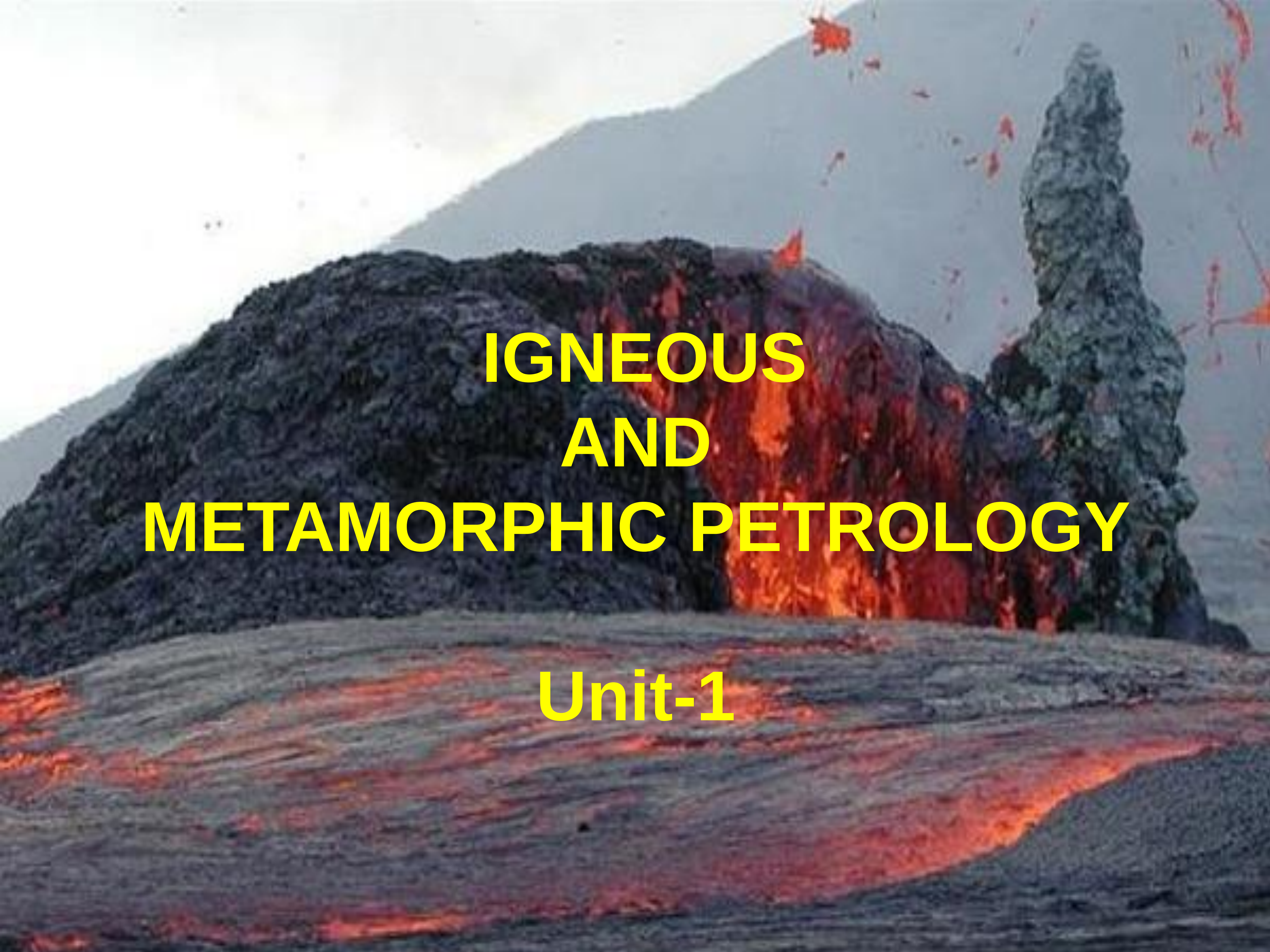


IGNEOUS AND METAMORPHIC PETROLOGY

