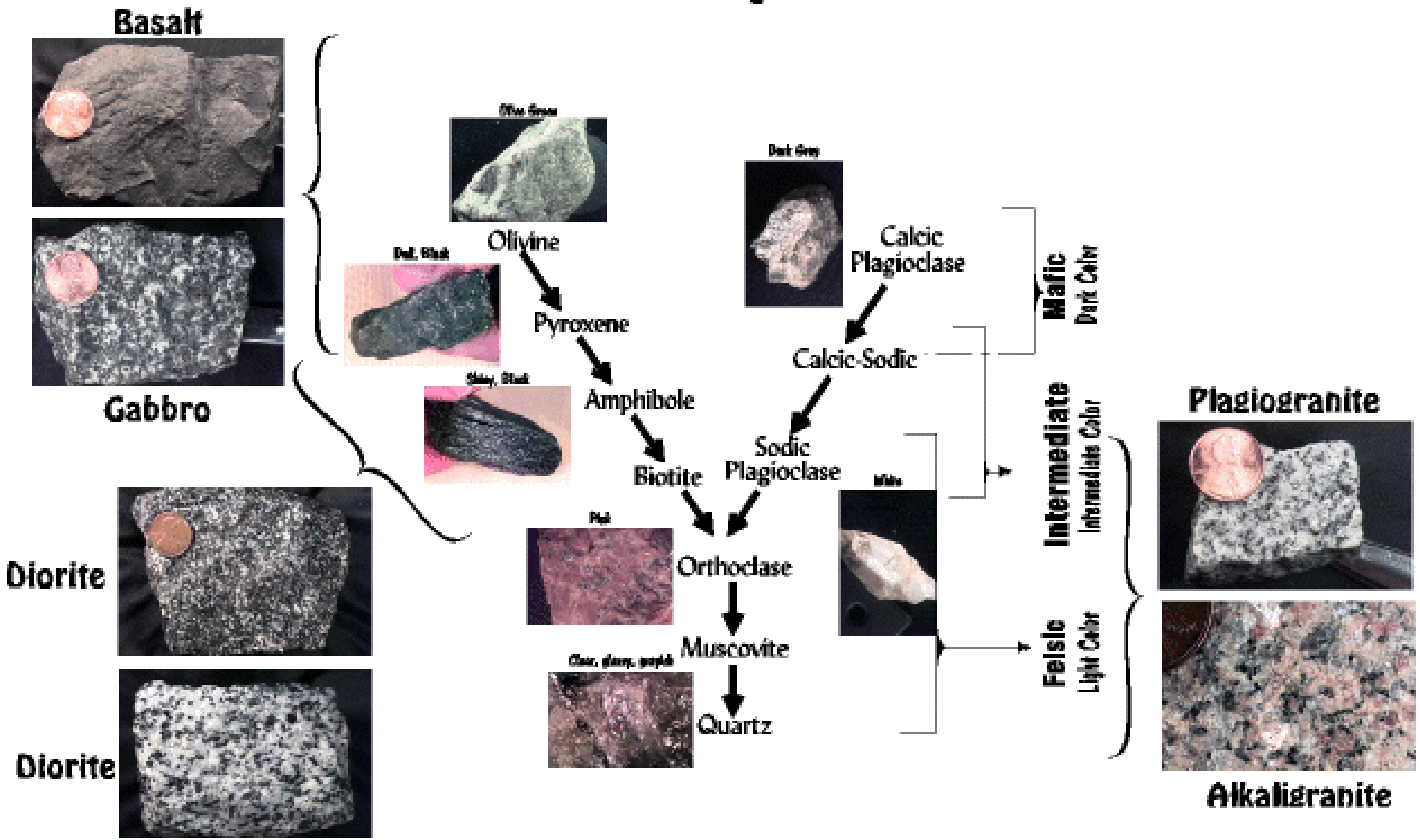

Potassuim Feldspar

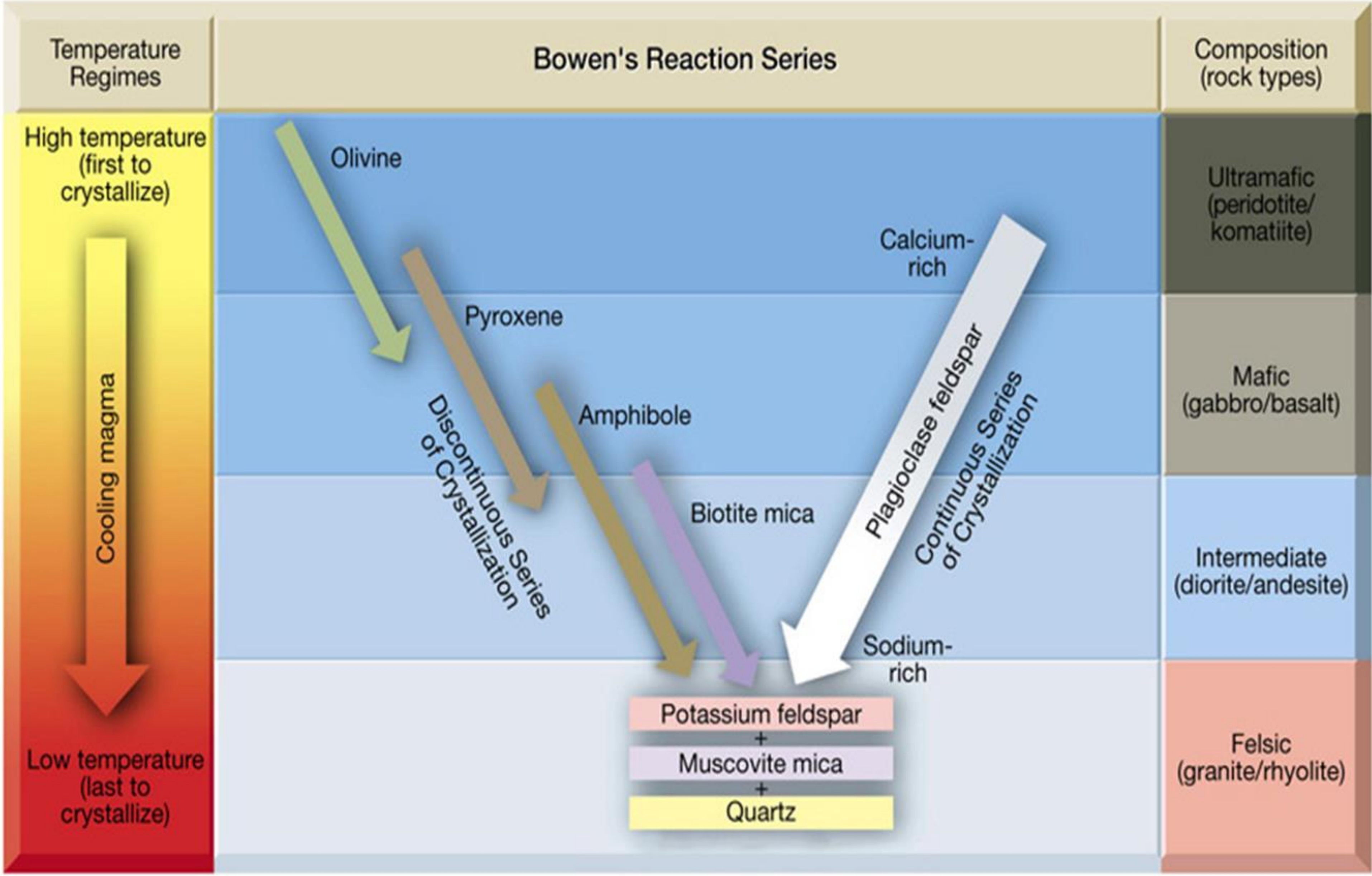

Muscovite


Quartz

Mafic ⟷ Felsic

Bowen's Reaction Series And Igneous Rock Classification





Temperature Regimes
Bowen's Reaction Series
Composition (rock types)
High temperature (first to crystallize)
Cooling magma
Low temperature (last to crystallize)
Olivine
Pyroxene
Amphibole
Biotite mica
Discontinuous Series of Crystallization
Calcium-rich
Plagioclase feldspar
Continuous Series of Crystallization
Sodium-rich
Potassium feldspar
+
Muscovite mica
+
Quartz
Ultramafic (peridotite/ komatiite)
Mafic (gabbro/basalt)
Intermediate (diorite/andesite)
Felsic (granite/rhyolite)

Tyrrell's Tabular Classification

1. This classification is based upon chemistry, mineralogy and texture.

2. Using the above information simplified table has been prepared which is known as Tabular Classification.

3. If we consider mineralogy, six vertical divisions are made in this tabular classification.

4. I – Quartz only, II - Quartz + Feldspar, III – Feldspar only, IV – Feldspar + Felspathoid, V – Felspathoid only, VI – Mafic only

5. Further, Tyrrel concentrated on what type of Feldspars are present in the rock type. Therefore, he divided Group II into rocks with Orthoclase and Rocks with Plagioclase.

6. Similarly Group III made of III sub-divitions, Predominant Alkali feldspar, Predominant Lime Plagioclase and Predominant Lime Soda Plagioclase

Texture Based:

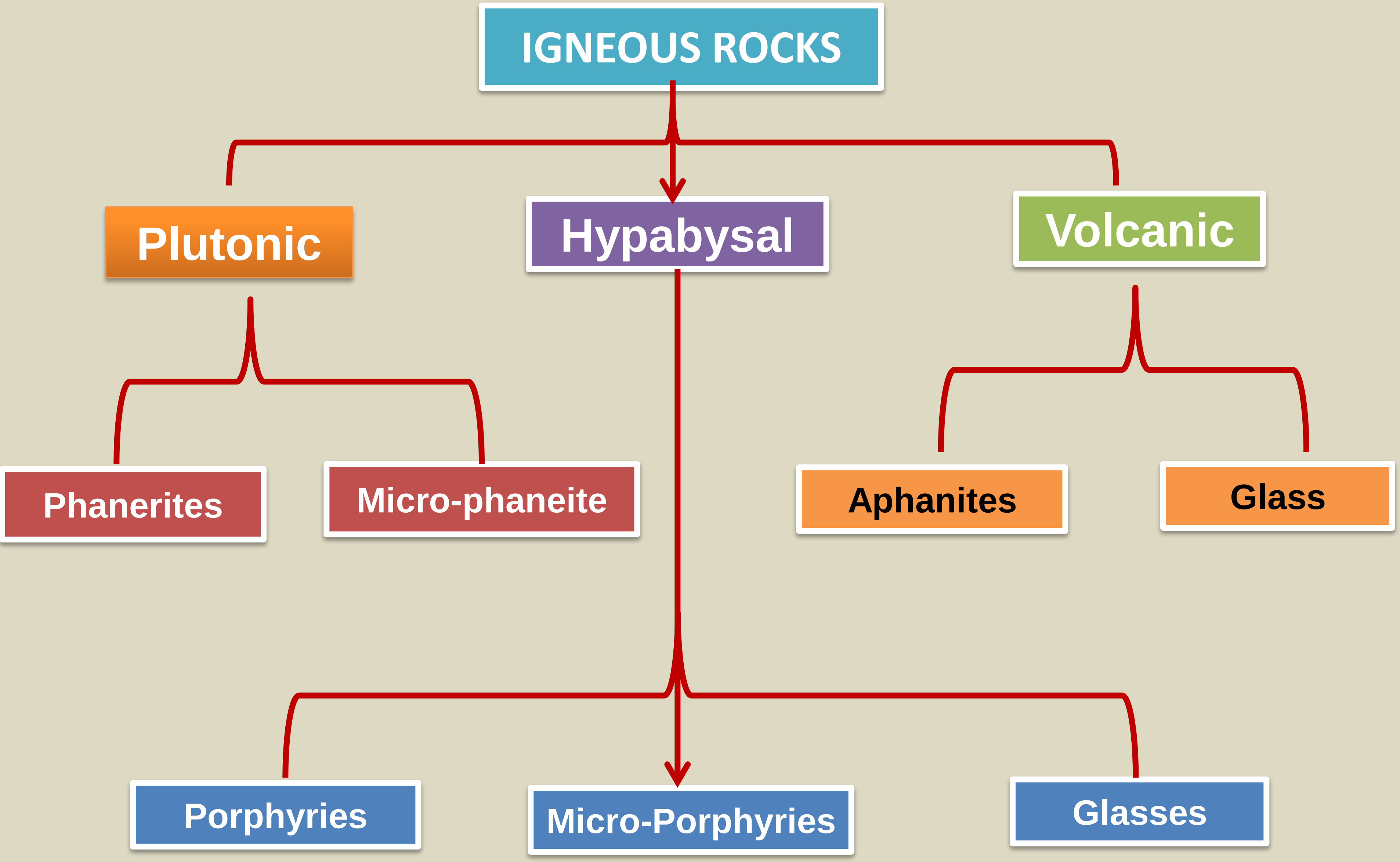
1. Based on texture three horizontal sub-divitions are made. Plutonic, Hypabyssal and Volcanic.

2. In plutonic region, he has considered felsic and mafic concentration. Thus he divided the plutonic sub divitions into felsic, mafelsic and mafic.

3. Hypabyssal in to Pegmatite (coarse grained), Lamprophyre (panidiomarphic) and Porphyrites (Porphyritic).

4. Volcanic – Aphanitic, Glasses

Tabular Classification



Chemistry Based:

1. Silica percentage play a major role. Vertical divisions I and II belongs to Over saturated rocks, III is Saturated and IV, V VI are belongs to under saturated rocks

	OVERSATURATED.			SATURATED.			UNDERSATURATED.		
	I Quartz.	II Quartz + Felspars		III Felspars.			IV Felspars + Felspathoids.	V Felspathoids.	VI Mafic Minerals, Predominant.
		Predominant Orthoclase.	Predominant Plagioclase.	Predominant Alkali Felspars (Or, Ab).	Predominant Soda-Lime Plagioclase.	Predominant Lime-Soda Plagioclase.			
PLUTONIC Felsic	Igneous Quartz Veins (Arizonite; Silexite)	Granite	Granodiorite (Tonalite)	Syenite	Diorite	Anorthosite	Nepheline-syenite	×	
PLUTONIC Mafelsic		×	×	×	×	Gabbro	Theralite and Teschenite	Ijolite	
PLUTONIC Mafic				×	×	×	×	×	Peridotite Picrite
HYPABYSSAL		←———	———	——— A p l i	t e s ———	———	———→		
		←———	———	——— P o r p h	y r i e s ———	———	———	———→	
			←———	——— L a m	p r o p h y	r e s ———	———	———	———→
		Granophyre Felsite				Dolerite	Tinguaite		
		←———	——— P i t c h	s t o n e ———	———→	Tachylyte			
VOLCANIC		Rhyolite	Dacite	Trachyte	Andesite	Basalt	Phonolite	Leucitophyre Nepheline-Basalt Leucite-Basalt	Olivine-rich Basalts Limburgite
		←———	——— P i t c h	s t o n e ———	———→	Tachylyte			
		←——— O b s i	d i a n ———→						
Average Silica Percentage	90	72	66	59	57	48	54·5	45	41

The essential features of the tabular or field classification are as follows:

a. **The Igneous rocks are first divided into Three main subdivisions** based on their mode of formation as indicated by their textural and structural features : **Plutonic, Hypabyssal and Volcanic.**

b. Textural divisions are then recognised in all the three subdivision as follows:

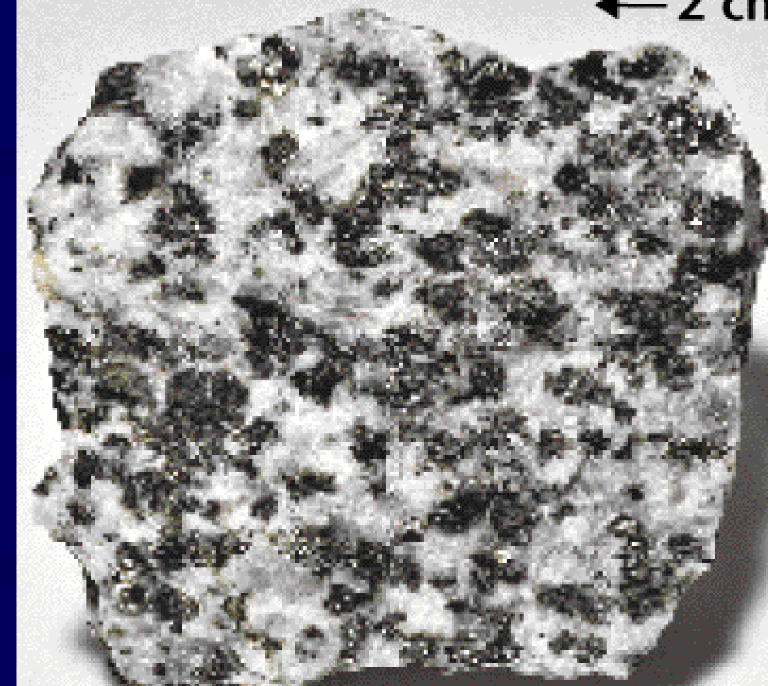
Plutonic Rocks	**:**	Phanerites (P), Microphanerites (M)
Hypabyssal Rocks	**:**	Porphyries (PO), Microporphyries (M) and Glasses (G)
Volcanic Rocks	**:**	Aphanites (A) and Glasses (G)

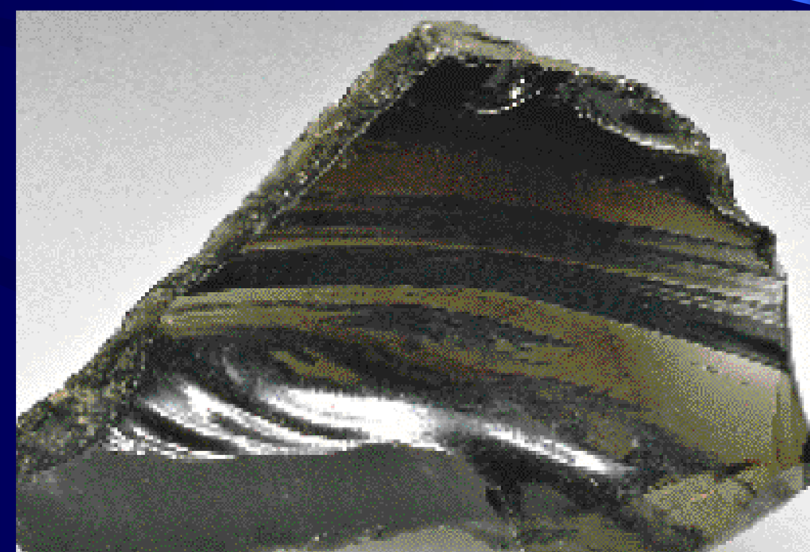
c. Each class of the above rocks is then subdivided into rock **subclasses** according to the relative abundance of following rock forming mineral assemblages:

i. **Quartz and Felspars**
ii. **Felspars**
iii. **Felspars and Felspathoids**
iv. **Ferro-magnesian minerals**

d. Further subdivision of some of these classes is made on the basis of predominance of particular type of a rock forming mineral.

e. The **relative abundance** of felsic and mafic minerals serves as a basis for broadly defining the saturation of the rock with silica.





(UL) Aphanitic, (UR) Phaneritic, (LL) Porphyritic, (LR) Glassy

PETROGRAPHY

The **description** and **systematic classification of rocks**, aided by the microscopic examination of thin sections.

PETROLOGY

The study of the **origin, occurrence, structure and history of rocks**, much broader process/study than petrography.

PETROGENESIS

A branch of petrology dealing with the **origin** and **formation of rocks.** Involves a **combination of mineralogical, chemical and field data.** **Petrologic, petrographic, and petrogenetic studies can be applied to igneous, metamorphic or sedimentary rocks**.

Acidic (silicic) igneous rocks

GRANODIORITE

Appearance: Light coloured, medium- to coarse-grained intrusive igneous rocks with more than 20% of quartz. Within feldspars, the Na-rich plagioclase prevails over K-feldspar (orthoclase). The mafic minerals are represented by amphibole, pyroxene and biotite. This is the intrusive equivalent of dacite. It is formed mostly in subduction zones (active continental margins) and collisional settings (e.g., Alps along the Insubric-Periadriatic line). It forms also small volume shallow intrusive bodies of andesitic to dacitic volcanoes.

Mineral content:

Essential minerals: Na-rich plagioclase > K-feldspar (orthoclase), quartz, biotite, amphibole

Accessory minerals: apatite, magnetite, zircon

Secondary minerals: sericite, chlorite, epidot

Tonalite: Feldspars are represented almost exclusively by Na-rich plagioclase.

DACITE

Appearance: Ligth grey coloured, often crystal-rich volcanic rock. The most abundant phenocrysts are plagioclase, the mafic minerals are usually represented by amphibole and biotite, occasionally orthopyroxene. It contains much less alkali feldspar and quartz. It occur most commonly in subduction zone volcanoes. The known largest volume pyroclastic deposit in the Earth (Fish Canyon Tuff) is composed by dacite.

Mineral content:

Essential minerals: Na-rich plagioclase > K-feldspar (sanidine), biotite, amphibole, pyroxene

Accessory minerals: quartz, titanite, apatite, magnetite, zircon

Secondary minerals: sericite, chlorite, epidot

GRANITE

Appearance: Light coloured, medium- to coarse-grained intrusive igneous rock containing more than 20% quartz and the amount of alkali feldspars (orthoclase) exceeds that of the plagioclase. The mafic minerals are usually biotite, but amphibole and pyroxene could also occur. Certain granite varieties muscovite, garnet and cordierite could be also found. Granites usually occur where thick continental crust developed, i.e. at subduction zones along active continental margin (e.g. Andes, Western USA) and at collision zones (e.g., Alps, Himalaya).

Mineral content:

Essential minerals: K-feldspar (orthoclase) > Na-rich plagioclase, quartz, biotite, amphibole

Accessory minerals: titanite, apatite, magnetite, zircon, muscovite, pyroxene, andalusite, cordierite, garnet, turmalin, topas

Secondary minerals: sericite, chlorite, epidot

ROCK TYPES

Monzogranite:

- Within feldspars the alkali feldspar has an amount of 35-65%.
- This is the most common granite type, called formerly also Adamellite (the Adamello granite is one of the most famous silicic igneous bodies at the Periadriatic line in the Alps)

Syenogranite:

within feldspars the alkali feldspar has an amount of 65-90%.

Alkáli granite:

within feldspars the alkali feldspar has an amount of >90%. The mafic minerals are alkali pyroxenes (aegirinaugite, aegirine) and alkali amphibole

Graphic granite:

quartz and orthoclase show oriented intergrowth. It forms from eutectic silicic melt.

Luxullianite (turmaline-granite):

in this granite type turmaline occurs in significant amount

Greisen:

A granite type showing metasomatic alteration.

Typical minerals occurring in this granite are significant amount of quartz and less muscovite and/or Li-mica, Topaz. Feldspar, fluorite, turmaline, berill, rutile, cassiterite, apatite are found as accessory minerals.

The feldspar and biotite in the original granite are replaced by quartz, Li-mica and caolinite.

Aplite:

Fine-grained granite with equigranular texture with orthoclase-microcline > Na-rich plagioclase and quartz. Mafic minerals are subordinate.

It represent highly evolved silicic melt with eutectic (haplogranitic) composition.

granophyre: It contains quartz and alkali feldspar in characteristic angular intergrowths. It is formed from eutectic melt.

The characteristic accessory minerals of peraluminiuous (S-type; the silicic magma is formed by melting of metasedimentary rocks) granites are Al-rich minerals, such as garnet, cordierite, andalusite and muscovite.

In the metaluminuous (I-type; the silicic magma is formed by melting of meta-igneous rocks) granites, amphibole and pyroxene represent the mafic minerals in addition to biotite.

The peraluminuous granites are characterized by the appearance of alkali mafic minerals such as alkali pyroxene and alkali amphibole.

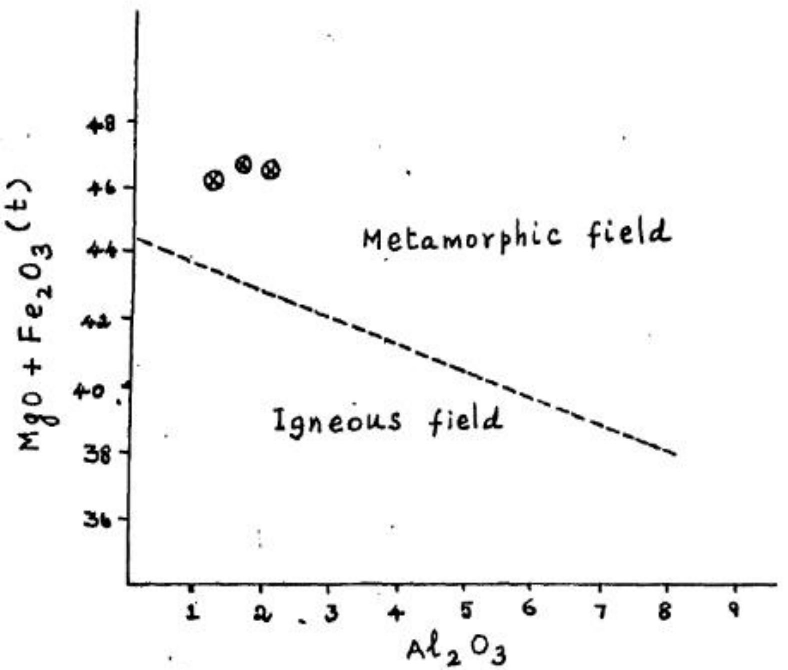
The feldspar content of the granite is also indicative on the origin of the silicic magma. If only one alkali feldpar type is found what often shows perthitic feature, it implies crystallization from relatively dry magma hipersolvus granites).

Two different feldspar types (K-feldspar and Na-rich plagioclase) suggest that the crystallization could take place from water-saturated magma (subsolvus granites).

CHARNOCKITE

- Charnockite is the principal rock type of high grade or granulite *facies* terrains.
- Sir Thomas Holland is remembered as the originator of the name charnockite, the greasy looking rock quarried around Pallavaram, Madras.
- Now the name charnockite has gained world wide renown.
- It was in Salem district, Holland (1891) first identified hypersthene granite.
- Later he named a similar rock at Pallavaram as charnockite (Holland, 1900).
- Though his views on the origin of charnockite has undergone significant changes in recent years, his observations are the foundation for new thoughts.

- Pichamuthu in 1953 has identified at least two generations of charnockites.
- 1.The banded type similar in appearance and origin to Peninsular gneiss but had undergone regional dynamo-thermal metamorphism.
- 2.Comparatively coarse grained greasy looking patches of charnockite developing within the Peninsular gneiss which might have developed due to metasomatism and palingenesis.
- Such a greasy looking charnockite developed within the Peninsular gneiss is seen at Ramasamimalai



Plots of orthopyroxene in charnockites falling well within the metamorphic field on a ($MgO + Fe_2O_3^{(t)}$) Vs Al_2O_3 diagram after Bhattacharya (1971)

- Charnockite/granulite belt of the Southern India being one of the largest granulitic provinces in the world occupies the extended parts of Karnataka, Tamil-Nadu and Kerala, bounding from the south the gneisses and metasediments of the oldest tectonic unit of the Indian shield - the Dharwar craton.
- In accordance to the isotopic dating, most of the charnockites from this region were formed in the late Archaen time 2500-2700 Ma.
- Only charnockites of Kerala are interpreted to be younger and correspondingly cover the time span 1930-540 Ma, according to U-Pd data [Srikantappa et. al., 1985].
- Age of charnockites from the area near Chennai is determined as 2555pm 140 Ma by use of Sm-Nd method and as 2563pm 65 by use of Rb-Sr

- Igneous microstructures in charnockites include a porphyritic texture (e.g., Ridley, 1992), characterised by euhedral to subhedral pyroxene and feldspar (e.g., Shelley, 1993; Frost et al., 2000), which may have a slight preferred orientation.
- Charnockitic augen gneiss in southern Norway in which the augen represent K-feldspar phenocrysts (e.g., Vernon, 1990) (Fig. 2), are an example of charnockites showing such a porphyritic texture.
- Further igneous microstructures include myrmekitic intergrowths of biotite-quartz plagioclase parallel to the biotite cleavage next to orthopyroxene (Ridley, 1992).

- The accessory minerals apatite and zircon are sometimes assumed to indicate a magmatic origin, especially if they are euhedral or contain melt inclusions.
- However, they may occur in magmatic charnockites as well as in granites, which means that they can be of little use to distinguish between magmatic charnockites and dehydrated granites

- Melt remnants are a clear indication of the igneous origin of charnockites and can be in the form of melt (or melt derived) inclusions (e.g., Roedder, 1984) or typical melt-related microstructures (Sawyer, 1999; Holness and Sawyer, 2008; Holne

. Metamorphic microstructures in charnockites

- Metamorphic recrystallisation, either in charnockites emplaced at granulite conditions or in dehydrated granitic rocks, results in a typical granoblastic granulite texture (e.g., Vernon, 2004).
- Dynamic recrystallisation may also result in the development of elongated quartz crystals or ribbons, sometimes of extraordinary size (up to a few cm's in a finer grained matrix). This form of "platy" quartz, once considered to be a typical characteristic of granulites

- The occurrence of supposed minerals of metamorphic origin, in particular garnet and also other Al-rich mineral phases such as cordierite, is sometimes used as an indication for a metamorphic origin of the charnockite.

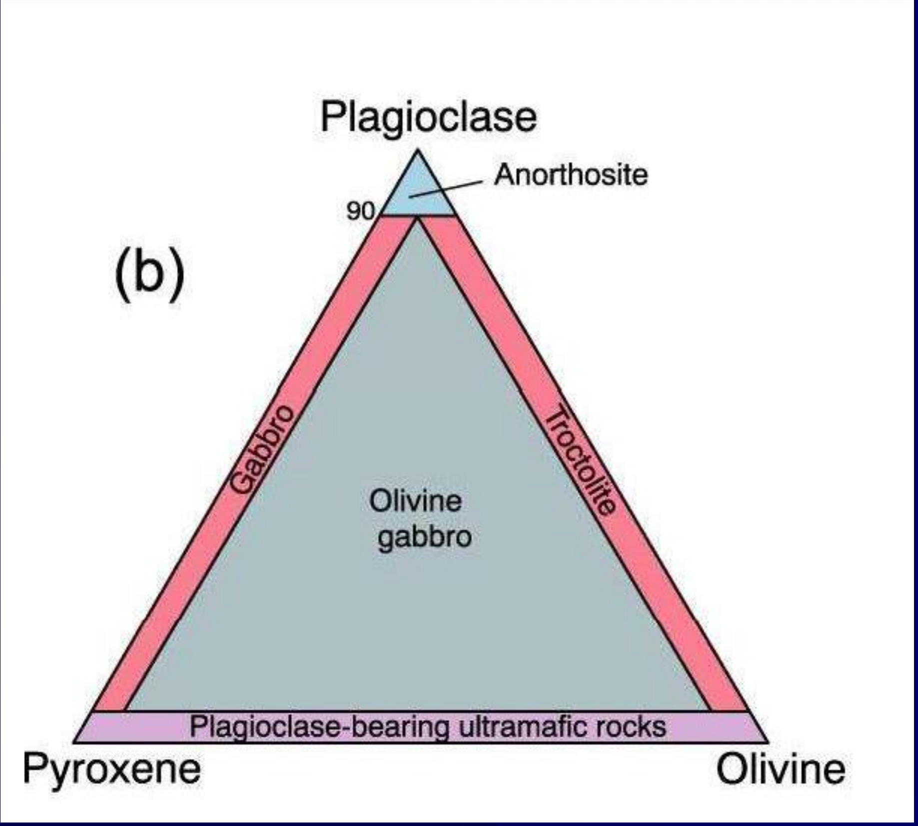
ANORTHOSITE

- Anorthosite is a phaneritic, intrusive igneous rock characterised by a predominance of plagioclase feldspar (90-100%) and a minimal mafic component (0-10).
- Pyroxene,ilmenite,magnetite,and olivine are the mafic mineral commonly present.
- Anorthosite is important in academic and economic fields.

- Anorthosite typically consist of 90-100% of plagioclase in the andesine-labradorite range.
- Mafic minerals never exceed 10% of the rock.

- Anorthosite can be classified on the following three ways :
  1) IUGS (International Union of Geological Society)
  2) Age of the formation
  3) Their occurrence and association
  - According to the age of the formation rock, they are classiflied as Proteroic anorthosite and Archean anorthosite.
  - According to the occurance, they are classified as Lunar, Massif, and Layered anorthosite.

IUGS classification



Proteroic anorthosite

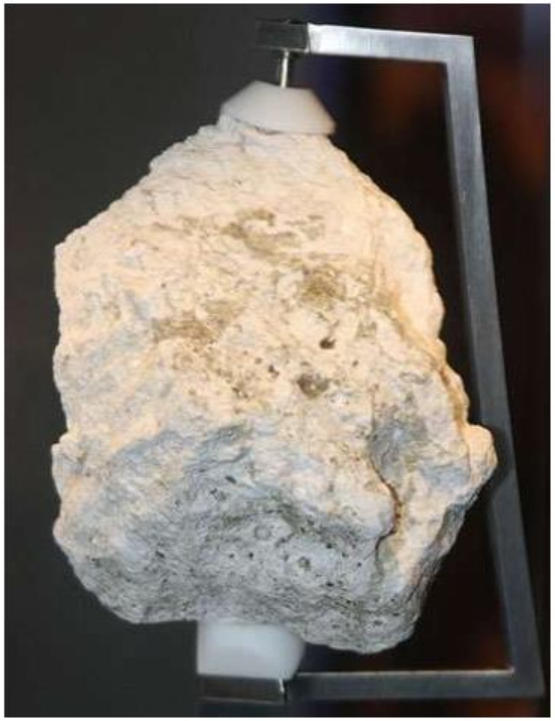
- They are formed during the Proterozoic era.
- They form stock to batholith size plutons.
- Apparently confined to high grade regional metamorphism terrians of Precambrian age.

Archean anorthosite

- They are emplaced during the Archean era.
- They are characterised by highly calcic plagioclase composition An_{85-100}.
- Chemically, calcic anorthistites layers are high in Al_2O_3.
- Their most characteristic feature is the presence of equant megacrysts of plagioclase surounded by a fine-grained mafic groundmass

Lunar anorthosite

- Probably formed the primitive lunar crust.
- It consist of highly calcic plagioclase with lesser orthopyroxene,olivine, Ca-clinopyroxene pigeonite and spinel(Mg-Al).
- They are light-coloured, quite fine-grained and Ca-content is close to 100%.
- It shows labradorescence.
- They are formed by cryetallization of An-rich plagioclase in the early



Layered anorthosite

- It is characterised by rythemic layering showing cumulus texture.
- Composed by plagioclase in the An_{70-100} range.

Massif anorthosite

- Layring is not found in massif anorthosite.
- It contain plagioclase of An_{35-65} range.

ORIGIN of anorthosite

Magmatic Origin:

- Massif anorthosite are magmatic and layered anorthosites are magmatic differentiation.
- It has been derived from a basic magma either grabbroic or dioritic in compsition.
- They are originated from early crystallisation and accumulation of anorthite-rich plagioclase and their staining off by filter pressing process.

Metasomatism:

- Process of metasomatic replacement attendant with higher grades of metamorphism is also an originating way of anorthosite.

Indian occurrence

1. Sittampundi,Oddanchatram, Kadavur areas of Tamil Nadu.
2. Karaput, Rambha, Banpur, Kalahandi area of Orissa.
3. Kondapalli of Andhra Pradesh.
4. Mayurbhanj of Rajasthan.
5. Bankura of Bengal.

CARBONATITE

- **Carbonatites** are plutonic igneous rock and found either in intrusive or extrusive igneous rocks more than 50% carbonate minerals are present .
- "Carbonatite" was introduced by the Norwegian petrographer W. Brugger (1921).
- Carbonatites are primarily composed of calcite (or dolomite) of igneous origin and silicate mineral are also present.
- Importance:

Academic-Carbonatite are derived from mantle.

Economic- Carbonatites contain rare earth elements.

•Carbonatites are composed of olivine, pyroxene, calcium carbonate,apatite.

• They range from essentially monomineralic types consisting nearly entirely of calcite or dolomite to varieties in which several rhombohedra carbonates are accompanied by numerous light and dark silicates and by phosphates, sulfates, iron oxide minerals, REE carbonates, sulfides, fluorides and Nb oxide species.

•Carbonatites are classed as calcitic sovite and alvikite varieties.The two are also distinguished by minor and trace element .

Carbonatites show coarse grain or fine grain texture in hand specimens and hypidiomorphic texture in thin section.

Fenite:

Fenite is the contact zone between carbonate and country rock enriched in alkalis i.e. Na and K. This fenite are the indicator zone that marks the presence of a carbonatite.

Classification:

- Based on dominant mineral
  - Calcite carbonatite
  - Dolomite carbonatite
- Based on whole rock analysis
  - Calciocarbonatite: >80% CaO
  - Magnesiocarbonatites: MgO > FeO+Fe2O3+MnO
  - Ferrocarbonatites: FeO+Fe2O3+MnO > MgO
  - Natrocarbonatites: Alkali-rich – Na, K, Ca

Origin of carbonatites:

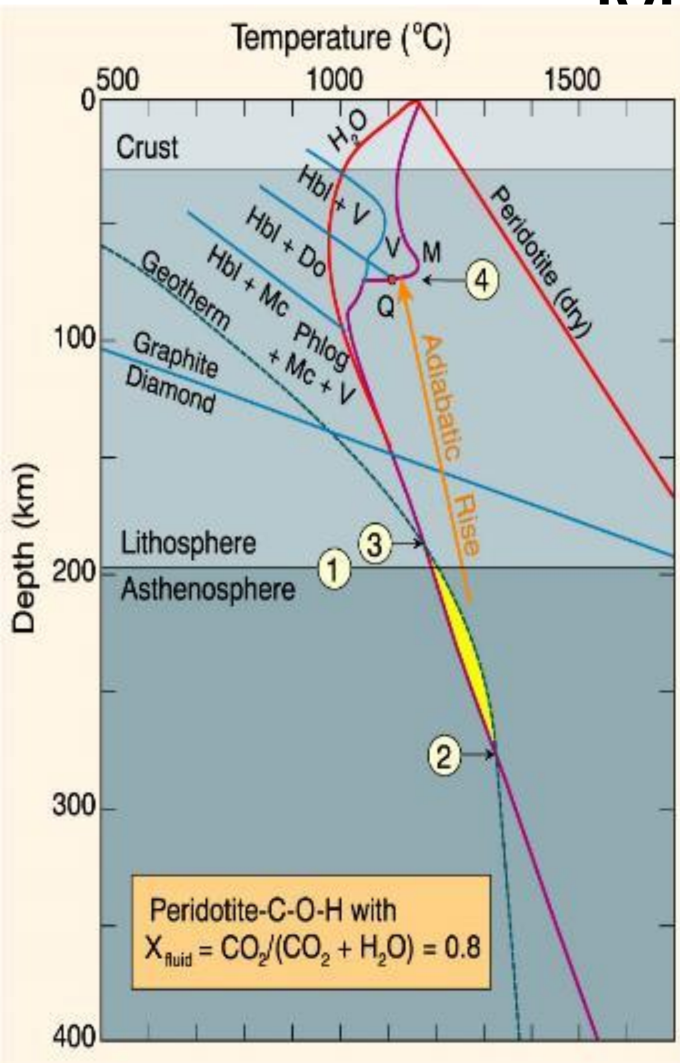
- Direct generation by low degree partial melts in the mantle and melt differentiation.
- Fractional crystallization of a carbonate alkaline silicate melt.
- Liquid immiscibility between a carbonate melt and a silicate melt.

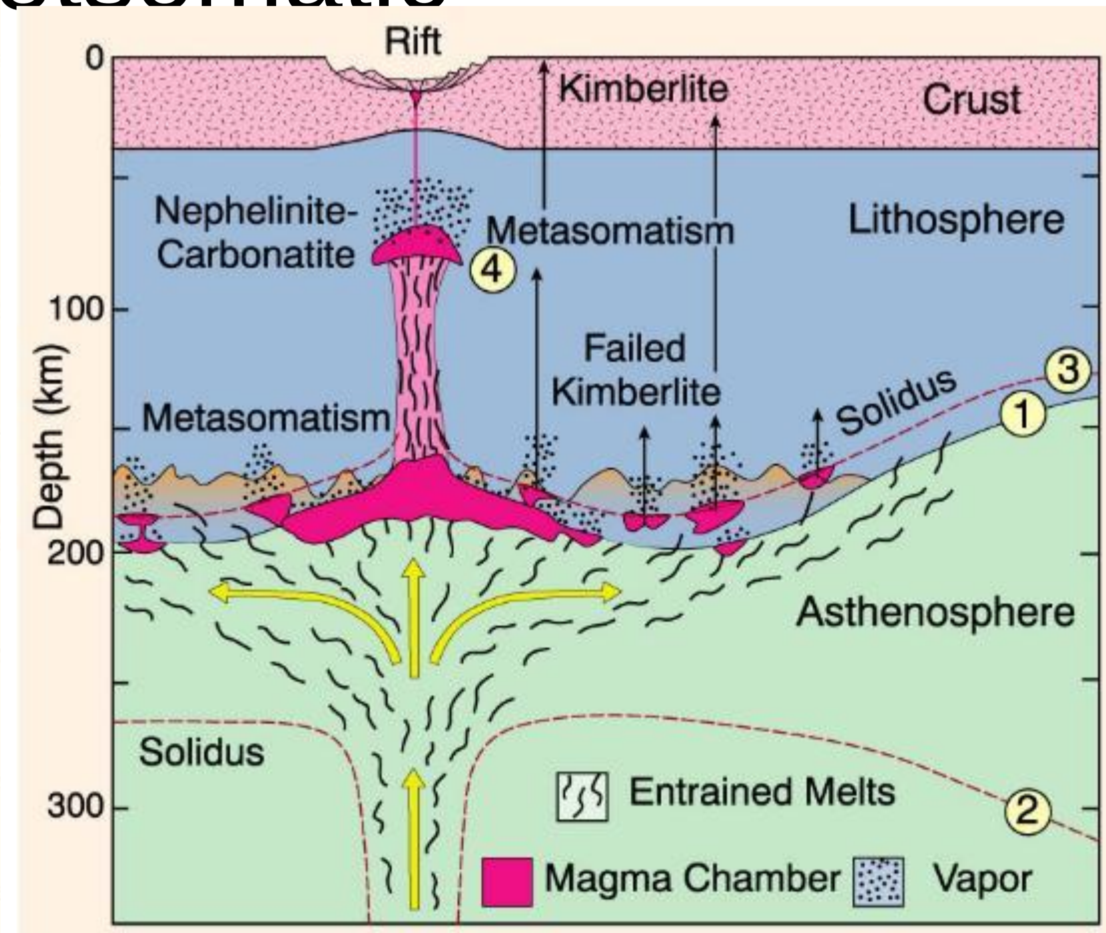
World occurrences of Carbonatites

Carbonatite Origin

- The similarity between silicate and carbonate phase trace and minor elements has convinced most petrologists that the carbonatites must originate together with the silicates, possibly from the same source, and not from limestones, as early workers had suggested

Origin of Carbonates
Igneous, Metamorphic, or Metsomatic





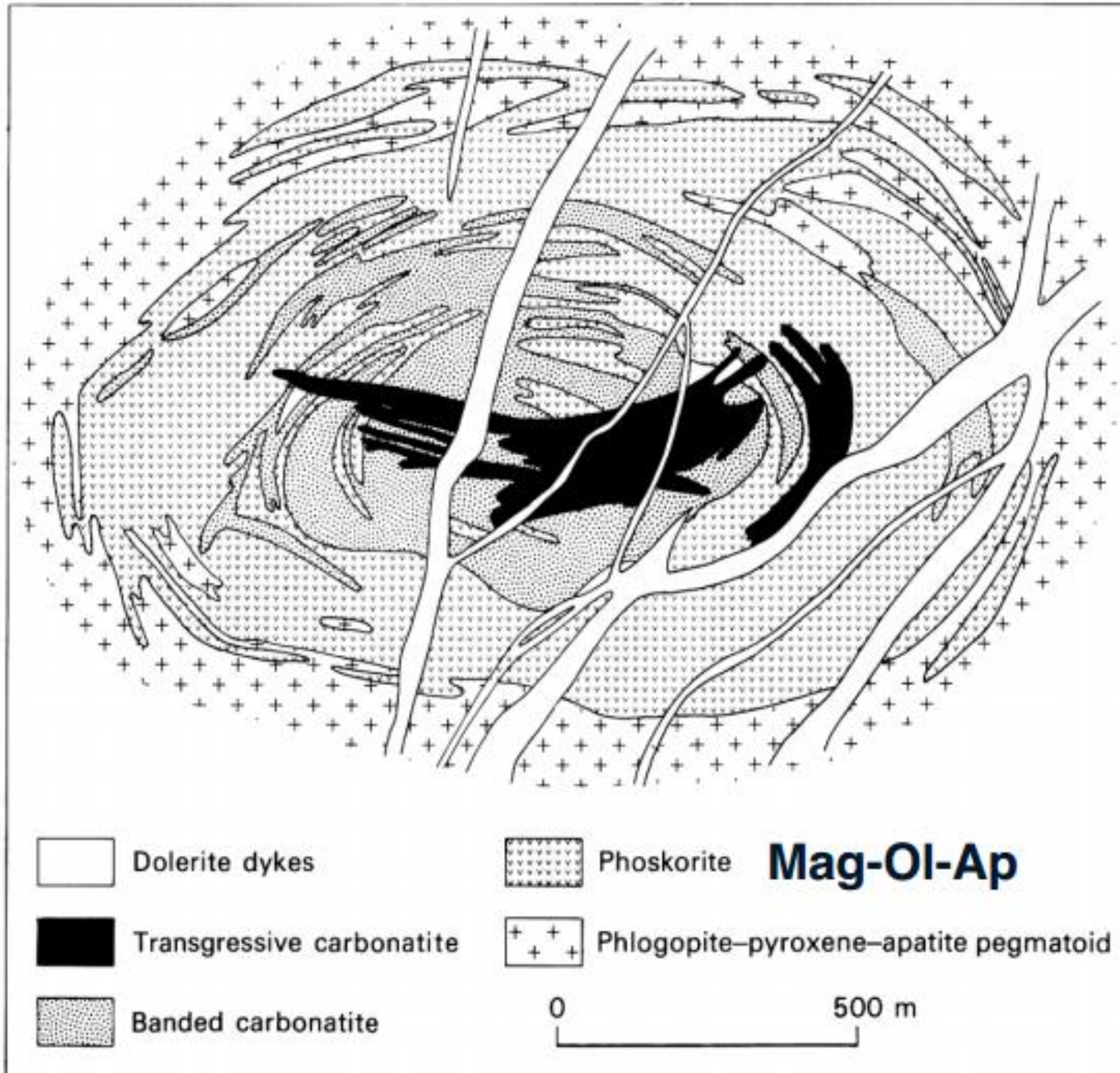
- Carbonatites occur in small ring complexes associated with silica poor rocks composed of nepheline and cpx (I.e. ijolites)