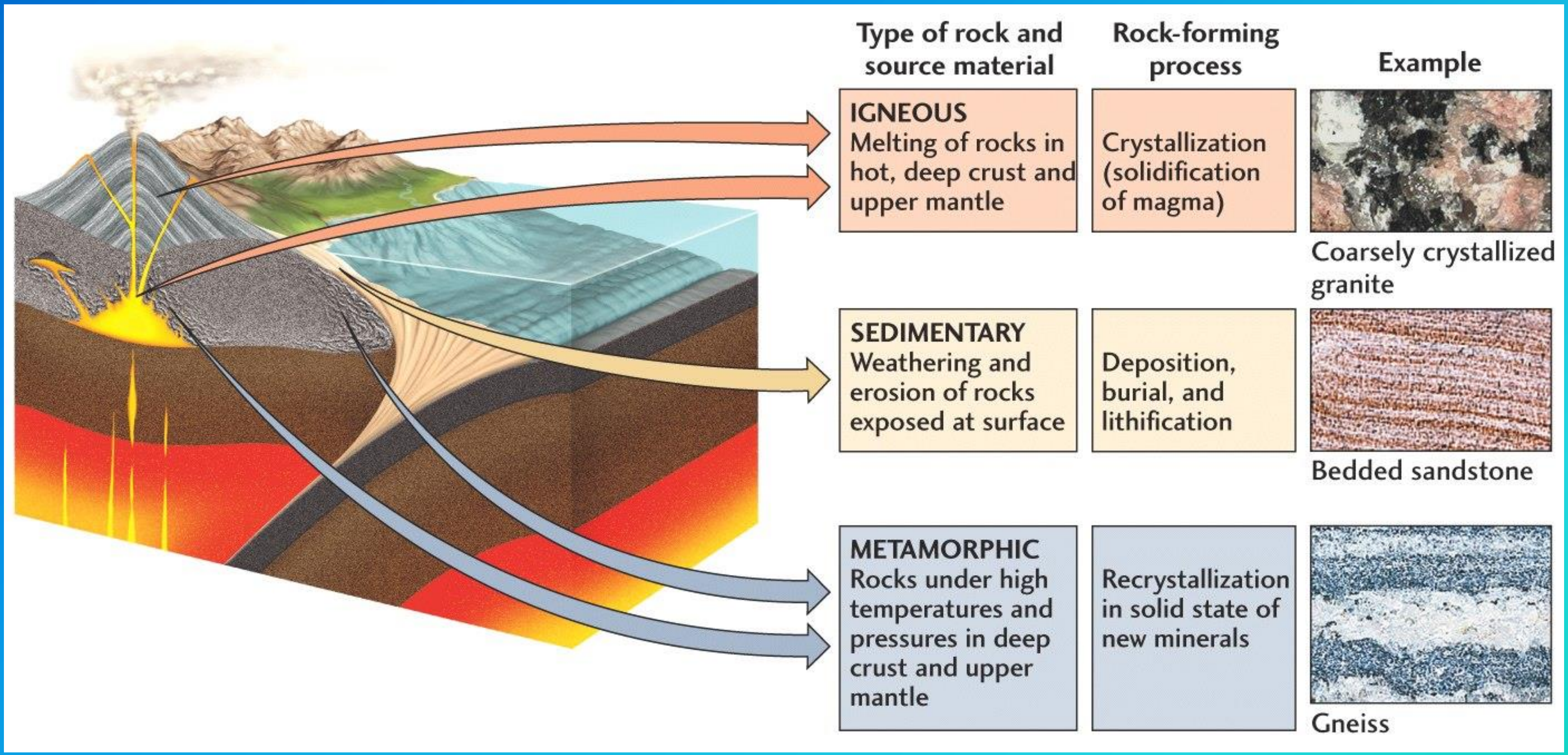
Unit-1

What is a Rock?