- Carbonatite complexes are concentrically arranged
    - rock types become progressively poorer in silica toward the core which is commonly occupied by carbonatite

- Typical succession of rocks from the rim to the core would consist of:
  nepheline syenite
  ijolite
  carbonatite with all rocks being cut by lamprophyric dikes

Guilbert and Park, 1985

122 m level Palabora



Carbonatites

- Carbonatite may also be concentrically zoned from an older, outer zone of calcite carbonatite (sovite), followed by a zone of dolomite carbonatite (beforsite) and a younger core of ankerite or siderite carbonatite
- Consistent with fractional crystallization of a carbonate melt.
- Typical carbonatite is composed of 75% carbonate with lesser amounts of cpx, phlogopite, alkali amphibole, apatite, magnetite, olivine etc.
- Carbonatites are highly variable in composition
- Rocks surrounding carbonatites have undergone intense sodium metasomatism (fenitization)

Best, 1982

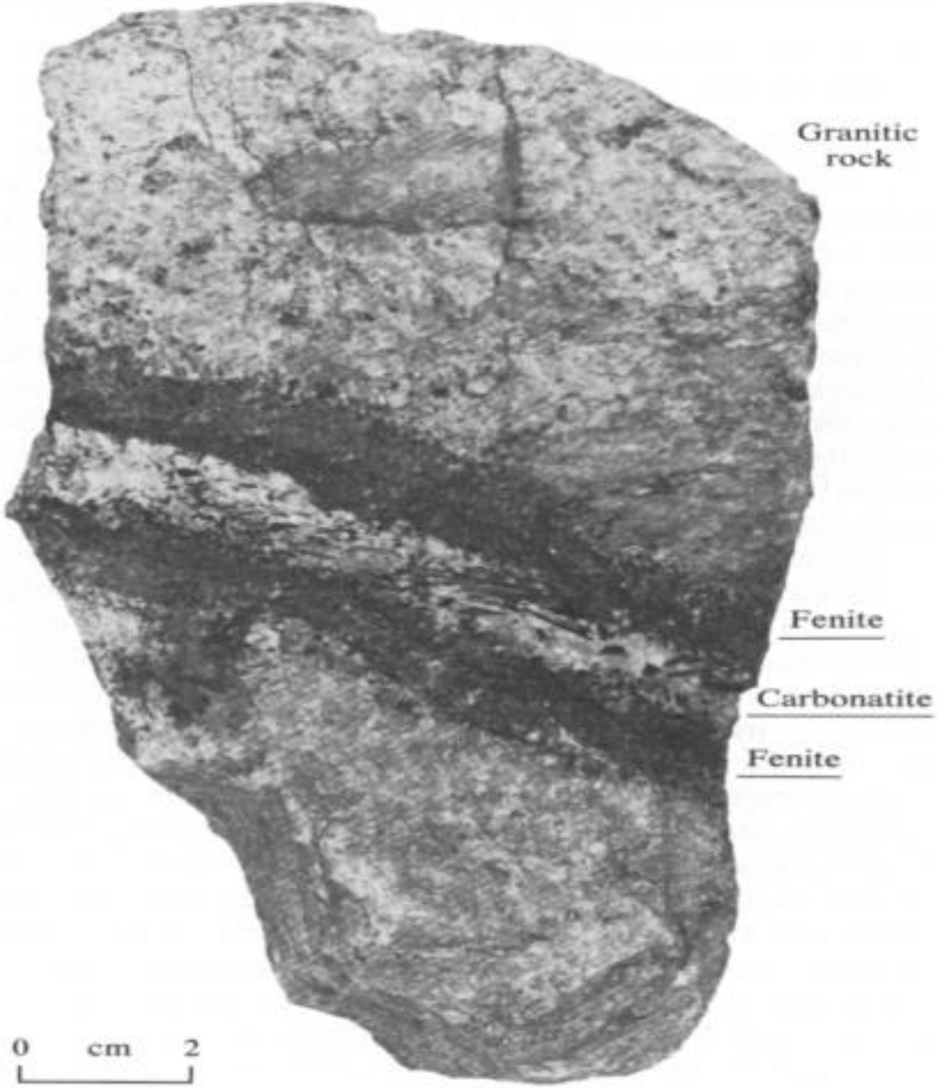


Figure 6-4 Thin dike of carbonatite with alkali amphibole emplaced into granite has produced fenite borders of similar amphibole and biotite.

Folded basic dikes within a carbonatite matrix.

Carbonatites

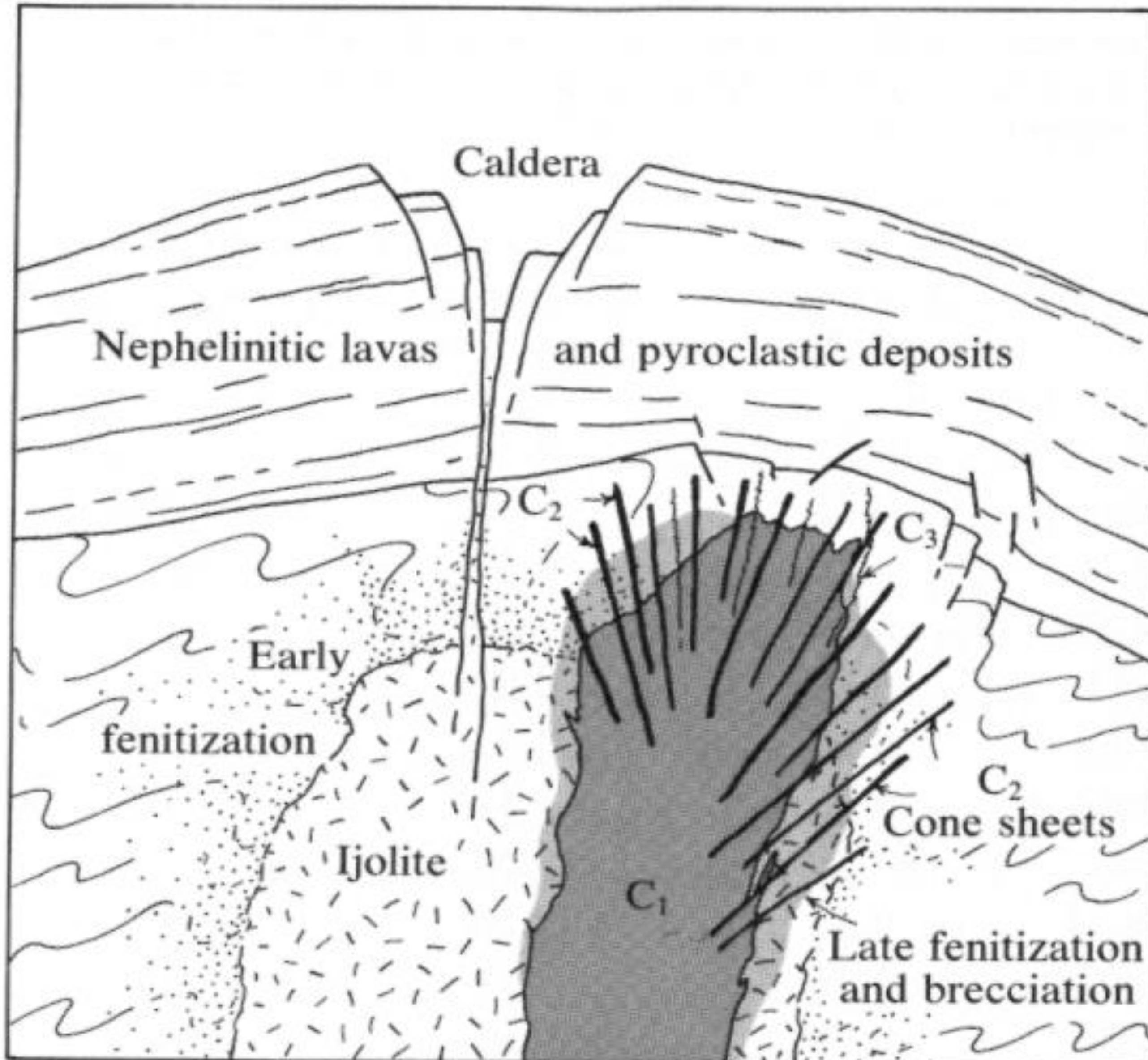
- Belong to alkaline igneous provinces and generally found in stable cratonic regions sometimes with major rift faulting such as the East African Rift Valley

- Not all alkalic rock provinces and complexes have associated carbonatites

- Carbonatitic activity is episodic and seems to have been related temporally and spatially to orogenic events

- Carbonatites often form clusters or provinces within which there may have been several episodes of activity

Best, 1982



Caldera
Nephelinitic lavas
and pyroclastic deposits
C2
C3
Early
fenitization
Ijolite
C1
C2
Cone sheets
Late fenitization
and brecciation

Carbonatites

- Siliceous country rocks may be converted to aegirine-bearing syenites that are termed fenites.
- Zones of fenitization are typically hundreds of meters wide.
- Large volumes of alkali-bearing solutions are given off during cooling.
- Experimental data show that sodium carbonate melts could separate as immiscible liquids from silicate magmas.
- Kjarsgaard and Hamilton 1988 - immiscibility field extends to low alkali compositions form directly as calcite carbonatites

Table 6-2 Comparison of average abundance of trace elements in carbonatite, all igneous rocks, and limestone (in ppm).

Best, 1982

	Carbonatite	Igneous rocks	Limestone
Sc	10	13	1
Co	17	18	0.1
Y	96	20	30
Zr	1120	170	19
Nb	1951	20	0.3
Mo	42	2	0.4
La	516	40	<1
Ce	1505	40	12

Source: After E. W. Heinrich, 1966, *The Geology of Carbonatites* (Chicago: Rand McNally).

Petrogenesis of Anorthosite
(Monomineralic Rock)

General

Anorthosites are derived from mafic or basic magmas

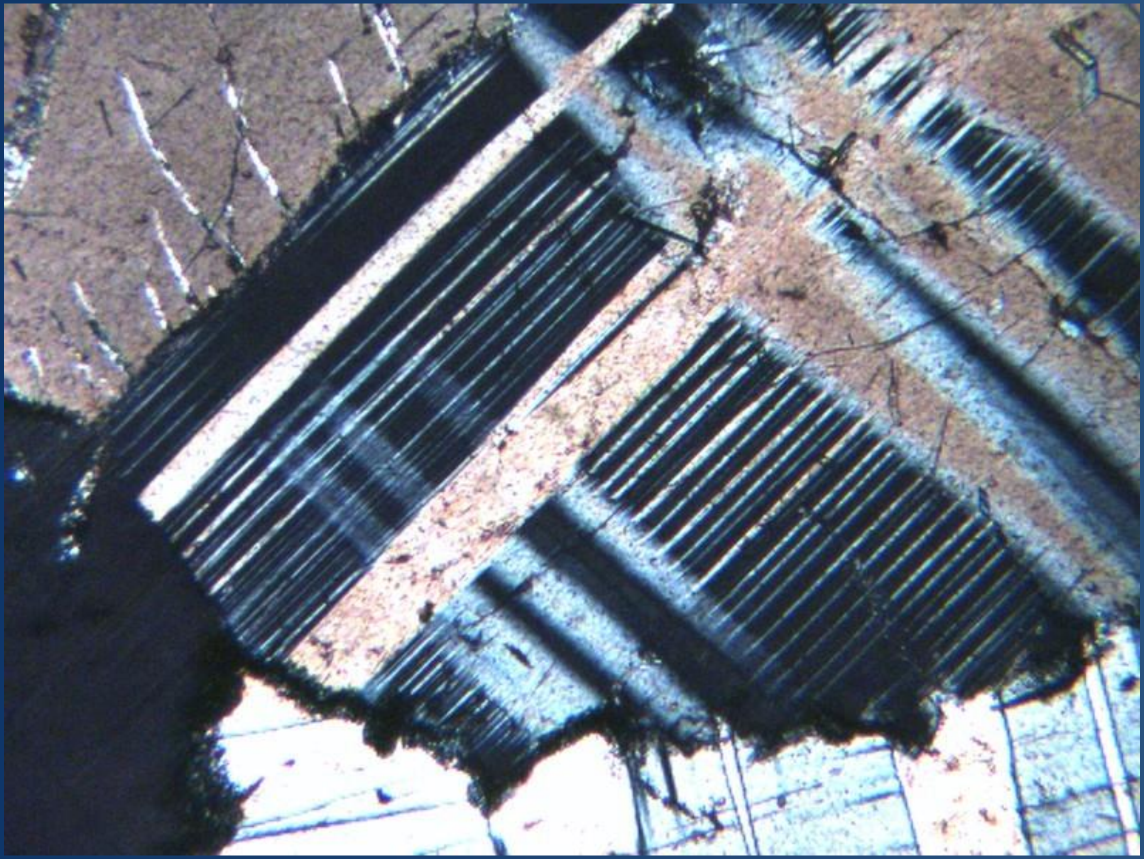
.

Fractional crystallization, diapiric (vertical) rise (of plagioclase crystals along with melt material), and lateral flow or injection (of plagioclase – melt mush by filter pressing processes) may be involved in the generation of anorthosites from their parental melts.

Mineralogy

- Phaneritic, intrusive igneous rock
- Composed of calcic plagioclase with less than 10% ferro-magnesium minerals.
- Plagioclase may be labradorite, bytownite, or anorthite, along with associated high-temperature mafic minerals (Pyroxene, ilmenite, magnetite, and olivine)
- The name is from anorthose, an old name for triclinic feldspars

- **Feldspar (in anorthosite)**
  made almost entirely of plagioclase feldspar. This rock shows the interlocking texture of the feldspars particularly well.
- Orange crystals are pyroxene..



- View of twinned plagioclase crystals, in a typical area of the anorthosite. Nominal magnification 50X, crossed-polarized transmitted light, long-axis field of view 1.6 mm.

Global Occurrences of Anorthosite

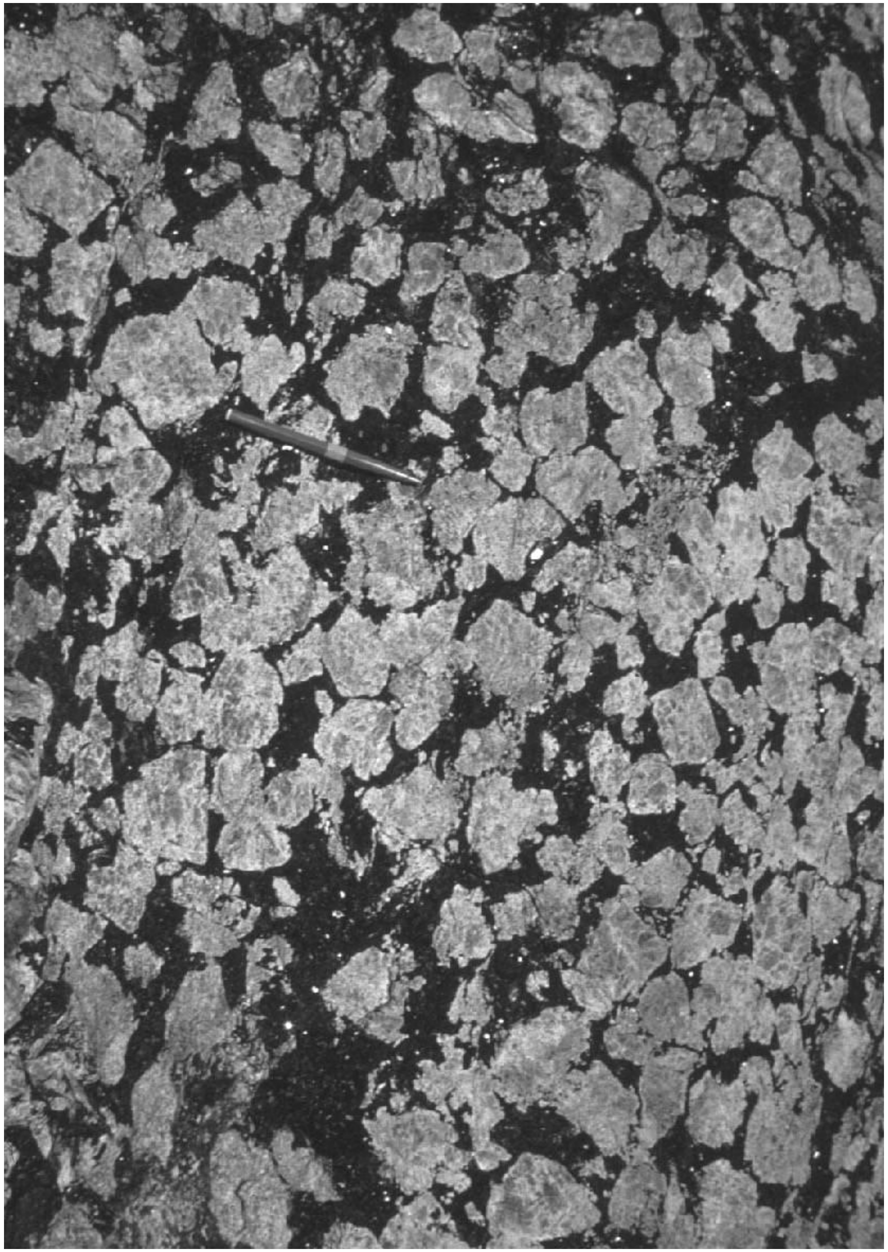
- 1. **Archean** anorthosite
- 2. Proterozoic "**massif-type**" anorthosite plutons
- 3. **Centimeter-to-100m thick layers** in layered mafic intrusions
- 4. Thin **cumulate layers** in ophiolites/oceanic crust
- 5. Small inclusions in other rock types (xenoliths and cognate inclusions)
- 6. **Lunar highland** anorthosites

Archean anorthosite

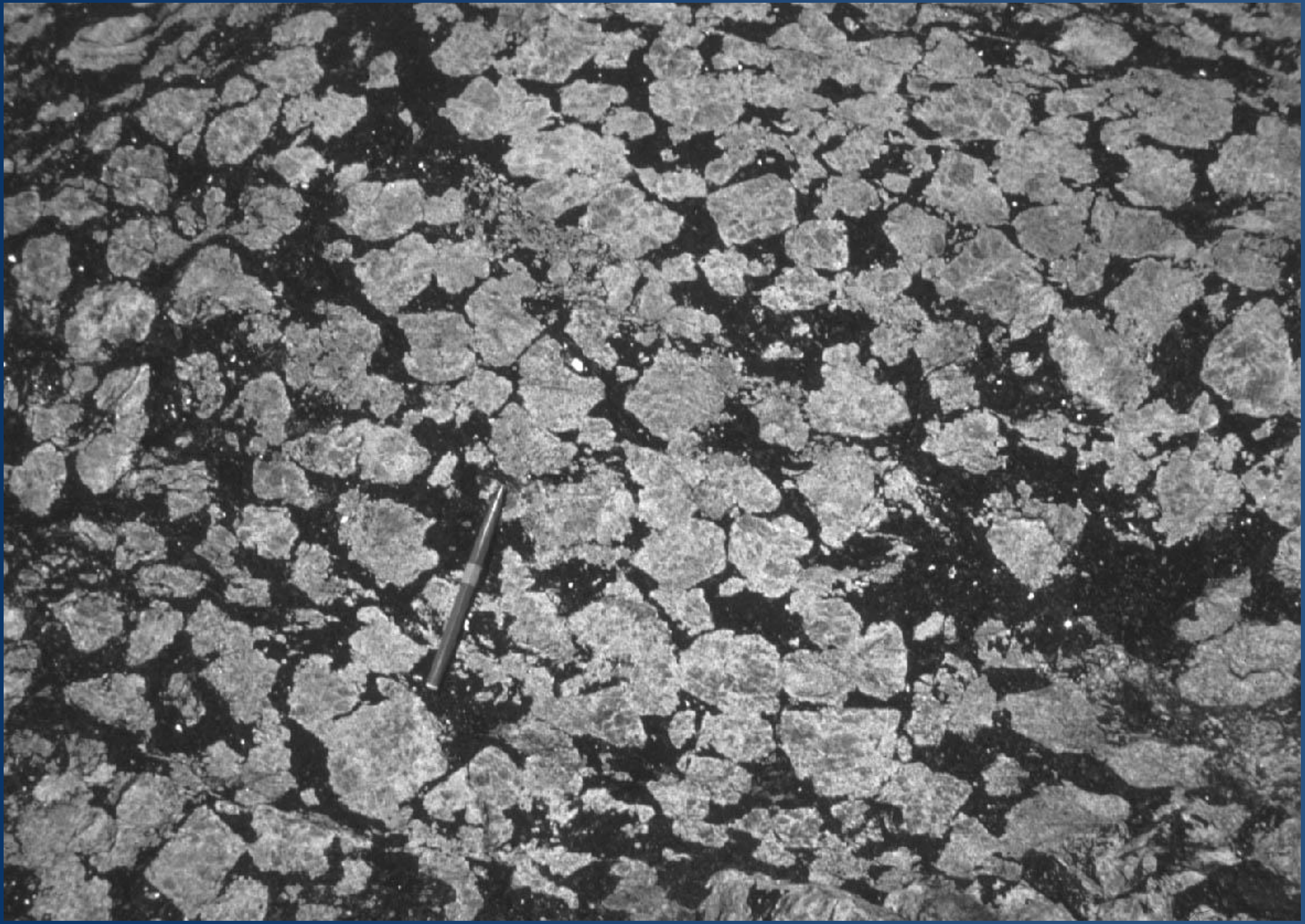
- Smaller amounts of anorthosite were emplaced during the Archaean eon (ca 3,800-2,400 Ma), although most have been dated between 3,200 and 2,800 Ma.

- They are distinct texturally and mineralogically from Proterozoic anorthosite bodies. Their most characteristic feature is the presence of equant mega-crysts of plagioclase surrounded by a fine-grained mafic groundmass.

Archean Anorthosites



- Hi-Ca plagioclase (An >80)
- Equant crystal habit
- Pl mega-crysts in a gabbroic matrix
- Sill-like bodies
- Associated with gabbroic intrusions in greenstone belts
- Commonly metamorphosed and deformed

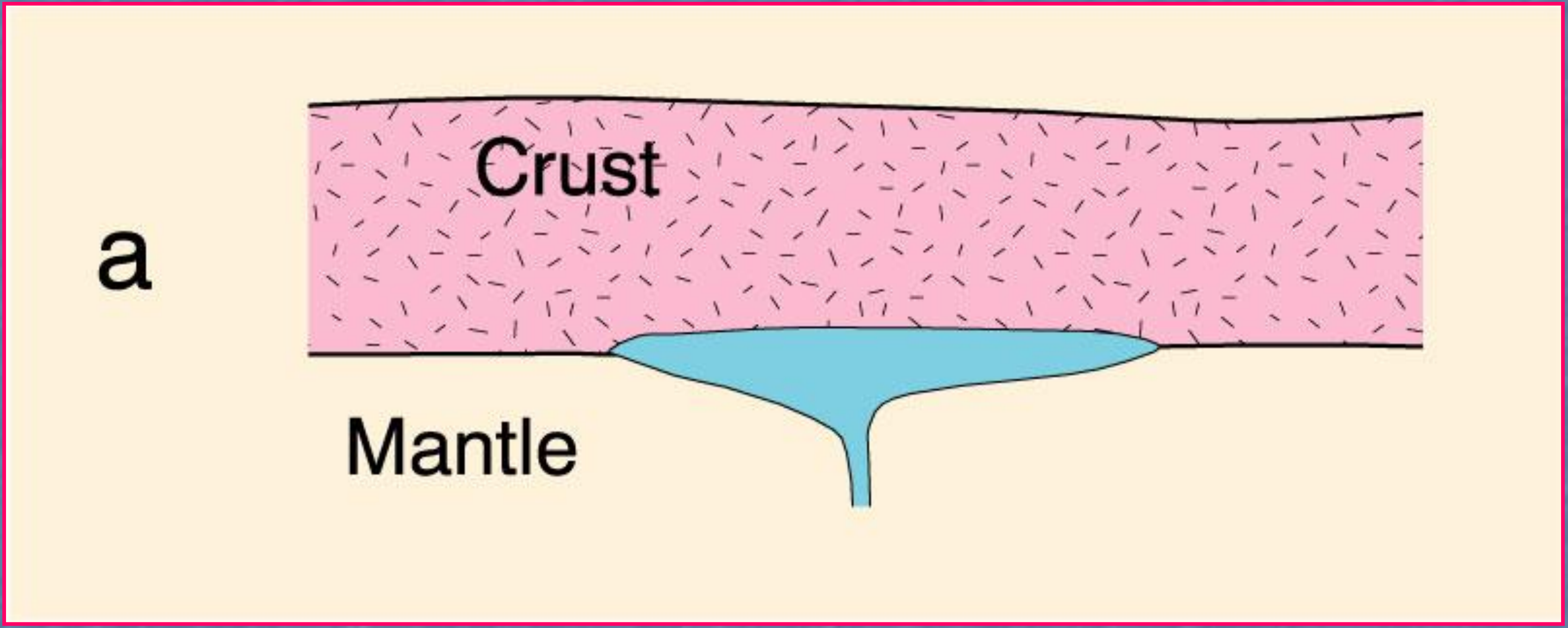


- Typical texture of Archean anorthosite. From the Fiskenæsset complex, W. Greenland. Myers (1985)
- most Proterozoic anorthosites are deformed, and such large plagioclase crystals have to form smaller crystals, leaving only the outline of the larger crystals behind.

Massif-type Anorthosites

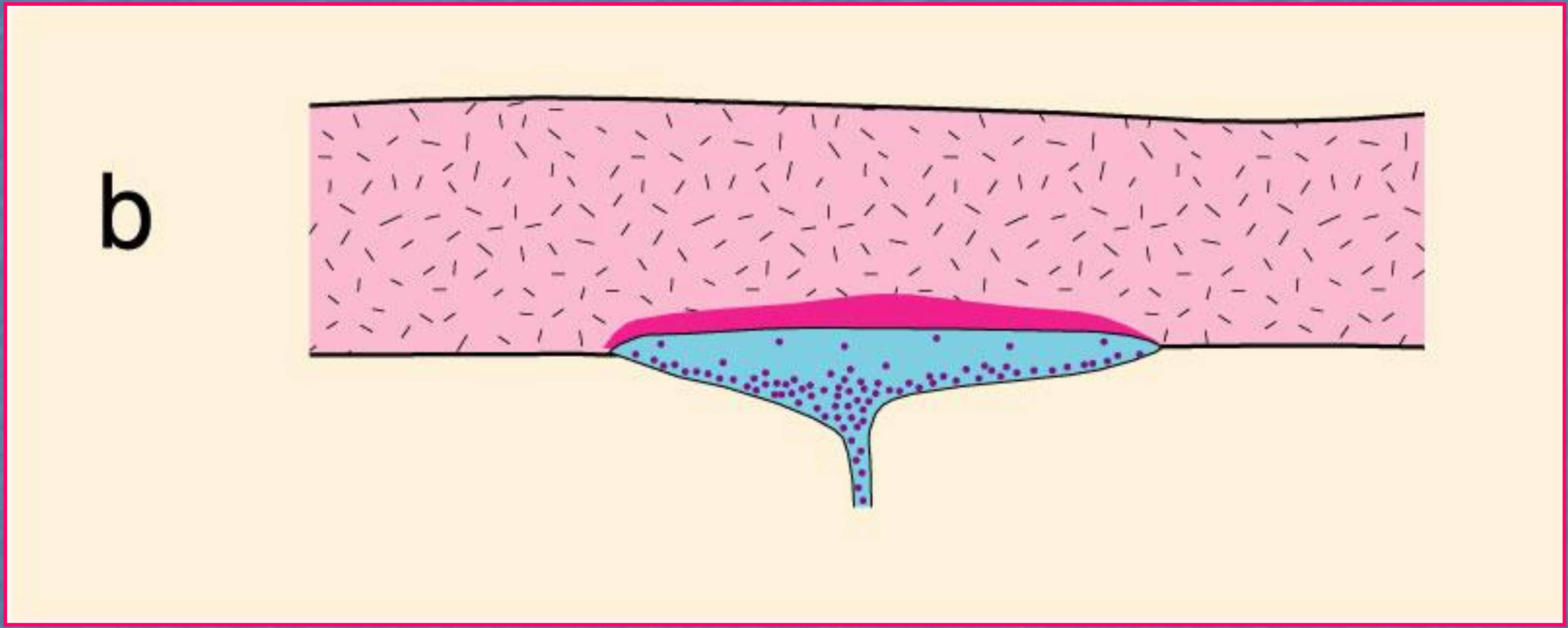
- Proterozoic age (1.7-0.9 Ga)
- Intermediate Pl composition (An 65-40)
- Tabular crystal habit
- Pl-adcumulates common (minor interstitial mafics)
- Large pluton-scale bodies
- Anorogenic setting
- Associated with K-/Fe-rich gabbros (jonuites) and “dry” felsic rocks (charnokites)

Model for the generation of Massif-type anorthosites



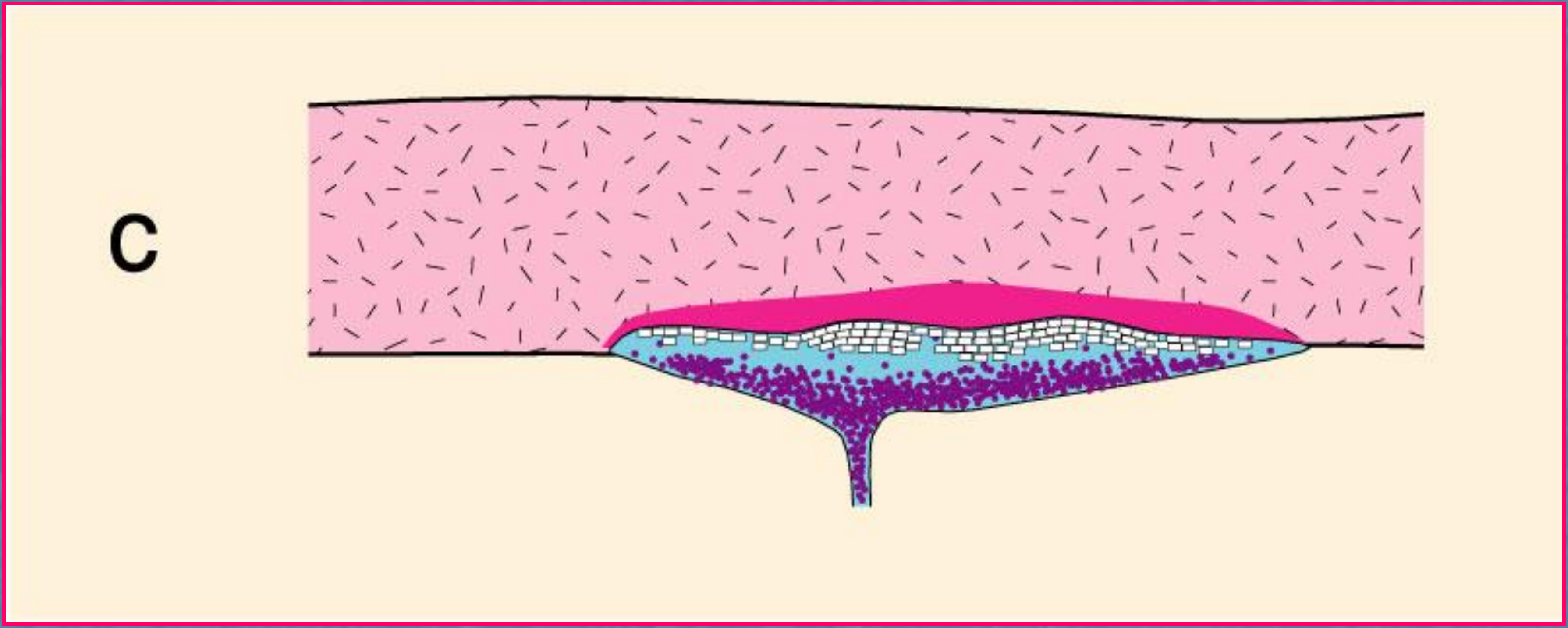
- **Mantle-derived magma underplates the crust as it becomes density equilibrated. Ashwall (1993)**

Model for the generation of Massif-type anorthosites



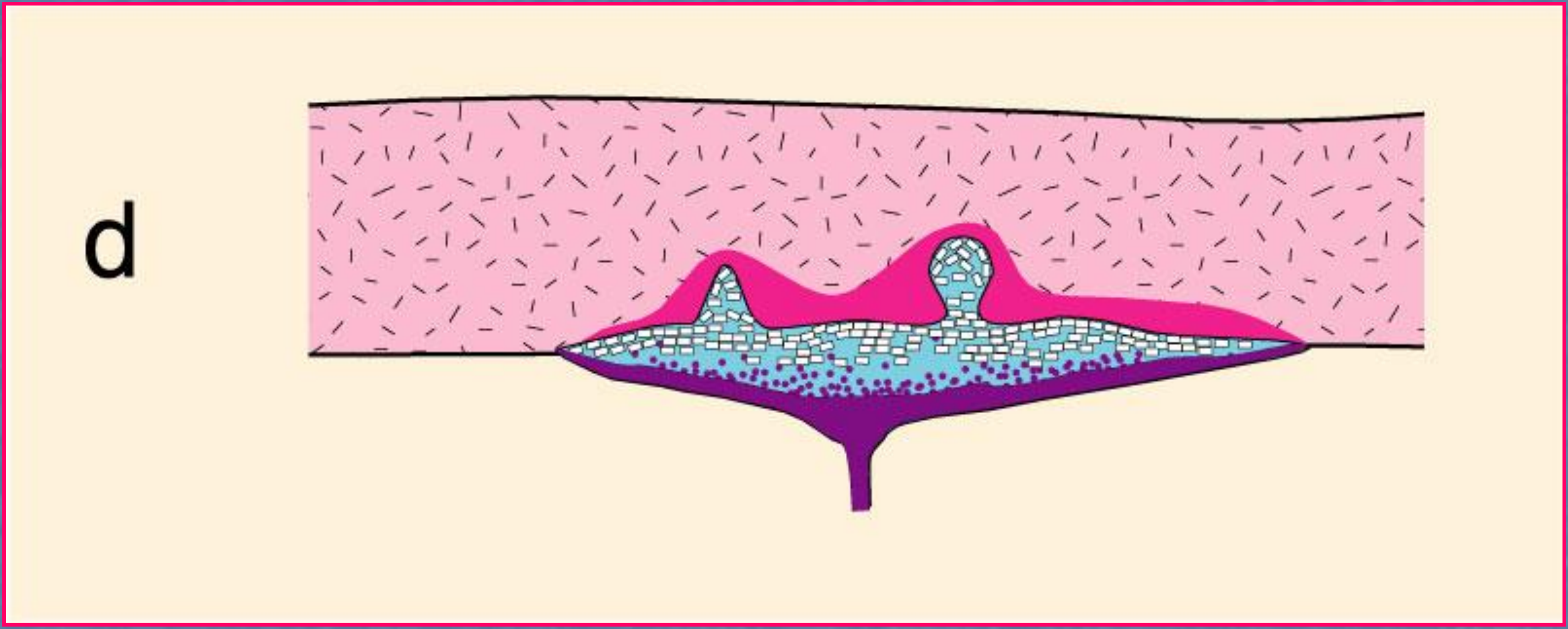
b. Crystallization of mafic phases (which sink), and partial melting of the crust above the ponded magma. The melt becomes enriched in Al and Fe/Mg. Ashwall (1993)

Model for the generation of Massif-type anorthosites



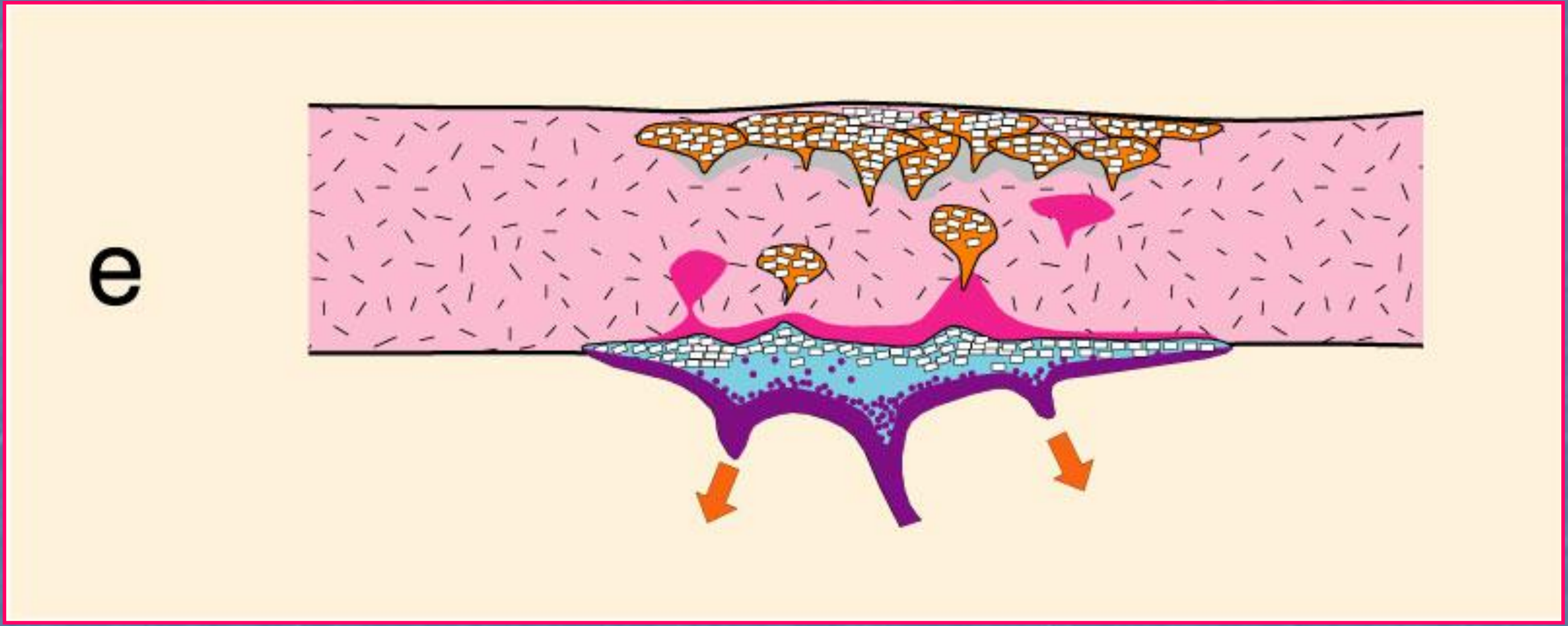
c. Plagioclase forms when the melt is sufficiently enriched. Plagioclase rises to the top of the chamber whereas mafics sink. Ashwall (1993)

Model for the generation of Massif-type anorthosites



d. Plagioclase accumulations become less dense than the crust above and rise as crystal mush plutons. Ashwall (1993)

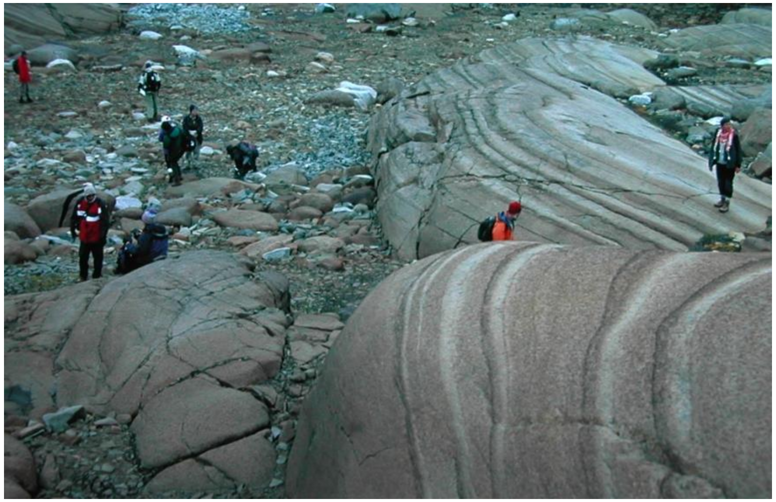
Model for the generation of Massif-type anorthosites

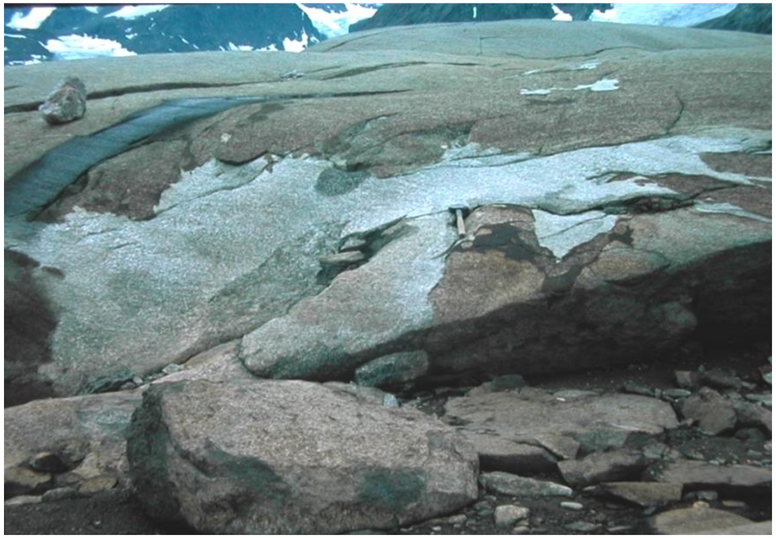


e. Plagioclase plutons coalesce to form massif anorthosite, whereas granitoid crustal melts rise to shallow levels as well. Mafic cumulates remain at depth or detach and sink into the mantle. Ashwall (1993)

Anorthosite Layers/Inclusions in Mafic Layered Intrusions

Skaergaard Intrusion





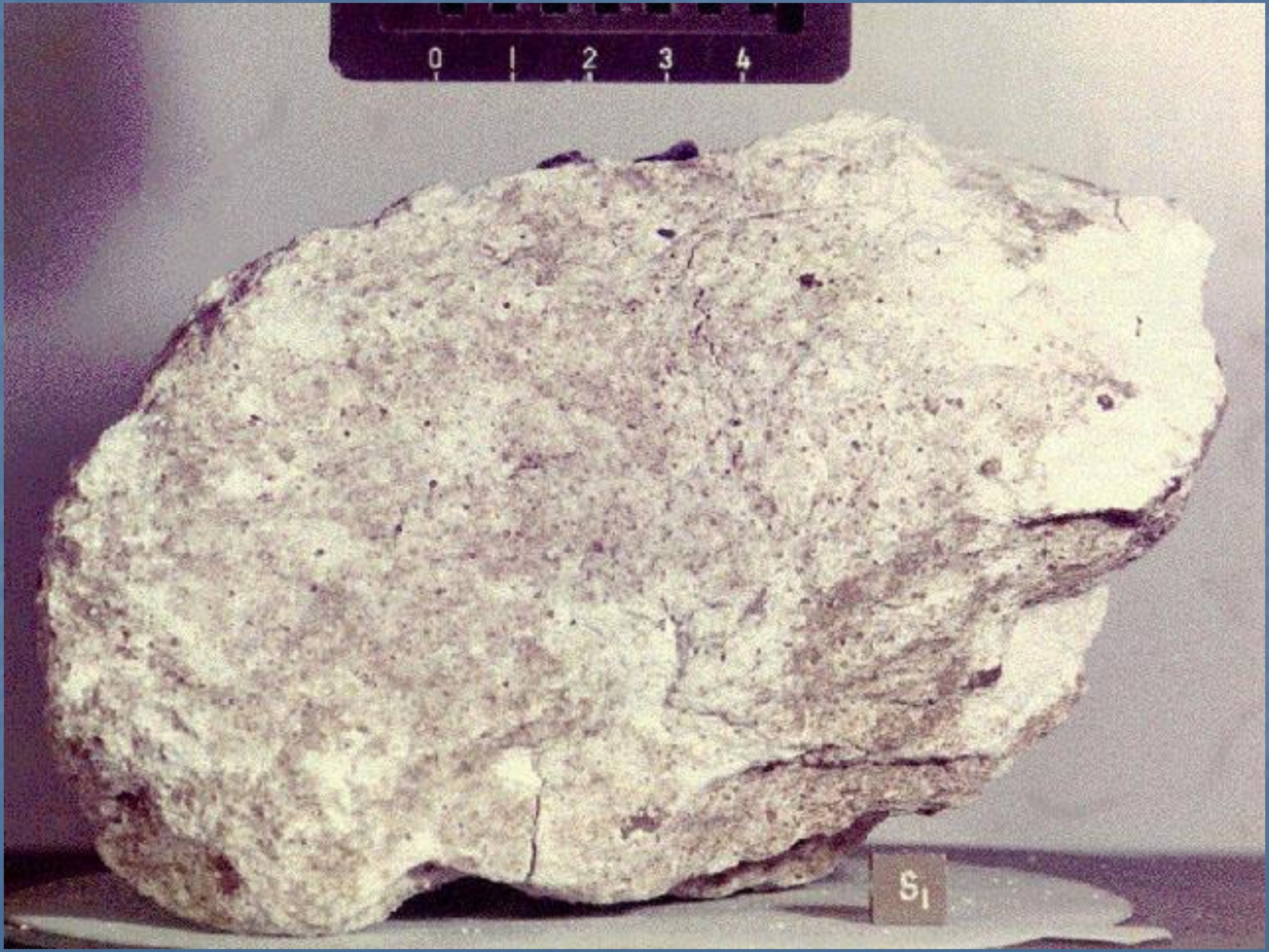
Bushveld Complex

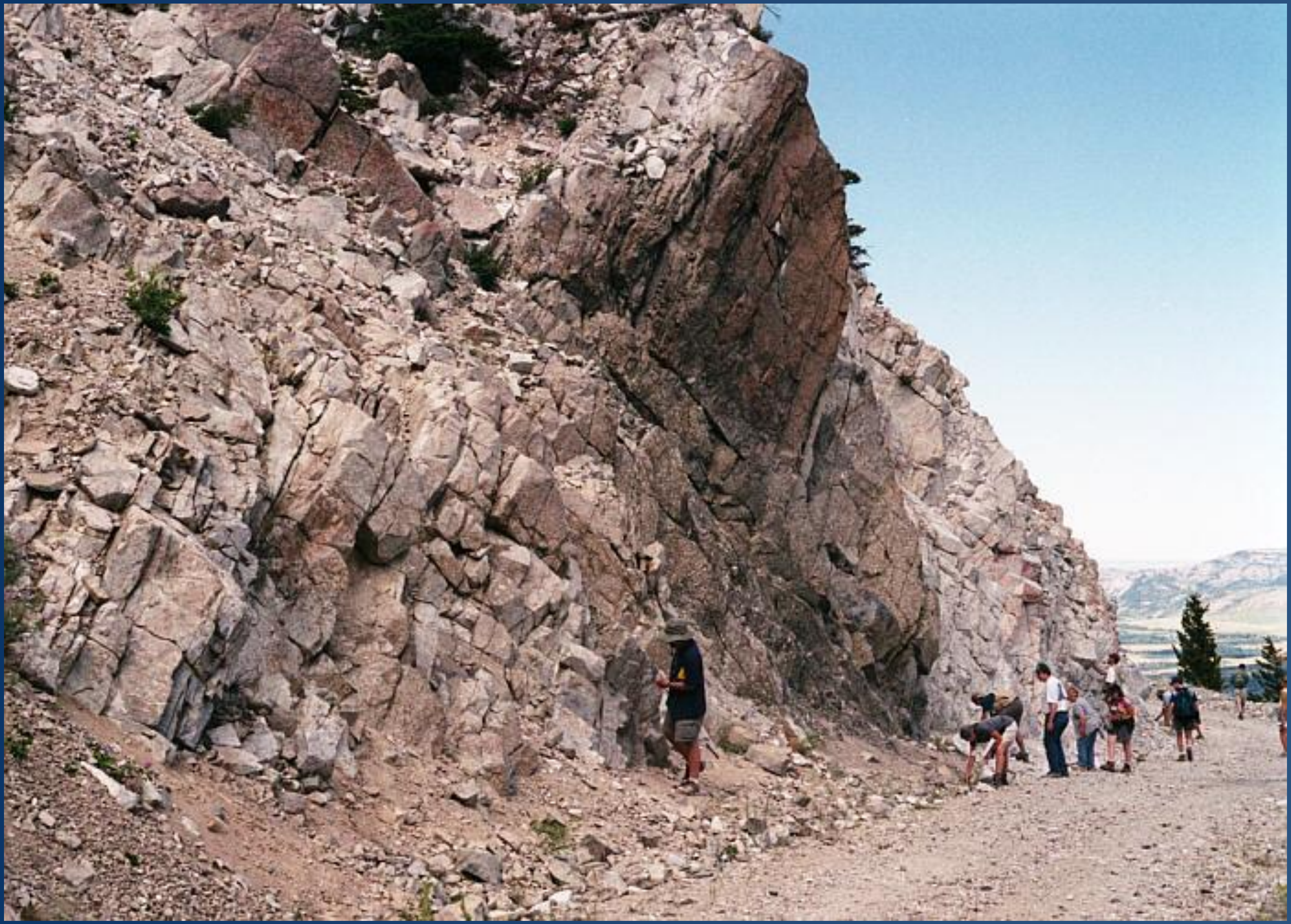
Stillwater Complex

Lunar anothosite

- An important rock type of the lunar highlands
- Probably formed the primitive lunar crust. APOLLO 16 has been determined to be 4.19 billion years old by the Argon method of dating.
- The fact that the lunar surface is literally covered with anorthosite suggests that the **Moon was once covered by oceans of molten magma**