Rock is a naturally occurring solid aggregate of one or more minerals

For example, granite, a common rock, is a combination of the minerals quartz and feldspar

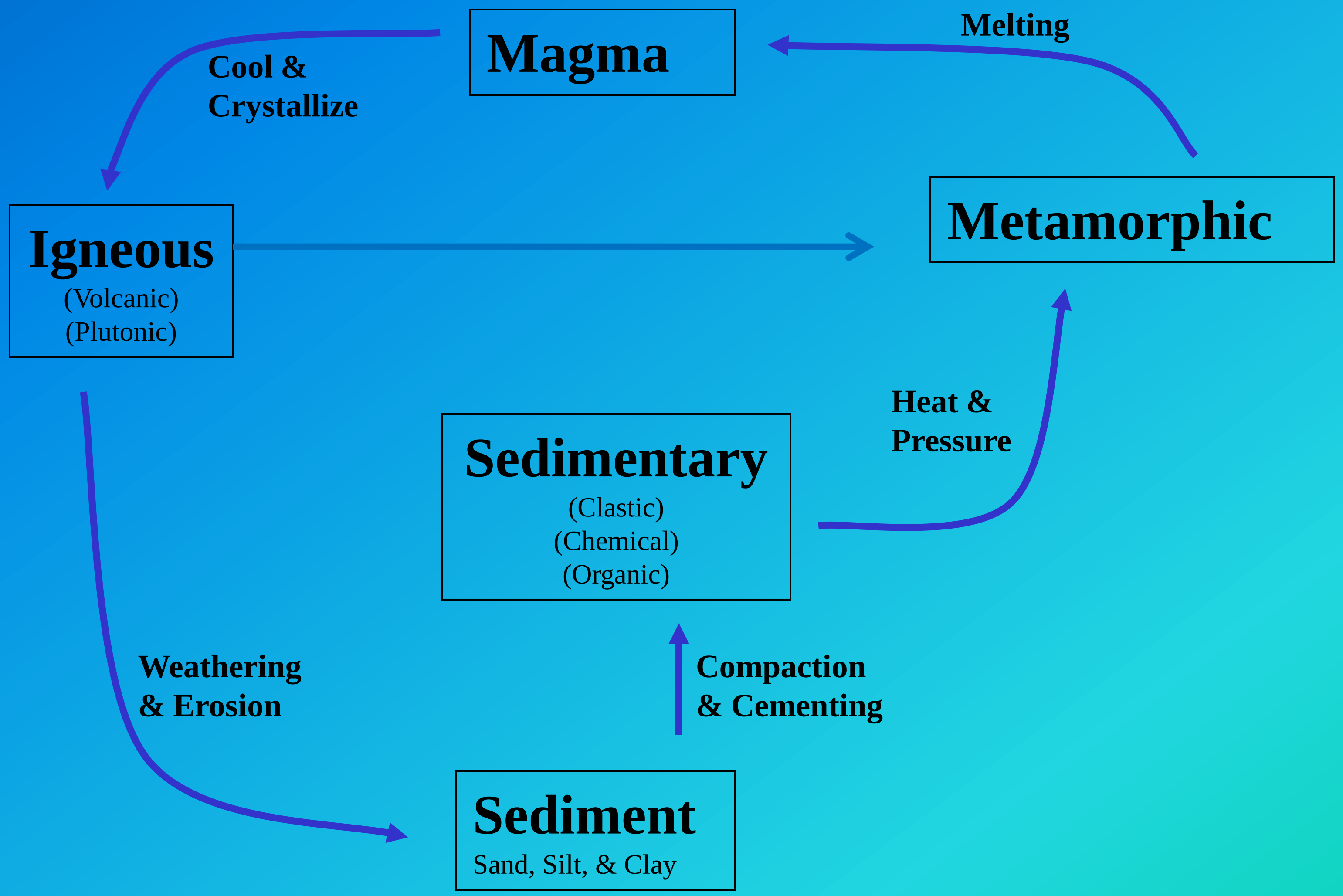
Three Types of Rocks



Igneous rock (derived from the Latin word Ignis means Fire)