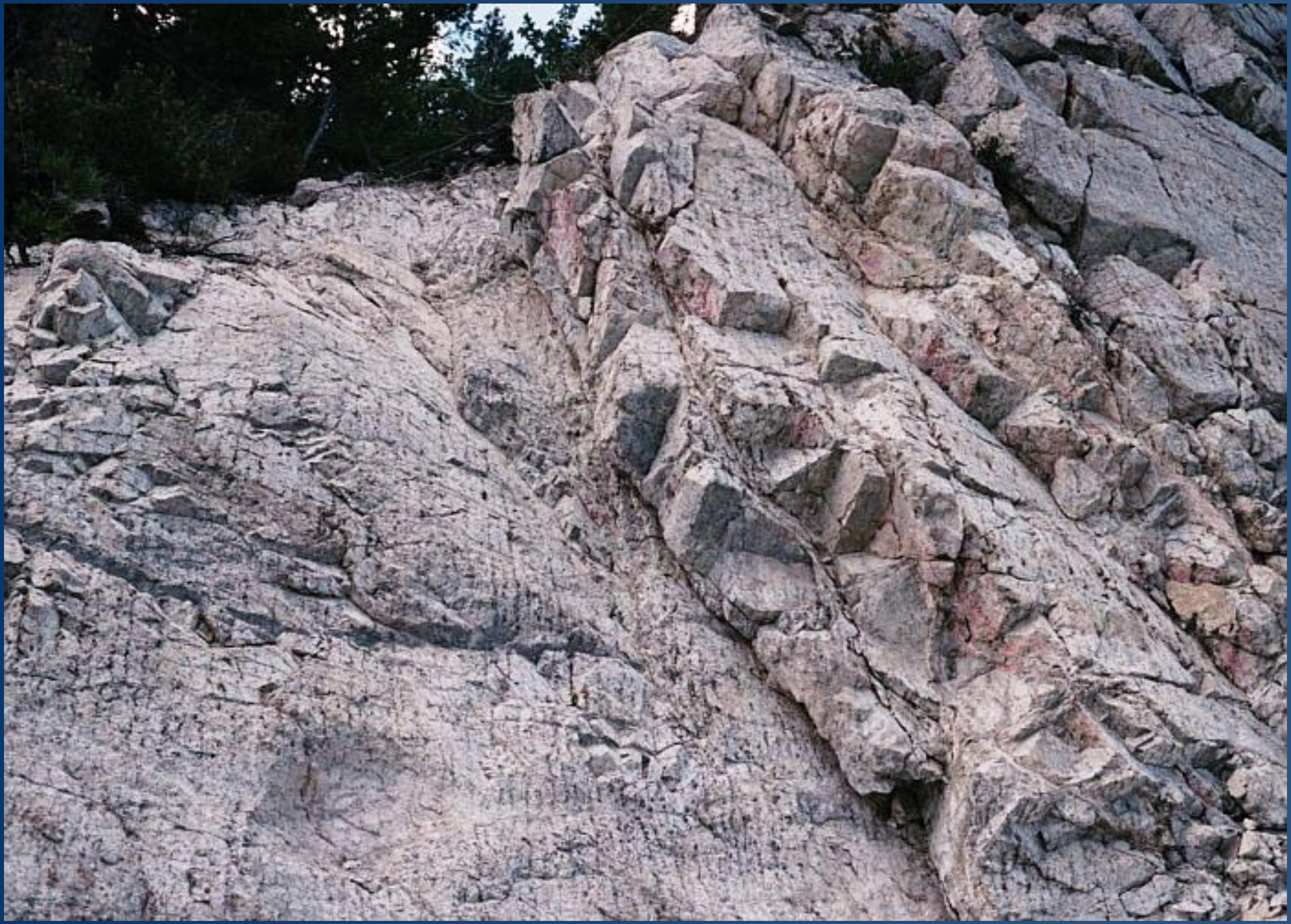
Lunar anothosite





- Light-colored rocks to the left (bottom) are gabbroic anorthosite, dark rock in the center is troctolitic gabbro, and the distant light colored rock is anorthosite.

- Contact between the anorthosite (right) and the troctolite (left).



- Roadcut with the famous "inch-scale layering" in anorthositie in the lower banded series.

- Closer view of the strikingly paired couplets of thin and thick anorthosite layers with intervening dark pyroxene

Anorthosites of Tamil Nadu

Confirmed anorthosite occurrences in Tamil Nadu include the following:

SITTAMPUNDI, KADAVUR, TOGAMALAI, ODDANCHATRAM, MANAPPARAI, CHINGLEPUT, PALANI HILLS, MANALUR, MADUKKARAI, METTUPALAYAM & KOTAGIRI.`

Petrogenesis of Pegmatites

- Several models have been proposed to explain the generation of pegmatites from granitic melts.

- The models have been derived from the results of experimental petrology of granitic systems.

- **PEGMATITE is a common plutonic rock, of variable texture and coarseness, that is composed of interlocking crystals of widely different sizes.**

- **The most spectacular pegmatites contain abnormally large crystals mixed with medium sized and smaller crystals. Crystals up to many meters long have been reported.**

- **Some pegmatite bodies are small irregular patches less than 1 cm. (0.4 in) across in larger masses of plutonic or metamorphic rocks.**

- **Others may be thousands of meters in length and hundreds of meters thick. Some appear as dikes, veins, or sills. Many have irregular outlines.**

- **Most pegmatites show symmetrical internal zonation.**

MINERALOGY AND COMPOSITION:

- Pegmatites may be composed of a variety of minerals. Terms such as granite pegmatite, gabbro pegmatite, syenite pegmatite, or names with any other plutonic rock type as prefix are used.
- Compositions in the range from granodiorite to granite are common. Large crystals of quartz, potassium feldspar, sodium rich plagioclase, and micas (e.g., muscovite and lepidolite) may be abundant.

GEOLOGICAL AGES:

- Pegmatites have provided radioactive minerals for use in radiometric age dating of many rock complexes.

THE ORIGIN OF PEGMATITES:

- As a result of the confusing variety of shapes, sizes, appearances, and field relationships, many origins have been proposed for pegmatites.

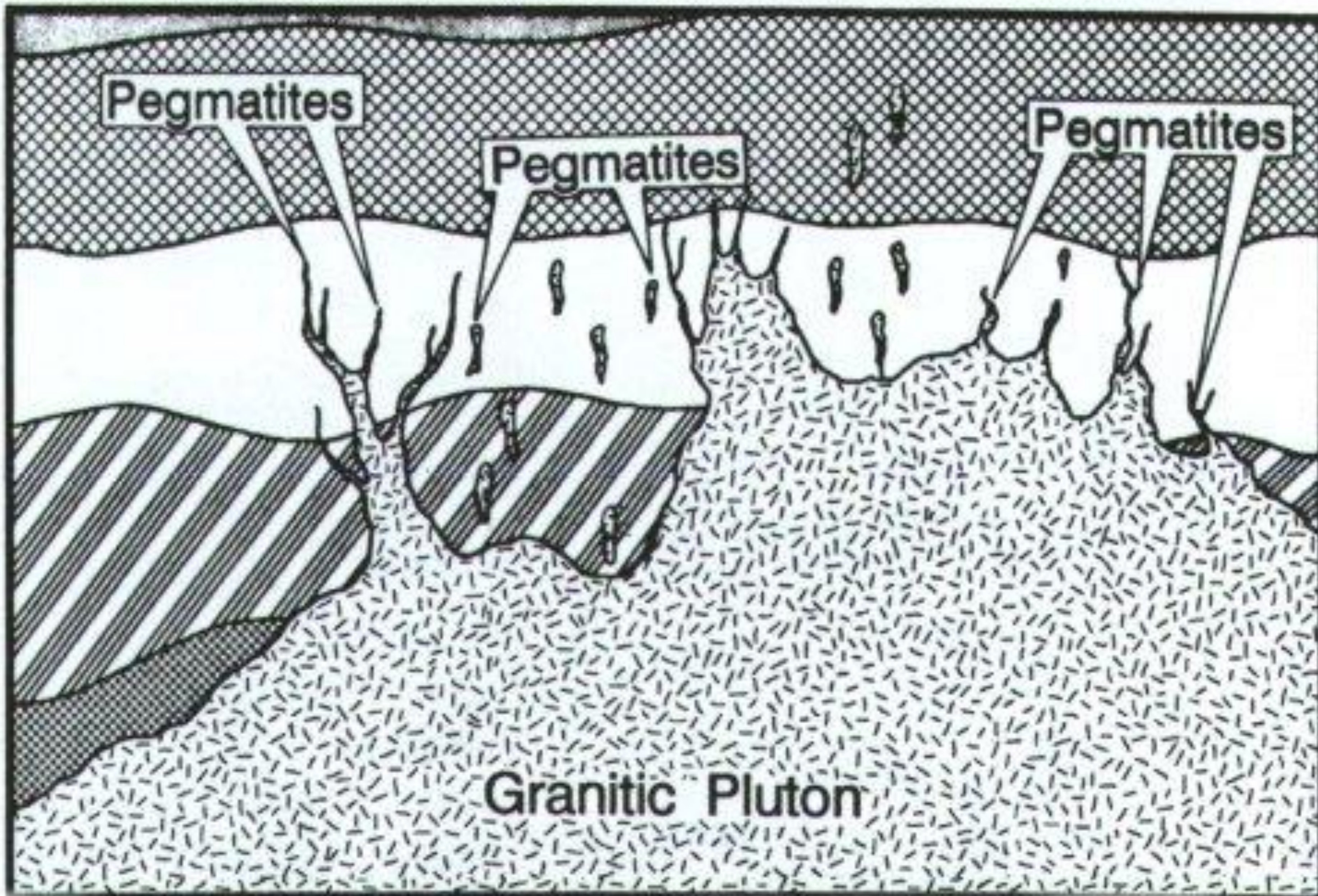
- Some dike like bodies showing clear INTRUSIVE relationships must be of igneous origin. These frequently cut across all other associated rocks and therefore represent material from late stages of crystallization of plutonic complexes.

- They were probably rich in volatile materials such as water, fluorine, chlorine, phosphorus, and sulfur.

- The occurrence of pegmatite corresponding to most plutonic rock compositions gabbros, diorites, syenites, anorthosites further recommends this possibility.

- Other pegmatites grade into the rocks that surround them and show no intrusive relationships. Such bodies may represent material produced by melting (anatexis) during metamorphism at high temperatures and pressures.

- This rock is pushed up as large veins of magma that was rich in volatile elements resulting in large crystals, usually surrounded by grantic rocks.


Pegmatites
Pegmatites
Pegmatites
Granitic Pluton

Pegmatite Dyke

Pegmatite

Pegmatite

- To be called a “pegmatite,” a rock should be composed almost entirely of crystals that are at least one centimeter in diameter.
- The name “pegmatite” has nothing to do with the mineral composition of the rock.
- **Pegmatite occurs in varying size from 1cm to km in length as well as width**

- Most pegmatites have a composition that is similar to **granite** with abundant **quartz**, **feldspar**, and mica.
- These are sometimes called “granite pegmatites” to indicate their mineralogical composition.
- However, compositions such as “gabbro pegmatite,” “syenite pegmatite,” and any other plutonic rock name combined with “pegmatite” are possible.

- It may occurs as vein/dyke or sill
- Many of them in lenticular in shape both strike and dip direction
- But many body in tabular shape and size
- Many pegmatite occurs as ZONED nature
- Pegmatites contain large size of quartz and feldspar mineral.
- More than 3m length mica book occurs along with pegmatite rock

- ZONED pegmatite is where quartz is surrounded by massive feldspar
- Secondly micas are developed around the central group of quartz
- In India workable mica deposits are found in Bihar Mica belt, Rajasthan…

Rajasthan

- Three types of pegmatite found in Rajasthan

1. Milky or Rose quartz in the core surrounded by large crystals of microcline
2. Core is quartz with few large crystals of microcline and very large crystals of beryl with big chunks of mica.
3. Core is large size of microcline surrounded by small quartz with large size of bery and mica.

- Pegmatites are sometimes sources of valuable minerals such as **spodumene** (an ore of lithium) and **beryl** (an ore of **beryllium**) that are rarely found in economic amounts in other types of rocks.
- They also can be a source of **gemstones**.
- Some of the world's best **tourmaline**, aquamarine, and **topaz** deposits have been found in pegmatites.

Pegmatite

- Intrusive igneous rocks
- Phaneritic texture
- Some times found with High Li concentration
- Spodumene

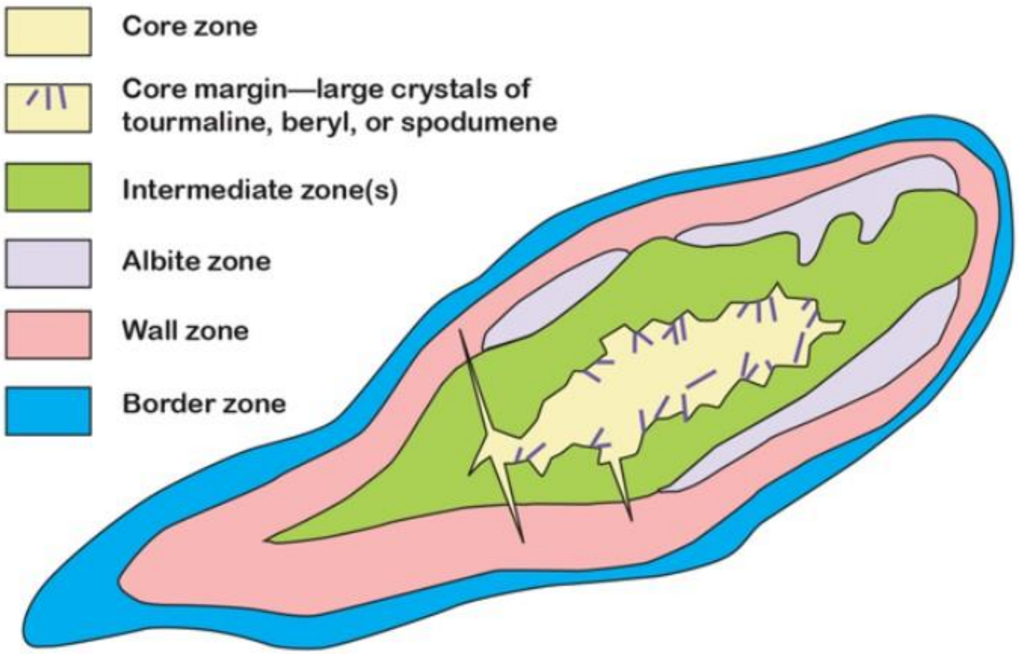
Pegmatite Formation

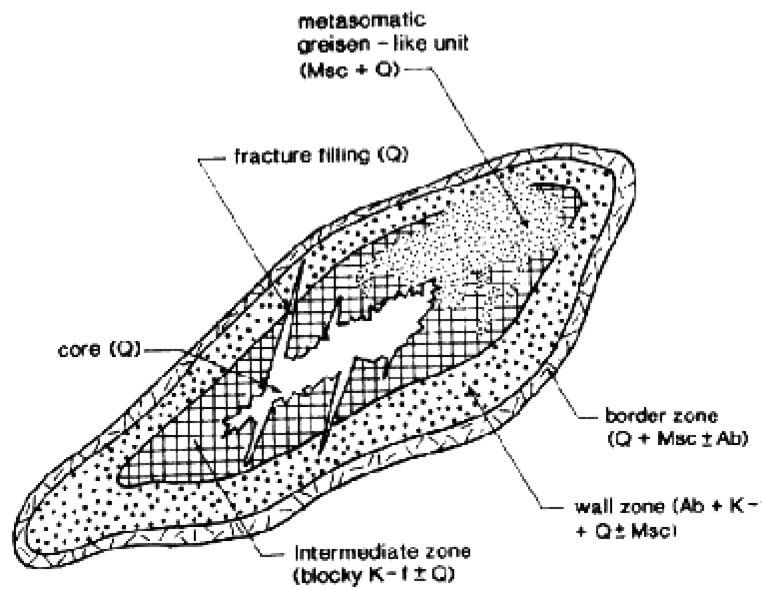
- Plate convergence
- Emplaced in orogenic back country
- Last components to crystallize
- Melts enriched with water, fluorine, phosphorus, and boron

Types of Zones

- Four zones of pegmatite were derived according to Cameron 1949.

1. Border Zone, 2. Wall Zone, 3. Intermediate and 4. Core zone


Core zone
Core margin—large crystals of tourmaline, beryl, or spodumene
Intermediate zone(s)
Albite zone
Wall zone
Border zone


metasomatic greisen – like unit (Msc + Q)
fracture filling (Q)
core (Q)
border zone (Q + Msc ± Ab)
wall zone (Ab + K – f + Q ± Msc)
intermediate zone (blocky K – f ± Q)

Border Zone

- Aplitic and fine grained quartz, muscovite, perthite are the essential minerals.
- Tourmaline beryl, apatite and garnet are the accessories..

Wall Zone

- These are coarser and much thicker than border zone
- It contains sheet mica , scrap mica and beryl
- Plagioclase is commonly prevailing

Intermediate Zone

- It is not very common
- It is not universally present
- They are composed of perthite or combination of plagioclase, perthite, quartz and both muscovite and biotite
- Huge masses of quartz, giant crystals of amblygonite, spodumene and perthite are common

Core Zone

- Usually the core is composed of quartz or quartz with scattered microcline crystals or only perthite
- Many pegmatite have more than one single unit as a core.
- If there are two or three units of same mineral composition, they referred as discontinuous series.

- An interesting genetic classification has been recently published By Piatnitsky. It follows:
- I. Monophasic pegmatites: (a) liquid magma pegmatites; (b) pneumatolytic pegmatites; (c) hydrothermal pegmatites.
- II. Polyphasic pegmatites.

- The classification submitted below is similar to those of Harker and Palache, with the addition of a division into simple and complex.
- Simple pegmatites are defined as those in which there has been no hydrothermal replacement.
- The complex Group includes most of the more famous pegmatites, in which hydrothermal replacement has taken place and Rarer minerals have been deposited.

- The simple pegmatite are classified into rock types according to the relative importance of the mineral constituents.
- The complex pegmatites are similarly classified, except that the hydrothermal minerals, No matter how abundant, are not considered in making the primary grouping.
- The hydrothermal minerals form the basis or dividing the complex pegmatites into subgroups

Acidic pegmatites are more abundant than basic, for two reasons:

(1) acidic intrusive magmas are much commoner, and

(2) as a general rule pegmatites are more acidic than the plutonic body from which they have been derived.

- The cubic volume occupied by complex pegmatites is insignificant when compared with that occupied by simple pegmatites.
- Because of the much greater mineralogical interest, the complex pegmatites receive many pages of description in geological literature.
- While the common pegmatites are but rarely mentioned.
- Most of the injected (lit-par-lit) pegmatites are of the simple type.

Uses of Pegmatite

Pegmatite rock has very few uses. However, pegmatite deposits often contain gemstones, industrial minerals, and rare minerals.

ARCHITECTURAL STONE

- Pegmatite rock has limited use as an architectural stone. Occasionally it is encountered in a dimension stone quarry that produces **granite** for architectural use.
- If the pegmatite is sound and attractive, it might be cut into slabs and polished for building facing, countertops, tile or other decorative stone products and sold commercially as a "granite."

GEMSTONE MINING

- Some of the world's best gemstone mines are in pegmatites.
- Gemstones found in pegmatite include: amazonite, **apatite**, aquamarine, **beryl**, **chrysoberyl**, **emerald**, **garnet**, **kunzite**, lepidolite, **spodumene**, **topaz**, **tourmaline**, **zircon**, and many others.
- Large crystals of excellent-quality material are often found in pegmatite.

RARE MINERALS

- Pegmatite is the host rock for many rare mineral deposits.
- These minerals can be commercial sources of: **beryllium**, bismuth, boron, cesium, lithium, molybdenum, niobium, tantalum, tin, titanium, tungsten, and many other elements.
- In most cases the mining operations are very small, employing less than a dozen people. If the mine contains nice crystals, the minerals are often more valuable as mineral specimens and faceting rough than being sold as an ore.

INDUSTRIAL MINERALS

- Pegmatite is often mined for industrial minerals.
- Large sheets of mica are mined from pegmatite.
- These are used to make components for electronic devices, retardation plates, circuit boards, optical filters, detector windows, and many other products.
- Feldspar is another mineral frequently mined from pegmatite. It is used as a primary ingredient for making glass and ceramics. It is also used as a filler in many products.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Genetic Models for the different Anorthosites

Archean Megacrystic Anorthosite [Phinney (1982), Emslie (1978)]

These anorthosites are derived from mantle derived iron rich tholeiite fractions of picritic or komatiitic protoliths (or from their partial melts).

Anorthosite generation is described in two stages:

First Stage:

High pressure crystallization of plagioclase in mantle melts at the crust – mantle boundary, i.e. formation and localization of magma chamber at this location.

Second Stage:

Ascent and consolidation of the plagioclase rich melt towards the lower and middle crust forming porphyritic plagioclase mega-crystal bearing anorthosite.

Coexisting mafic minerals are derived from the minor mafic melt fraction emplaced along with the plagioclase crystal - melt.

Proterozoic Massif Anorthosites [Bowen (1917), Emslie (1980)]

- **These anorthosites are derived from depleted basic or mafic or picritic magmas of upper mantle protoliths. The host magma ascends and localizes at the Moho to form a lopolithic magma chamber. Fractionation is initiated in the melt.**

- **The slow cooling promotes development of plagioclase as phenocrystals which tend to float or be suspended in the magma mass. Minor mafic minerals accumulate at the base of the magma chamber (or) may be reverted back to the mantle (or) be resorbed by new and hotter magma batches from the upper mantle.**

Layered Anorthosites [Todd (1982), Irving (1975)]

- **Layered anorthosites are derived from mafic or ultramafic magmas of upper mantle protoliths. Fractional crystallization and gravitative settling processes occur.**

- **The plagioclase pheno-crystals tend to float or be suspended in the magma mass and the minor mafic minerals accumulate at the base of the magma chamber. The source magma melt may under go one or several stages of differentiation to form the anorthosite layers.**

The following is envisaged in multi-stage differentiation of anorthosite forming magma:

a. **Formation of ultramafic magma of olivine boninite compositional.**

b. **Separation of this magma into two fractions: one fraction is rich in MgO and FeO, the other fraction is rich in Al_2O_3, CaO ± Na_2O, by liquid immiscibility.**

c. **Vertical layering of basal mafic fraction and upper felsic fraction.**

d. **Crystallization of basal layer to form: Dunite, Peridotite, Pyroxenite and upper layer to form anorthosite. Troctolite, gabbro or norite form in between these layers.**

Chromite, magnetite, ilmenite – rutile, PGE, Ni+Co+Cu deposits, Ti – V magnetite are the associated deposits. Residual Au may accumulate in the residual fluid to form an anorthosite hosted Au deposit.

Ophiolitic and Oceanic Anorthosites

The Ophiolitic anorthosites are associated with ophiolite sequences and their tectonic regimes. The oceanic anorthosites are related to layered gabbro complexes and MOR magma chambers. Source melt is tholeiitic basalt of MOR or Island Arc magmas (basic to calc-alkaline).

Lunar Anorthosites

These anorthosites are either iron rich type (ferroan) or alkali rich type (alkali rich) based on FeO and CaO± Na_2O respectively. Anorthosite meteorites are called as **Pallasites.**

Anorthosite Inclusions or Xenoliths

Cognate anorthosite is cogenetic with the enclosing older anorthosite. Xenolithic anorthosite originate from varied sources in the upper mantle and lower crust.

Anorthosites of Tamil Nadu

Confirmed anorthosite occurrences in Tamil Nadu include the following: **SITTAMPUNDI, KADAVUR, TOGAMALAI, ODDANCHATRAM, MANAPPARAI, CHINGLEPUT, PALANI HILLS, MANALUR, MADUKKARAI, METTUPALAYAM ,& KOTAGIRI.`**

Petrogenesis of Eclogites

- **Earlier theories of eclogite generation include the following:**

- **Metasomatism of gabbros by basic fluids in a high stress or shearing environment in the deep crust (Sorenson, 1953; Smulikovski,1960; Cogne,1096).**

- **Dry metamorphism of mafic igneous rocks under high stress (Grubermann,1903;Kranck,1935;Bearth, 1959).**

- **Metamorphism of sediments of appropriate composition under high pressure conditions (Hahn & Weinheimer,1959).**

- **Metamorphism of basic dikes in a deep seated dry basement rock along convergent plate boundaries (DeWit & Strong 1975).**

- **Crystallization of a mafic magma under high pressure within the magma chamber can allow formation of garnet and pyroxene (Holland, 1900; Eskola, 1921; Vesco, 1953).**

Acidic (silicic) igneous rocks
GRANODIORITE

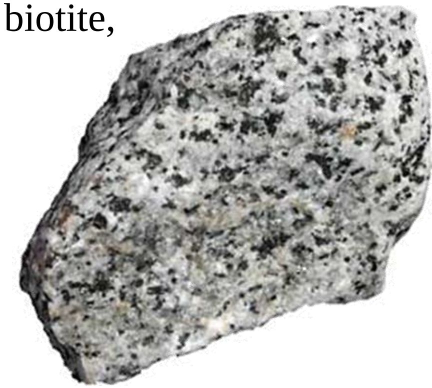
Appearance: Light coloured, medium- to coarse-grained intrusive igneous rocks with more than 20% of quartz. Within feldspars, the Na-rich plagioclase prevails over K-feldspar (orthoclase). The mafic minerals are represented by amphibole, pyroxene and biotite. This is the intrusive equivalent of dacite. It is formed mostly in subduction zones (active continental margins) and collisional settings (e.g., Alps along the Insubric-Periadriatic line). It forms also small volume shallow intrusive bodies of andesitic to dacitic volcanoes.

Mineral content:

Essential minerals: Na-rich plagioclase > K-feldspar (orthoclase), quartz, biotite, amphibole

Accessory minerals: apatite, magnetite, zircon

Secondary minerals: sericite, chlorite, epidot



Tonalite: Feldspars are represented almost exclusively by Na-rich plagioclase.

DACITE

Appearance: Ligth grey coloured, often crystal-rich volcanic rock. The most abundant phenocrysts are plagioclase, the mafic minerals are usually represented by amphibole and biotite, occasionally orthopyroxene. It contains much less alkali feldspar and quartz. It occur most commonly in subduction zone volcanoes. The known largest volume pyroclastic deposit in the Earth (Fish Canyon Tuff) is composed by dacite.

Mineral content:

Essential minerals: Na-rich plagioclase > K-feldspar (sanidine), biotite, amphibole, pyroxene

Accessory minerals: quartz, titanite, apatite, magnetite, zircon

Secondary minerals: sericite, chlorite, epidot

GRANITE

Appearance: Light coloured, medium- to coarse-grained intrusive igneous rock containing more than 20% quartz and the amount of alkali feldspars (orthoclase) exceeds that of the plagioclase. The mafic minerals are usually biotite, but amphibole and pyroxene could also occur. Certain granite varieties muscovite, garnet and cordierite could be also found. Granites usually occur where thick continental crust developed, i.e. at subduction zones along active continental margin (e.g. Andes, Western USA) and at collision zones (e.g., Alps, Himalaya).

Mineral content:

Essential minerals: K-feldspar (sanidine) > Na-rich plagioclase, quartz, biotite, amphibole

Accessory minerals: titanite, apatite, magnetite, zircon, muscovite, pyroxene, andalusite, cordierite, garnet, turmalin, topas

Secondary minerals: sericite, chlorite, epidot

ROCK TYPES

Monzogranite:

- Within feldspars the alkali feldspar has an amount of 35-65%.
- This is the most common granite type, called formerly also Adamellite (the Adamello granite is one of the most famous silicic igneous bodies at the Periadriatic line in the Alps)

Syenogranite:

within feldspars the alkali feldspar has an amount of 65-90%.

Alkáli granite:

within feldspars the alkali feldspar has an amount of >90%. The mafic minerals are alkali pyroxenes (aegirinaugite, aegirine) and alkali amphibole

Graphic granite:

quartz and orthoclase show oriented intergrowth. It forms from eutectic silicic melt.

Luxullianite (turmaline-granite):

in this granite type turmaline occurs in significant amount

Greisen:

A granite type showing metasomatic alteration.

Typical minerals occurring in this granite are significant amount of quartz and less muscovite and/or Li-mica, topas. Feldspar, fluorite, turmaline, berill, rutile, cassiterite, apatite are found as accessory minerals.

The feldspar and biotite in the original granite are replaced by quartz, Li-mica and caolinite.

Aplite:

Fine-grained granite with equigranular texture with orthoclase-microcline > Na-rich plagioclase and quartz. Mafic minerals are subordinate.

It represent highly evolved silicic melt with eutectic (haplogranitic) composition.

granophyre: It contains quartz and alkali feldspar in characteristic angular intergrowths. It is formed from eutectic melt.

Granite

The term **"Granite"** is derived from latin word ***"Granum"*** meaning "grain" because of its granular nature.

Mineralogically:

- ✓**Essential minerals** - Quartz , Feldspar
- ✓**Accessory minerals** – Biotite, muscovite , amphibole.
- ✓Other accessories are **zircon, apatite, ilmenite, magnetite, sphene, pyrite** etc.

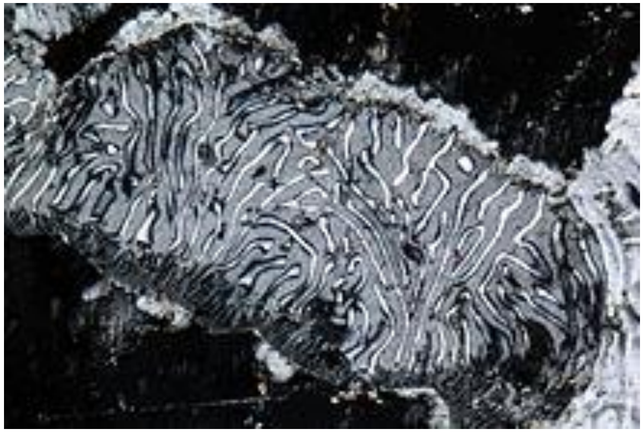
Texturally:

Medium to coarse grained crystalline rock generally exhibiting **Hypidiomorphic texture** and **Intergrowth textures** (perthite, Antiperthite, Myrmekite, Graphic, Granophyric, rapakivi).

Chemically : SiO_2 - > 65 %, (other oxides vary)

Perthite: It is used to describe an intergrowth of two feldspars. An intergrowth of albite or oligoclase with a microcline host, occasionally also with a orthoclase host. The intergrowths or exsolution lamellae of the albite are visible as white lines coursing through the K feldspar groundmass. Common in granite and pegmatites.

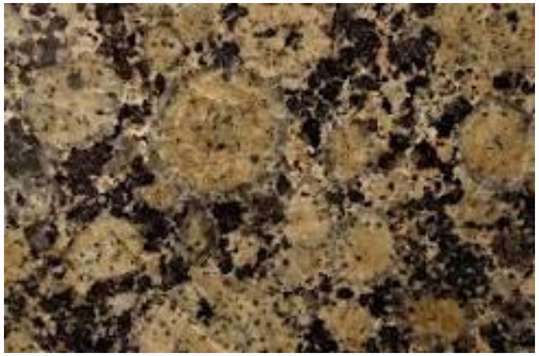
Antiperthite: A feldspar rock consisting of plagioclase containing lamellae of orthoclase



Myrmekite describes a vermicular, or wormy, intergrowth of quartz in plagioclase. The intergrowths are microscopic in scale, typically with maximum dimensions less than 1 millimeter. The plagioclase is sodium-rich, usually albite or oligoclase. Myrmekite is formed under metasomatic conditions, usually in conjunction with tectonic deformations.

Graphic texture Intergrowth of quartz and alkali feldspar.

Rapakivi granite is a hornblende-biotite granite containing large rounded crystals of orthoclase each with a rim of oligoclase (a variety of plagioclase). The name has come to be used most frequently as a textural term where it implies plagioclase rims around orthoclase in plutonic rocks.



Q-A-P classification of Granitoids
(a part of QAPF classification)

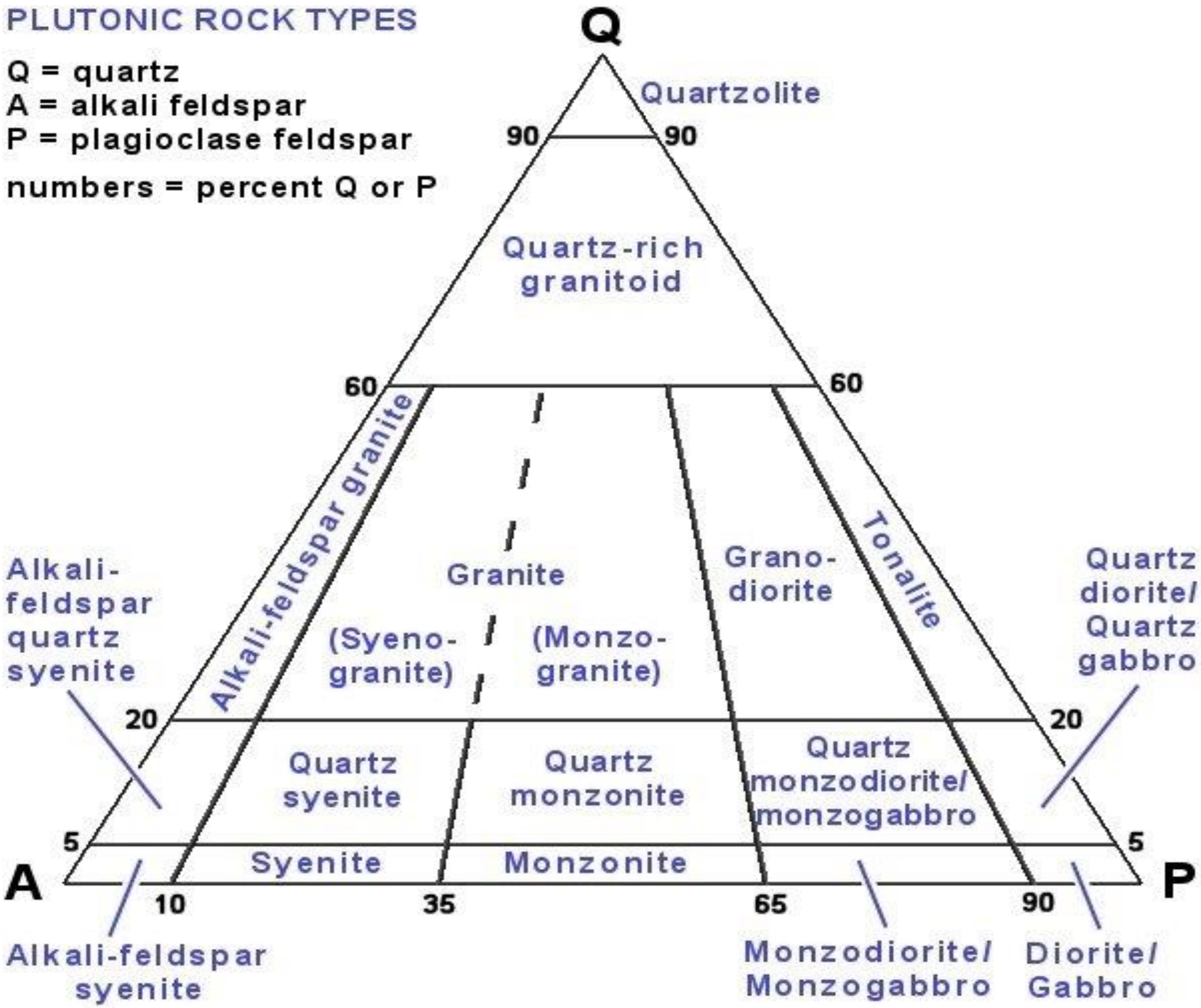
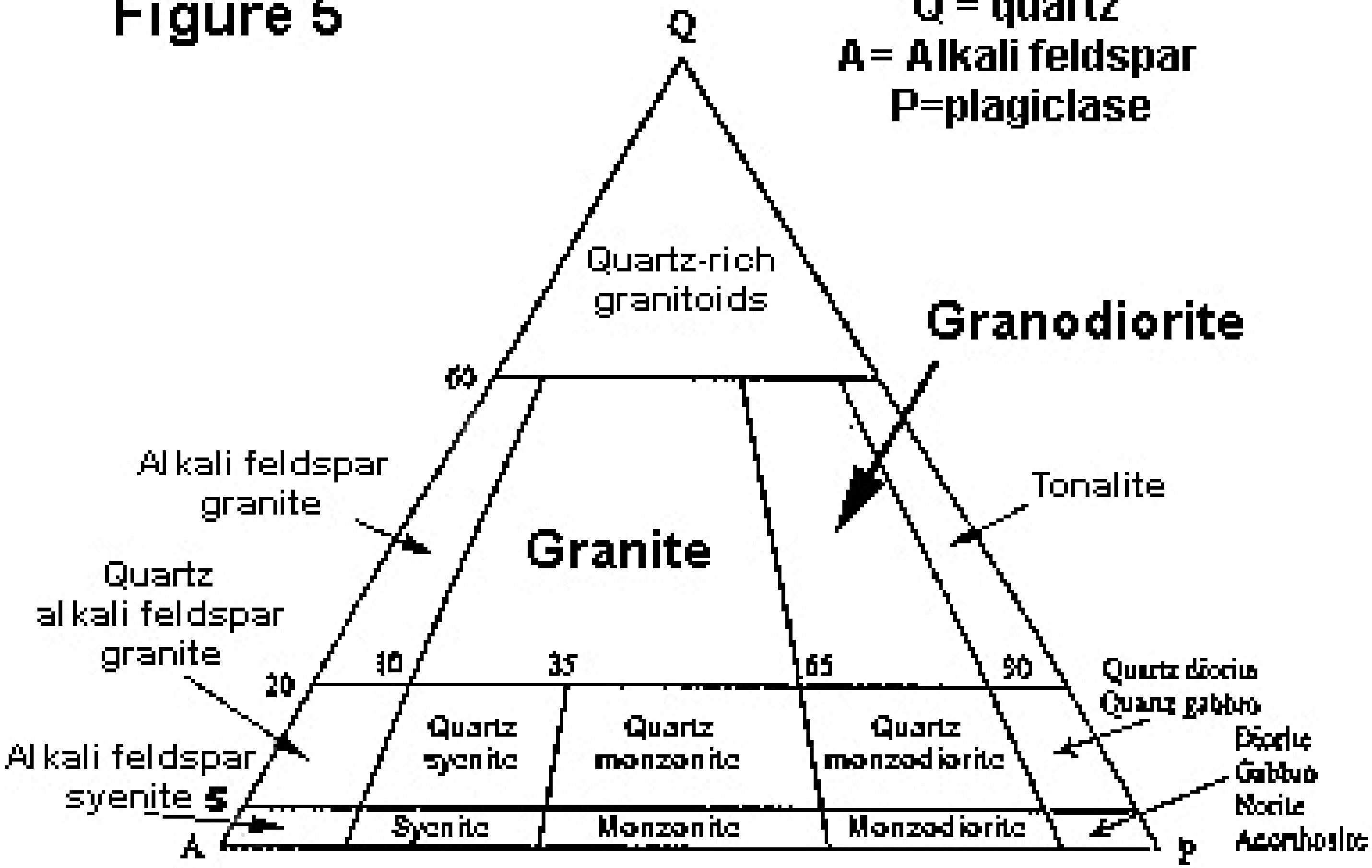


Fig.1. After IUGS (1973)

Figure 5

IUGS classification of plutonic rocks
Q = quartz
A= Alkali feldspar
P=plagiclase



Adapted from LeMaitre, R., 1989, A classification of Igneous Rocks ad Glossary of Terms.

Granite classification based on alumina Saturation (by Shand):

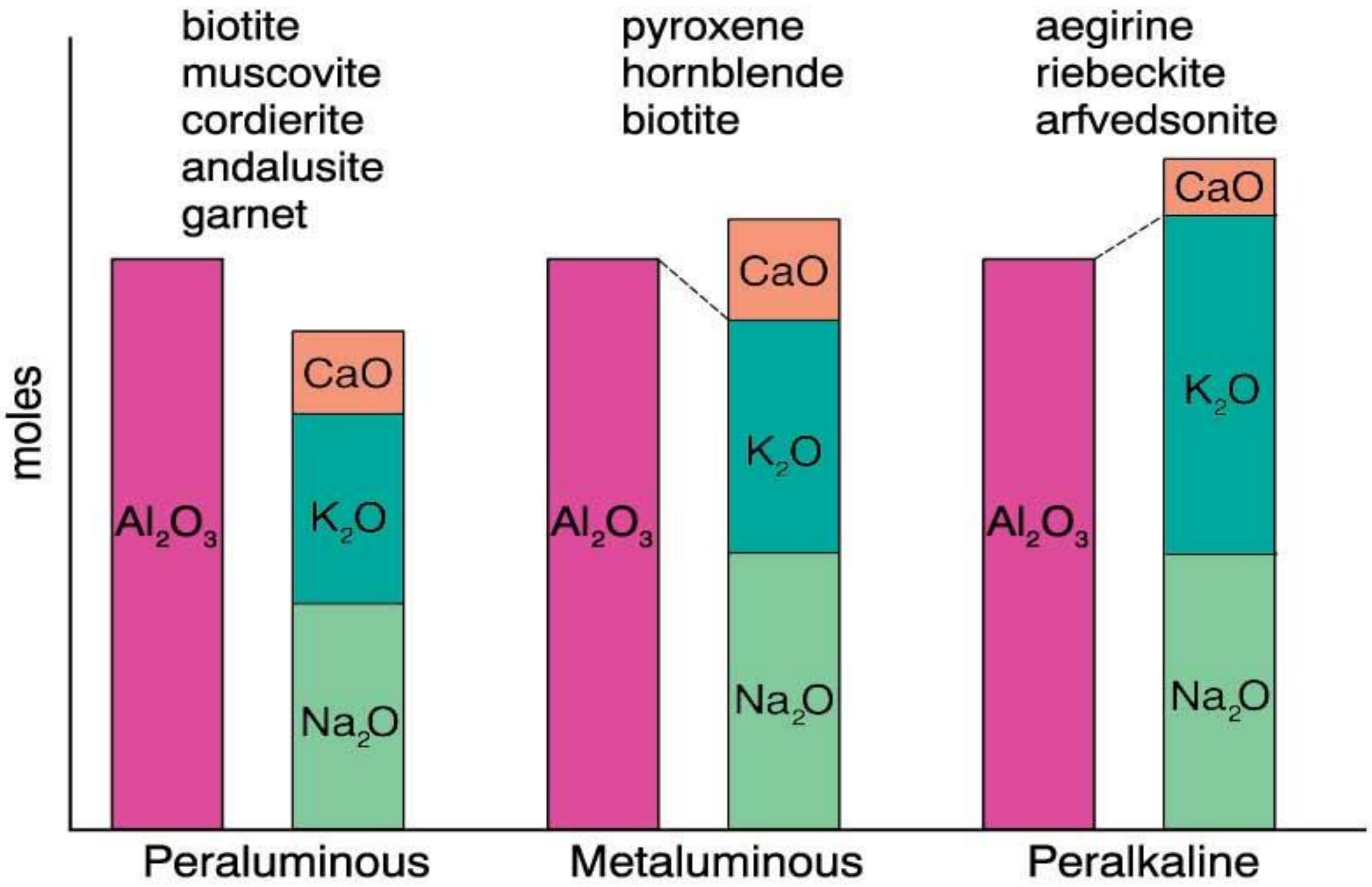


Fig 2. Alumina saturation classes based on the *molar* proportions of $Al_2O_3/(CaO+Na_2O+K_2O)$ ("A/CNK") after Shand (1927).

Alphabetic (S-I-A-M) Classification of Granitoids:

By Chappell and White (1974)

- ✓ **S-type Granitoid (**sedimentary protolith)
- ✓ **I-type Granitoid**(igneous protolith)
- ✓ **M-type Granitoid** (direct mantle source)

By Loiselle and Wones (1979)

- ✓ **A-type Granitoid** (anorogenic type)

S-Type Granitoids:

- ✓Derived due to partial melting of sedimentary and metasedimentary rock.
- ✓S-type are more common in collision zones.
- ✓These are peraluminous granites [i.e. they have molecular Al_2O_3 > (Na_2O + K_2O+CaO)].
- ✓S-type granites are charecterised by presence of muscovite, biotite and marginally higher SiO_2 contents.

- ✓ e.g. Himalayan Granites

I-Type Granitoids:

✓Derived due to partial melting of **igneous proloith.**

✓Deep seated igneous or metaigneous rocks of lower continental crust subjected to partial melting due upwelling of mantle material to higher levels.

✓Generally metaluminous granites, expressed mineralogically by the absence of peraluminous minerals like muscovite. But there are exceptions.

✓I-type granites are charecterised by presence of hornblende / alkali amphiboles ± biotite.

M-Type Granitoids:

✓Derived due to fractional crystallisation of basaltic magma.
✓Relatively Plagioclase rich**(plagiogranite of ophiolite).**
✓Associated with Gabbros and Tonalites.
✓Characteristics of Subduction zone.

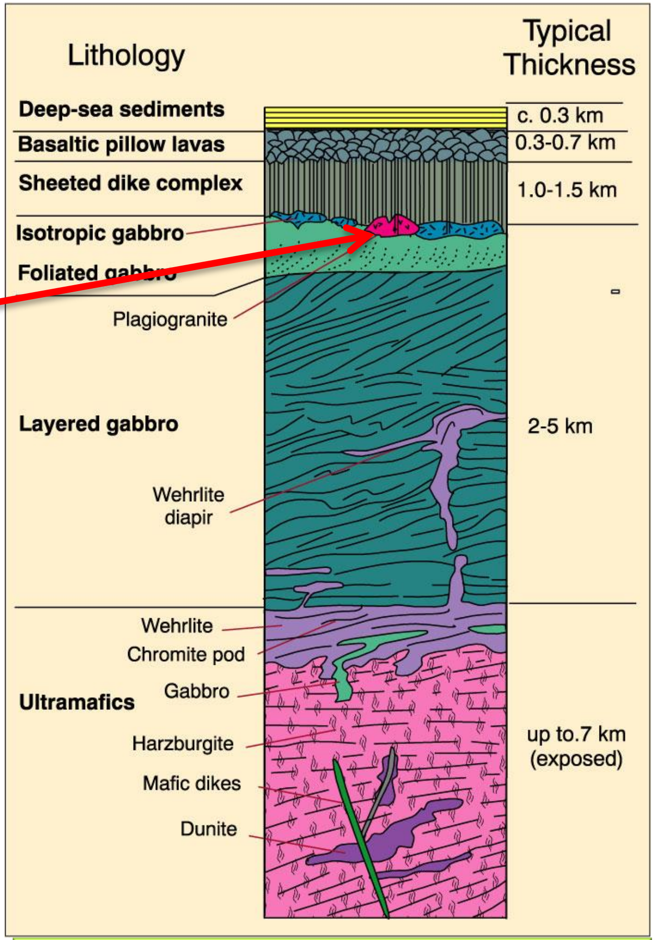


Fig.3. Ophiolite Sequence

A-Type Granitoids:

A-type granites are emplaced in either within plate anorogenic settings or in the final stages of an orogenic event.

Characterised by:

✓High SiO_2 **(~73.81%)**
✓High F contents **(6000 to 8000 ppm)**
✓Presence of **fluorite** is an important characteristic of A-type granites.

Criteria	M-Type	I-Type	S-Type	A-Type
Comp	Plagiogranite	Tonalite-Granite Tonalite-predominet granodiorite	Leucogranite with narrow compositional range	High K-Granite, ±Syenite
Ch.Minerals	hb+bt+cpx	hb+bt+ magnetite + sphene	Ilmenite, red bt, muscovite gt+ monozite	Green bt
Xenoliths	Mafic	MIxed	Chiefly metasediments	mixed
Tectonic characteristics	Pretectonic	Pretectonic to syntectonic	Sytectonic to post techtonic	Post tectonic
Tectonic setting	Ophilite	Arc or collisional orogeny	collisional orogeny	Anorogeny
Source	Fractional Xll^{n} of MORB, CAB-Cal alkaline basalt	CAB-Cal alkaline basalt IAB-Island Arc Basalt	Partial melting of sediments	Partial melting of lower crust
Mineralisation	Cu & Au	Cu & Mo	Sn, W, U. Th, Li	Sn-W, Ta Nb fluorite, rare metals and Li

S-I-A- M Classification of Granitoids:

Type	SiO_2	K_2O/Na_2O	Ca, Sr	A/(C+N+K)*	Fe^{3+}/Fe^{2+}	Cr, Ni	$\delta^{18}O$	$^{87}Sr/^{86}Sr$	Misc	Petrogenesis
M	46-70%	low	high	low	low	low	< 9‰	< 0.705	Low Rb, Th, U Low LIL and HFS	Subduction zone or ocean-intraplate Mantle-derived
I	53-76%	low	high in mafic rocks	low: metal-uminous to peraluminous	moderate	low	< 9‰	< 0.705	high LIL/HFS med. Rb, Th, U hornblende magnetite	Subduction zone Infracrustal Mafic to intermed. igneous source
S	65-74%	high	low	high peraluminous	low	high	> 9‰	> 0.707	variable LIL/HFS high Rb, Th, U biotite, cordierite Als, Grt, Ilmenite	Subduction zone Supracrustal sedimentary source
A	high → 77%	Na_2O high	low	var peralkaline	var	low	var	var	low LIL/HFS high Fe/Mg high Ga/Al High REE, Zr High F, Cl	Anorogenic Stable craton Rift zone

* *molar* $Al_2O_3/(CaO+Na_2O+K_2O)$

Data from White and Chappell (1983), Clarke (1992), Whalen (1985)

Classification of Granitoid Rrocks based on Tectonic Setting:

OROGENIC:

✓Mountain building resulting from compressive stresses associated with subduction.

e.g. Continental collision granites- Himalayas.

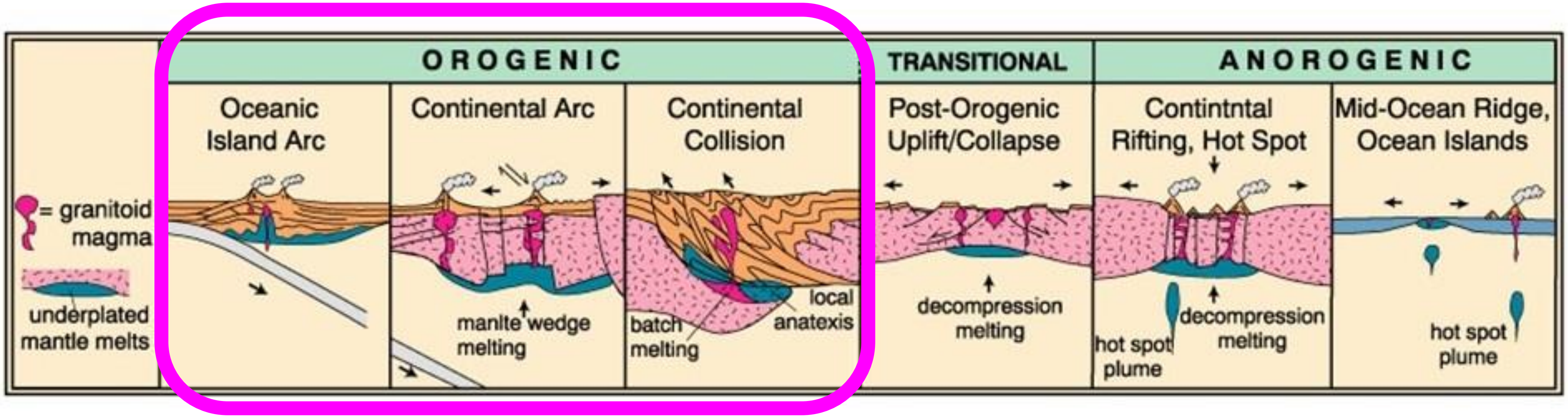


Fig.4. A Classification of Granitoid Rocks Based on Tectonic Setting. After Pitcher (1983) in K. J. Hsü (ed.), *Mountain Building Processes*, Academic Press, London; Pitcher (1993), *The Nature and Origin of Granite*, Blackie, London; and Barbarin (1990) *Geol. Journal*, 25, 227-238. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Classification of Granitoid Rrocks based on Tectonic Setting:

ANOROGENIC:

✓Magmatism within plate or at a spreading plate margin.

✓Here magmatism occurs in settings that are not genetically related with compressive orogeny.

e.g. Yellowstone-snake river plain in USA

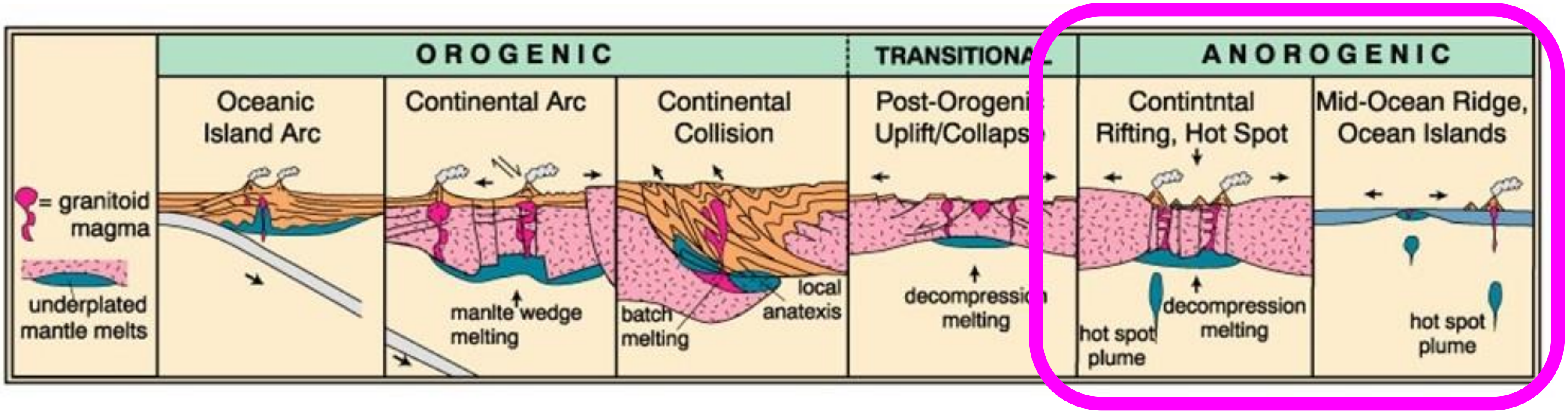


Fig.5. A Classification of Granitoid Rocks Based on Tectonic Setting. After Pitcher (1983) in K. J. Hsü (ed.), *Mountain Building Processes*, Academic Press, London; Pitcher (1993), *The Nature and Origin of Granite*, Blackie, London; and Barbarin (1990) *Geol. Journal*, 25, 227-238. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Classification of Granitoid Rrocks based on Tectonic Setting:

TRANSITIONAL /POST-OROGENIC :

✓Magmatism takes place after the main orogenic event. (because it needs a precursor orogeny two diverse groups exist whether they are orogenic or anorogenic).

e.g. Late Caledonian plutons of Britain

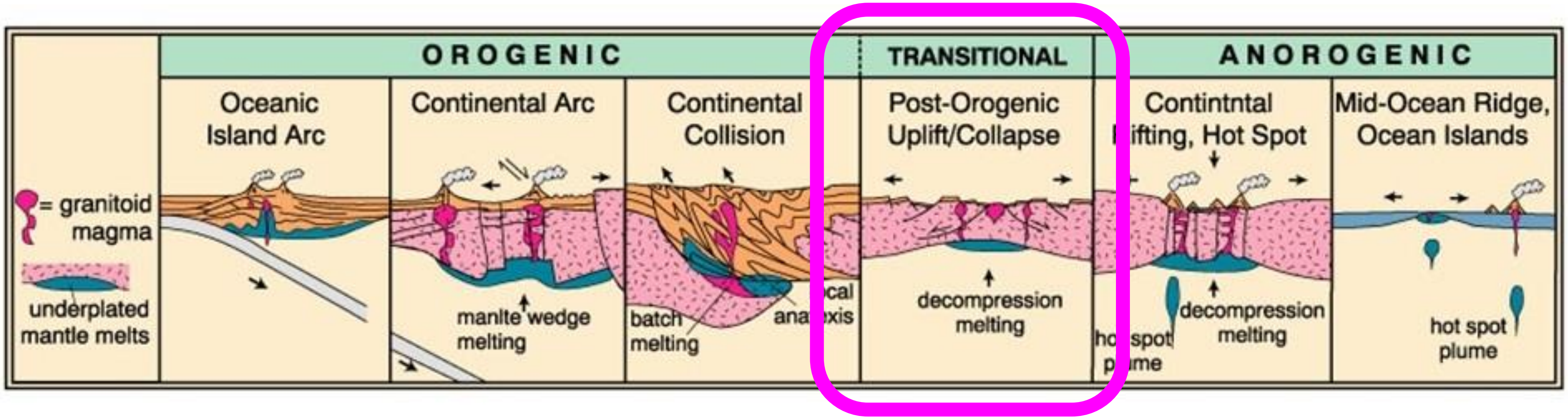


Fig.6. A Classification of Granitoid Rocks Based on Tectonic Setting. After Pitcher (1983) in K. J. Hsü (ed.), *Mountain Building Processes*, Academic Press, London; Pitcher (1993), *The Nature and Origin of Granite*, Blackie, London; and Barbarin (1990) *Geol. Journal*, 25, 227-238. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Petrogenesis:

✓Magmatic Origin

✓Metasomatic Transformation (Granitisation)

❖**Bowen's** studies showed that a basaltic magma can give rise to acid magma (granitic) due to differentiation.

❖Extensive field studies , in high grade terranes, showed that extensive metasomatic transformation was capable of bringing about compositional changes insitu of a variety of pre-existing rocks to create granites **(H.H.Read).**

✓Most granitoids of significant volume occur in areas where the **continental crust** has been **thickened** by orogeny, either continental arc subduction or collision.

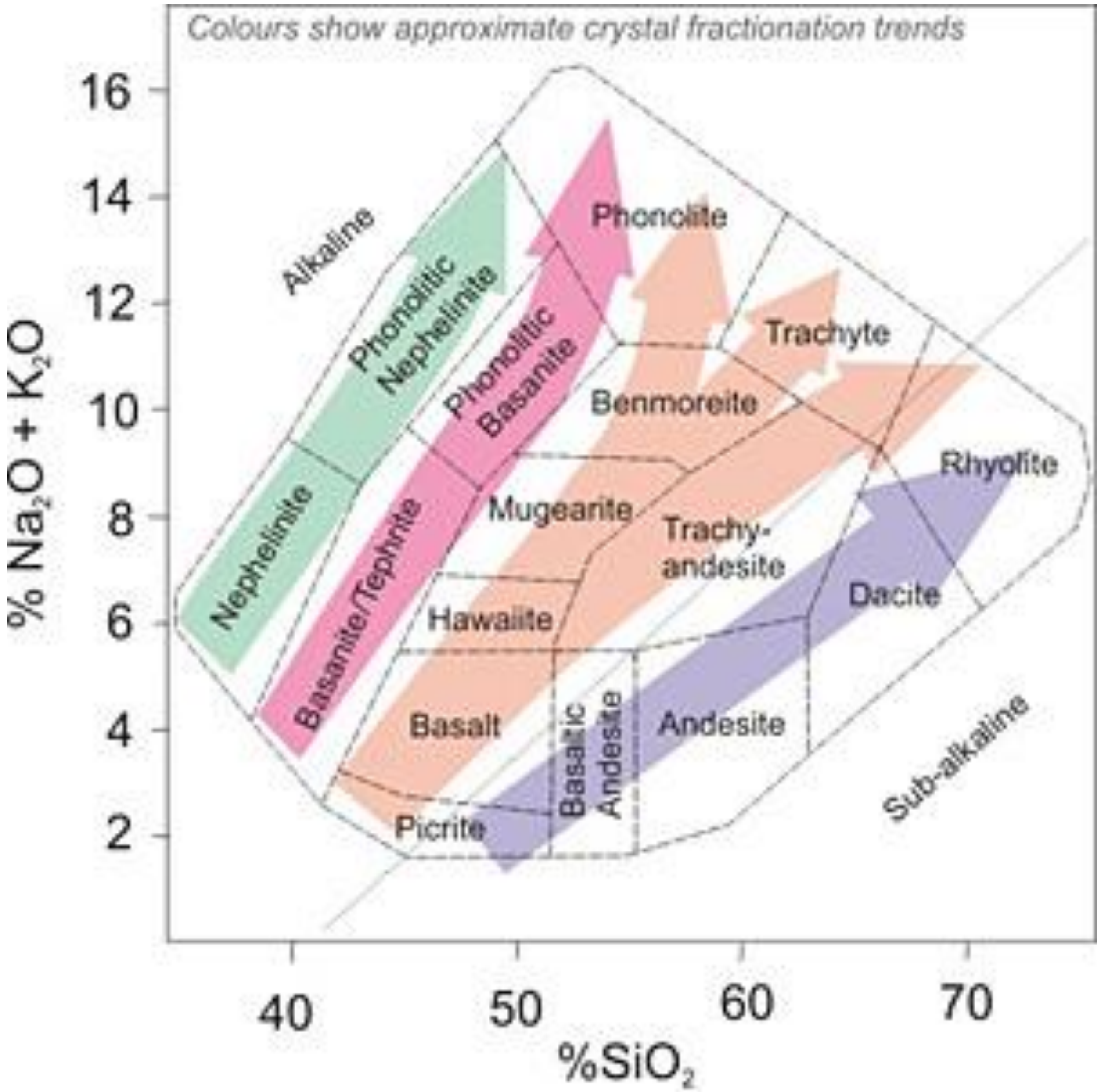
✓Because the crust is solid in its normal state, some **thermal disturbance** is required to form granitoids.

✓Most workers are of the opinion that the majority of granitoids are derived by **crustal anatexis**, but that the **mantle may also be involved**. The mantle contribution may range from that of a **source of heat** for crustal anatexis, or it may be the **source of material as well.**

Alkaline Rocks

- Alkaline igneous rocks are those with an excess of alkali metals ($Na_2O + K_2O$) over silica.
- Alkaline rocks are relatively rare, however, they exhibit significant variation in mineralogy and, therefore, comprise a large number of rock types.
- Many alkaline rocks are silica-undersaturated and contain feldspathoid minerals, mainly nepheline and leucite, many also contain alkali feldspars. They can, however, be silica-saturated and oversaturated.
- A subset of alkaline rocks are potassic or ultrapotassic, such as kimberlites, lamproites and shonsonites.

- Alkaline rocks are found in a wide range of tectonic environments but are particularly common in ocean islands and continental rifts.
- The occurrence of alkaline rocks can be extrusive or intrusive.
- Extrusive alkaline rocks comprise both lavas and pyroclastic rocks formed by accumulation of ejecta from explosive eruptions.
- Alkaline parental magmas generally originate by melting of mantle rocks at smaller degrees of partial melting or greater depth than sub-alkaline magmas.



Colours show approximate crystal fractionation trends
% $Na_2O + K_2O$
16
14
12
10
8
6
4
2
40
50
60
70
%SiO_2
Alkaline
Sub-alkaline
Phonolitic Nephelinite
Nephelinite
Phonolitic Basanite
Basanite/Tephrite
Phonolite
Trachyte
Benmoreite
Mugearite
Trachy-andesite
Hawaiite
Rhyolite
Dacite
Basalt
Basaltic Andesite
Andesite
Picrite

Syenite and Nepheline Syenite

- Plutonic Igneous rocks made up of predominantly by alkali feldspar and alkali feldspar with Nepheline.
- In Syenite the accessary mineral are quartz and plagioclase
- In Nepheline Syenite, albite present which may considered in this case as alkali feldspar.
- In Syenite, the mafic minerals may be hornblende, biotite or aguite, therefore it may be called as Hornblende syenite, Biotite syenite and Aguite syenite.
- Syenite which are rich in alkali feldspar and devoid of plagioclase are called **Alkali-Syenite.**
- Alkali syenite with little accessary of quartz is named as Nordmarkite,

Syenite and Nepheline Syenite

- Larvikite is a special type of monzonite in Syenite verity which contain anorthoclase (blue feldspar) and olivine, magnetite, boitite and titanaguite as mafic minerals.
- Mafic minerals augmented alkali syenite is called as Shonkinite
- In alkali syenite, Plagiclase feldspar with equal amount of alkali feldspar are called Monzonite
- In Nepheline syenite, the mafic minerals may be biotite soda-amphiboles, soda-pyroxenes, apatite, garnet, zircon and sphene.
- If the Nepheline syenite contains albite as the only alkali feldspar it is termed as Canadite.
- The Nepheline bearing rock corresponding to monzonite is called as monzonite Nepheline syenite
- If labrodorite is dominant feldspar in nepheline bearing rock, it is called as Theralite

Carbonatite

- Intrusive igneous, hypabyssal
- Igneous rock in which the **carbonate minerals** are primary
- **Apatite and pyrochlore** are often considered essential
- Accessory: Siderite, calcite, dolomite, or ankerite
- Less common accessory minerals: Mg-rich magnetite, phlogopite, and pyrite

Carbonatite Occurrence

- Carbonatites occur as plugs with surface areas of up to 8 km^2.
- They are enclosed in mafic alkaline rings.
- Mafic rocks include biotite pyroxenite, ijolite, nephelinite (35% nepheline, 65% mafic on average), and jacupirangite (rocks consisting of pure magnetite, magnetite with accessory pyroxene, pyroxene with accessory magnetite, or pyroxene and nepheline with biotite and olivine).

CARBONATITES

- Carbonatites are perhaps the most unusual of all lavas. They are defined, when crystalline, by having more than 50% carbonate (CO_3-bearing) minerals, and typically they are composed of less than 10% SiO_2.

- There are only 330 known carbonatite localities on Earth, most of which are shallow intrusive bodies of calcite-rich igneous rock in the form of volcanic necks, dikes, and cone-sheets. These generally occur in association with larger intrusions of alkali-rich silicate igneous rocks.

- Extrusive carbonatites are particularly rare, and appear to be restricted to a few continental rift zones, such as the Rhine valley and the East African rift system.

- Most carbonatite lavas have low eruption temperatures, between 500 and 600 degrees Centigrade. They typically have low viscosities due to their lack of silica polymerization. Thus, carbonatite flows are generally only a few centimeters thick, with surface textures.

- Some active carbonatite flows are enriched in alkalies (Na and K) - these are called **natro-carbonatites**. Soon after their eruption, dark natro-carbonatite flows will cool and rapidly turn white due to reaction with atmospheric water.

Genesis[edit]

Carbonatites are *rare*, *peculiar* igneous rocks formed by unusual processes and from unusual source rocks. Three models of their formation exist:

1. direct generation by very low degree partial melts in the mantle and melt differentiation
2. liquid immiscibility between a carbonate melt and a silicate melt
3. peculiar, extreme crystal fractionation

Evidence for each process exists, but the key is that these are unusual phenomena. Historically, carbonatites were thought to form by melting of limestone or marble by intrusion of magma but geochemical and mineralogical data discount this. For example, the carbon isotopic composition of carbonatites is mantle-like and not like sedimentary limestone.

Mineralogy[edit]

Primary mineralogy is highly variable, but may include natrolite, sodalite, apatite, magnetite, barite, fluorite, ancylite group minerals, and other rare minerals not found in more common igneous rocks. Recognition of carbonatites may be difficult, especially as their mineralogy and texture may not differ much from marble save for the presence of igneous minerals. They may also be sources of mica or vermiculite.

Carbonatites are classed as calcitic sovite (coarse textured) and alvikite (finer textured) varieties or facies. The two are also distinguished by minor and trace element composition.[4][5] The terms *rauhaugite* and *beforsite* refer to dolomite- and ankerite-rich occurrences, respectively. The alkali-carbonatites are termed *lengaite*. Examples with 50 - 70% carbonate minerals are termed *silico-carbonatites*.[5] Additionally carbonatites may be either enriched in magnetite and apatite or rare earth elements, fluorine and barium.[6]

Natrocarbonatite is made up largely of two minerals, nyerereite (named after Julius Nyerere, the first president of independent Tanzania) and gregoryite (named after John Walter Gregory, one of the first geologists to study the East African Rift and author of the book *The Great Rift Valley*). These minerals are both carbonates in which sodium and potassium are present in significant quantities. Both are anhydrous and when they come into contact with the moisture in the atmosphere, they begin to react extremely quickly. The black or dark brown lava and ash erupted begins to turn white within a few hours.

GEochemistry

Carbonatite is composed predominantly of carbonate minerals and extremely unusual in its major element composition as compared to silicate igneous rocks, obviously because it is composed primarily of Na_2O and CaO plus CO_2.

Most carbonatites tend to include some silicate mineral fraction; by definition an igneous rock containing >50% carbonate minerals is classified as a carbonatite. Silicate minerals associated with such compositions are pyroxene, olivine, and silica-undersaturated minerals such as nepheline and other feldspathoids.

Geochemically, carbonatites are dominated by incompatible elements (Ba, Cs, Rb) and depletions in compatible elements (Hf, Zr, Ti). This together with their silica-undersaturated composition supports inferences that carbonatites are formed by low degrees of partial melting.

A specific type of hydrothermal alteration termed *fenitization* is typically associated with carbonatite intrusions. This alteration assemblage produces a unique rock mineralogy termed a *fenite* after its type locality, the Fen Complex in Norway. The alteration consists of metasomatic halos consisting of sodium rich silicates arfvedsonite, barkevikite and glaucophane along with phosphates, hematite and other iron and titanium oxides.[6]

Occurrences

Associated igneous rocks typically include ijolite, melteigite, teschenite, lamprophyres, phonolite, foyaite, shonkinite, silica undersaturated foid-bearing pyroxenite (essexite), and nepheline syenite.

Carbonatites are typically associated with undersaturated (low silica) igneous rocks that are either alkali (Na_2O and K_2O), ferric iron (Fe_2O_3) and zirconium-rich agpaitic rocks or alkali-poor, FeO-CaO-MgO-rich and zirconium-poor miaskitic rocks.[6]

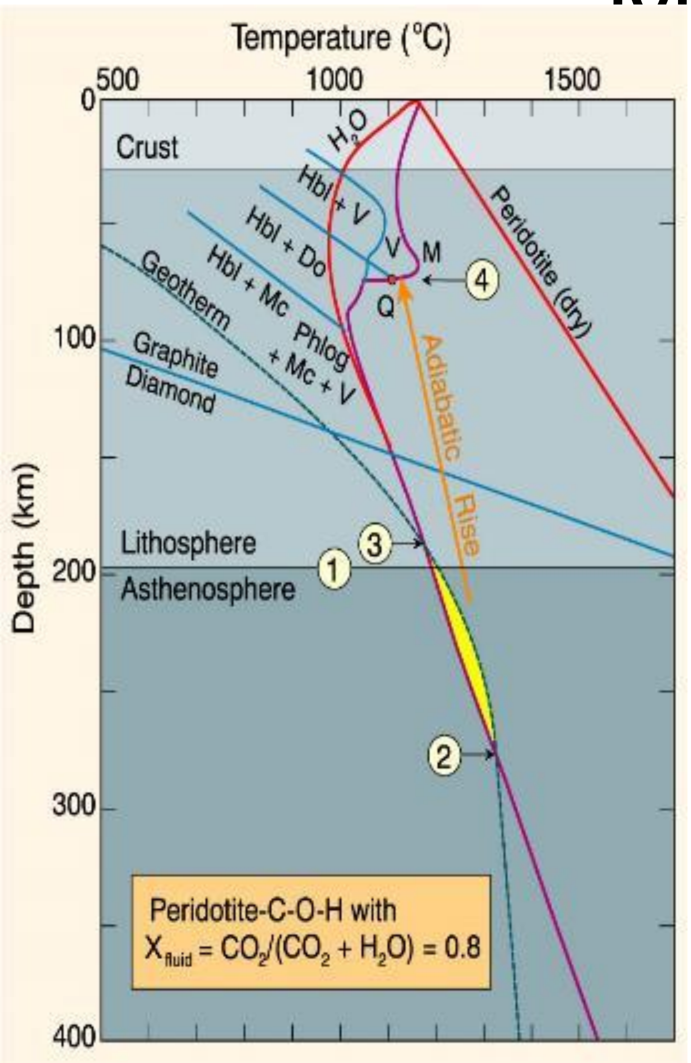
The Mount Weld carbonatite is unassociated with a belt or suite of alkaline igneous rocks, although calc-alkaline magmas are known in the region. The genesis of this Archaean carbonatite remains contentious as it is the sole example of an Archaean carbonatite in Australia.

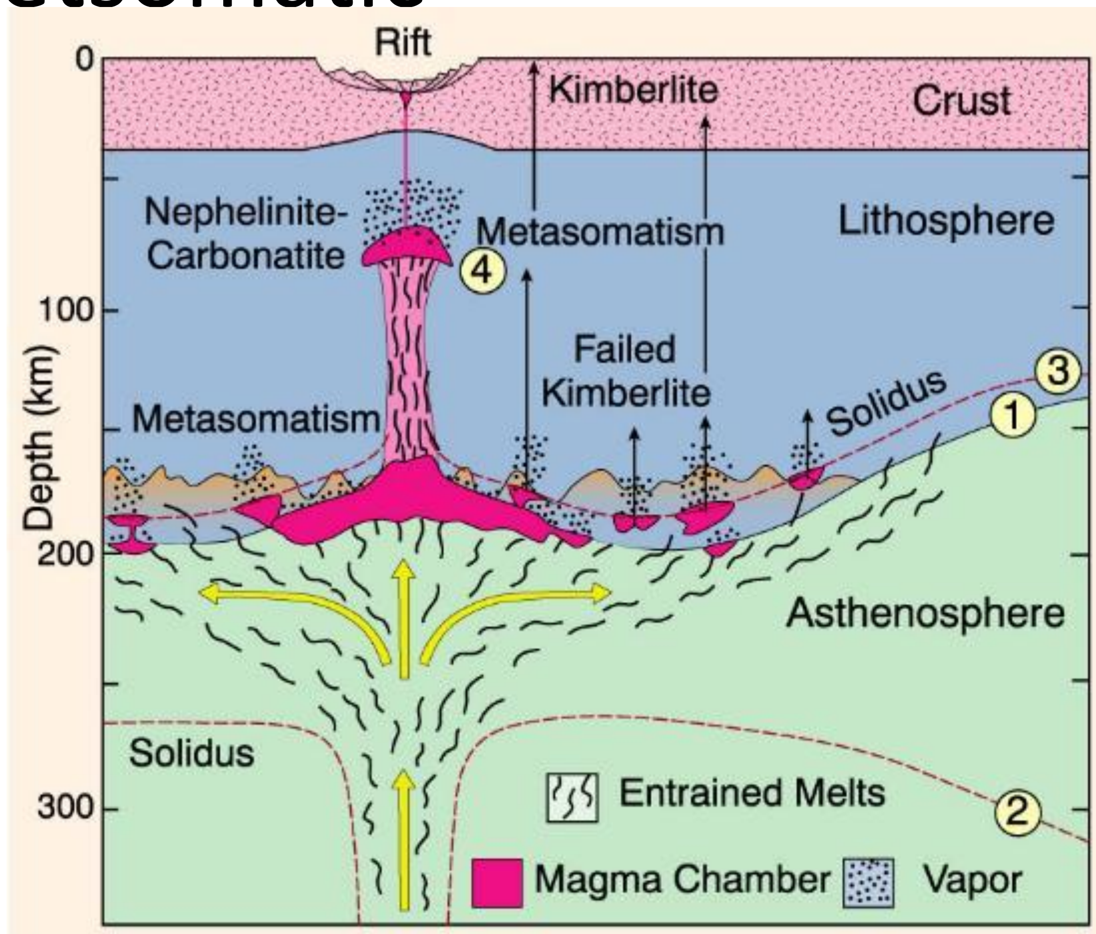
Carbonatite Origin

- The similarity between silicate and carbonate phase trace and minor elements has convinced most petrologists that the carbonatites must originate together with the silicates, possibly from the same source, and not from limestones, as early workers had suggested

Origin of Carbonates

Igneous, Metamorphic, or Metsomatic





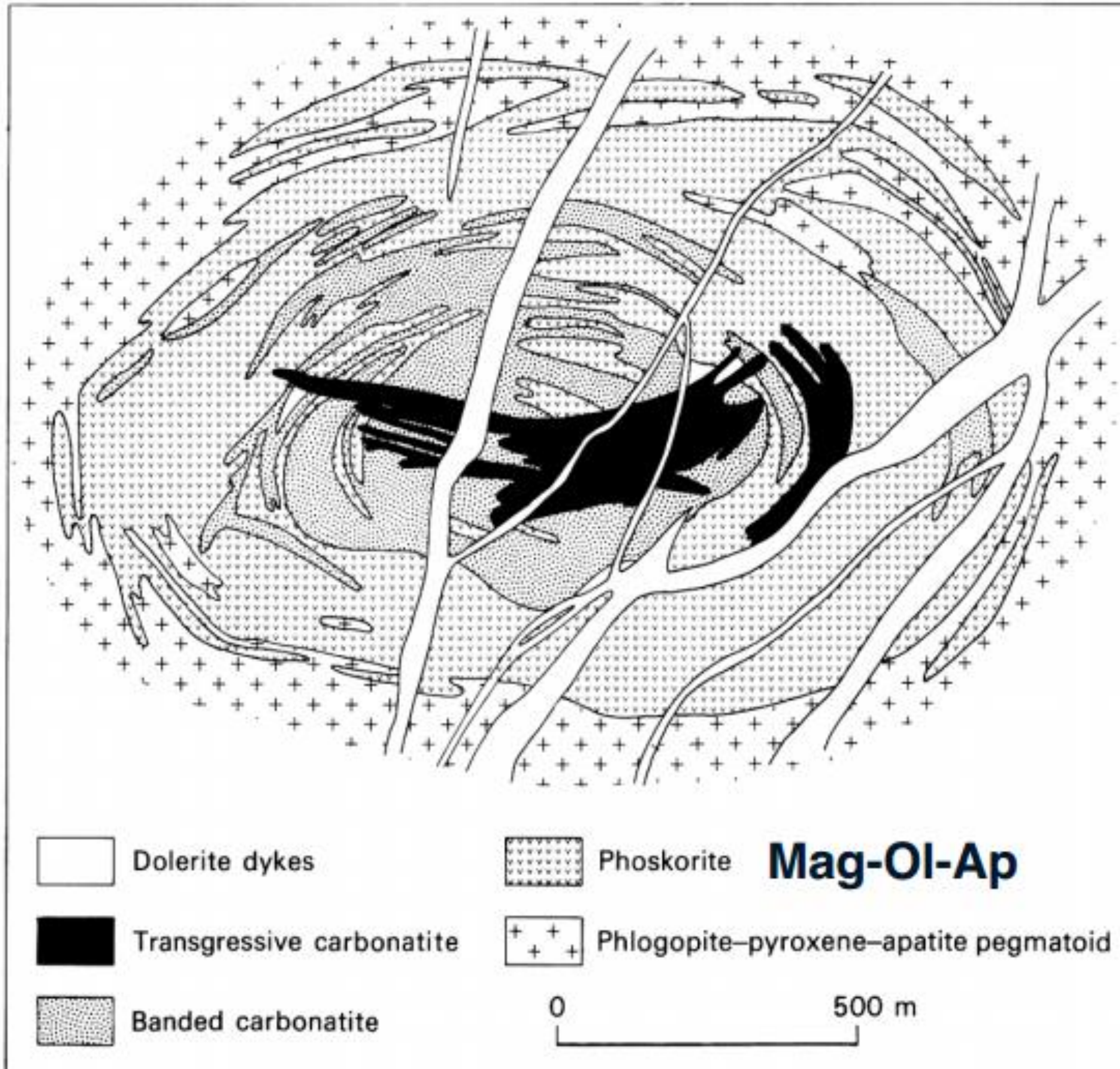
- Carbonatites occur in small ring complexes associated with silica poor rocks composed of nepheline and cpx (I.e. ijolites)

- Carbonatite complexes are concentrically arranged
    - rock types become progressively poorer in silica toward the core which is commonly occupied by carbonatite

- Typical succession of rocks from the rim to the core would consist of:
  nepheline syenite
  ijolite
  carbonatite with all rocks being cut by lamprophyric dikes

Guilbert and Park, 1985

122 m level Palabora



Carbonatites

- Carbonatite may also be concentrically zoned from an older, outer zone of calcite carbonatite (sovite), followed by a zone of dolomite carbonatite (beforsite) and a younger core of ankerite or siderite carbonatite
- Consistent with fractional crystallization of a carbonate melt.
- Typical carbonatite is composed of 75% carbonate with lesser amounts of cpx, phlogopite, alkali amphibole, apatite, magnetite, olivine etc.
- Carbonatites are highly variable in composition
- Rocks surrounding carbonatites have undergone intense sodium metasomatism (fenitization)

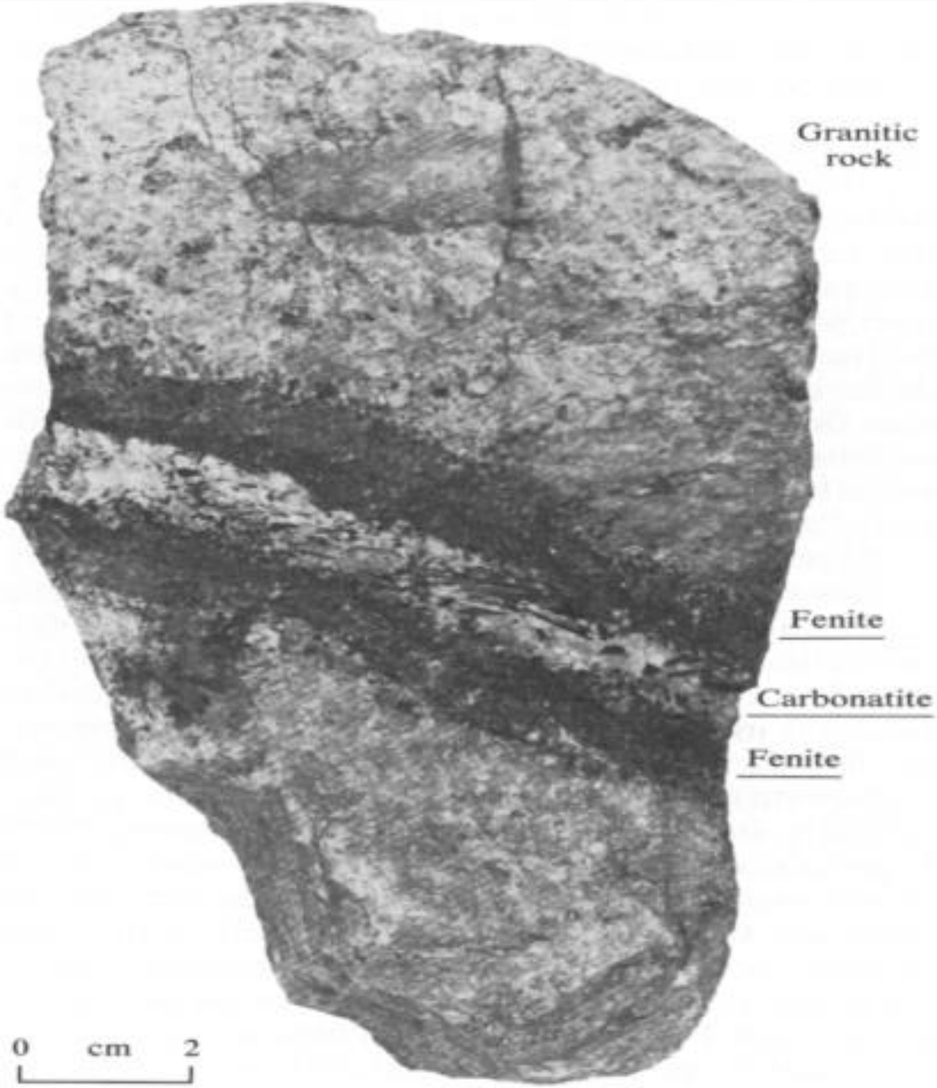


Figure 6-4 Thin dike of carbonatite with alkali amphibole emplaced into granite has produced fenite borders of similar amphibole and biotite.

Best, 1982

Folded basic dikes within a carbonatite matrix.

Carbonatites

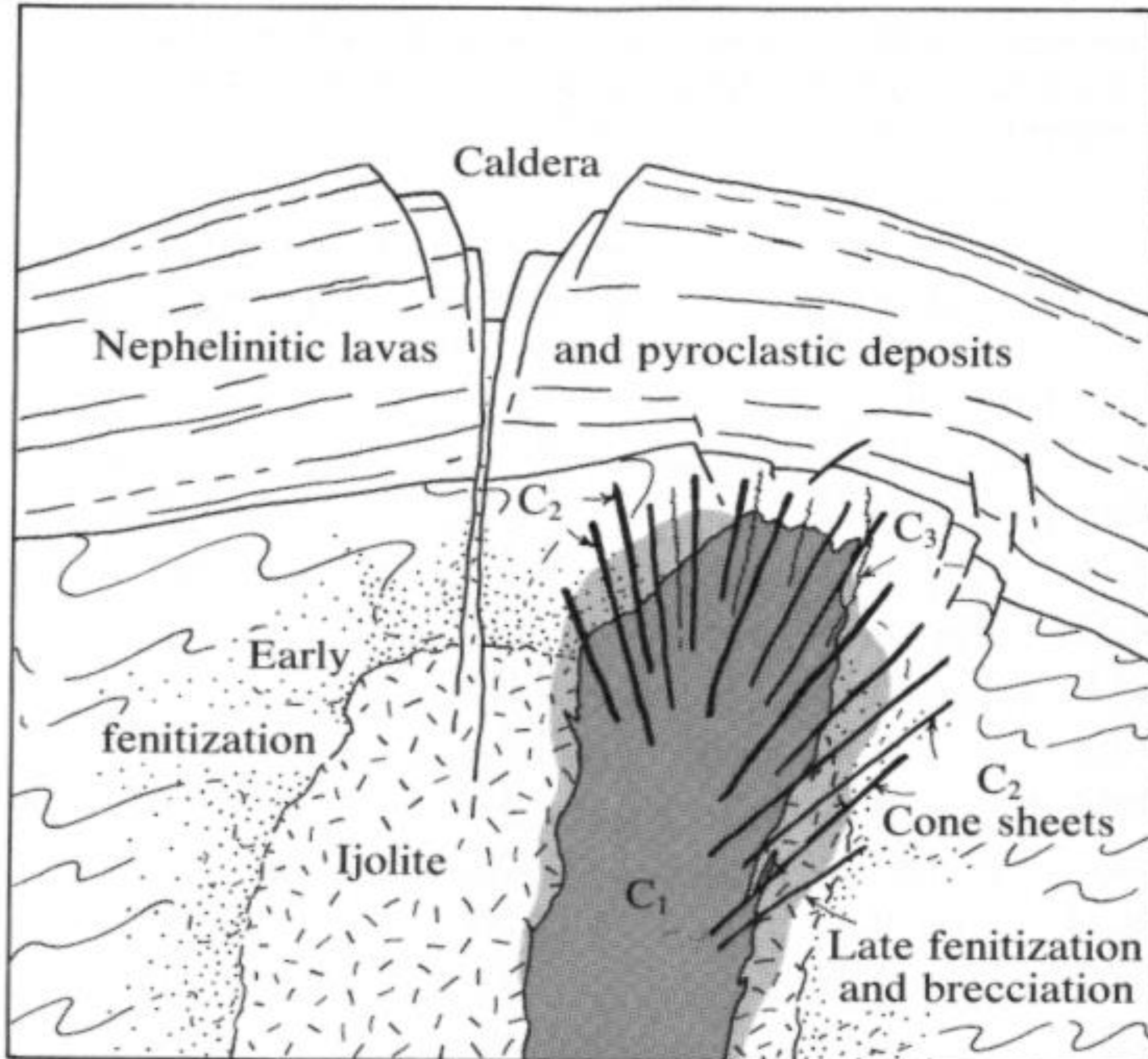
- Belong to alkaline igneous provinces and generally found in stable cratonic regions sometimes with major rift faulting such as the East African Rift Valley

- Not all alkalic rock provinces and complexes have associated carbonatites

- Carbonatitic activity is episodic and seems to have been related temporally and spatially to orogenic events

- Carbonatites often form clusters or provinces within which there may have been several episodes of activity

Best, 1982


Caldera
Nephelinitic lavas
and pyroclastic deposits
C2
C3
Early
fenitization
Ijolite
C1
C2
Cone sheets
Late fenitization
and brecciation

Carbonatites

- Siliceous country rocks may be converted to aegirine-bearing syenites that are termed fenites.
- Zones of fenitization are typically hundreds of meters wide.
- Large volumes of alkali-bearing solutions are given off during cooling.
- Experimental data show that sodium carbonate melts could separate as immiscible liquids from silicate magmas.
- Kjarsgaard and Hamilton 1988 - immiscibility field extends to low alkali compositions form directly as calcite carbonatites

Table 6-2 Comparison of average abundance of trace elements in carbonatite, all igneous rocks, and limestone (in ppm).

Best, 1982

	Carbonatite	Igneous rocks	Limestone
Sc	10	13	1
Co	17	18	0.1
Y	96	20	30
Zr	1120	170	19
Nb	1951	20	0.3
Mo	42	2	0.4
La	516	40	<1
Ce	1505	40	12

Source: After E. W. Heinrich, 1966, *The Geology of Carbonatites* (Chicago: Rand McNally).