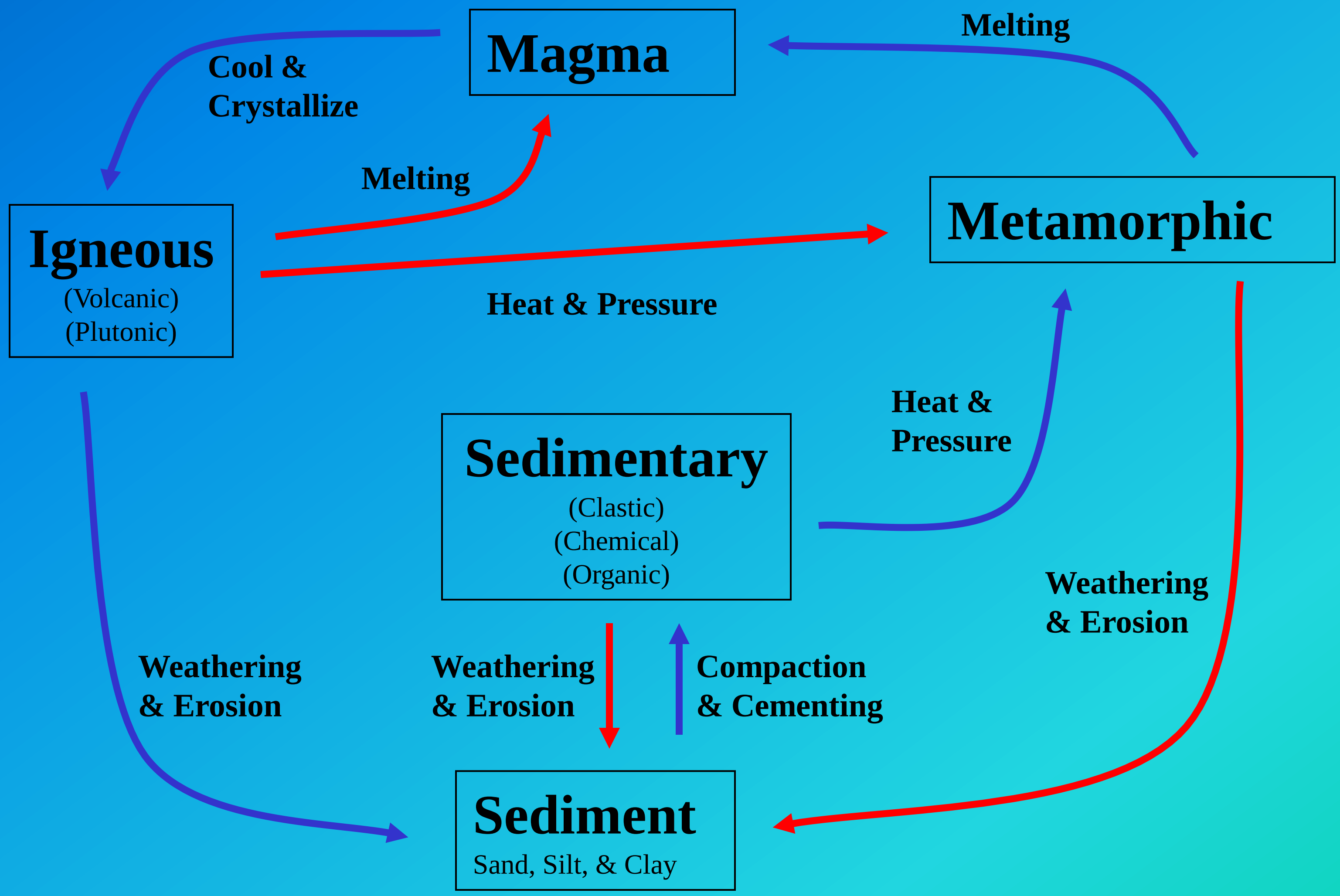

dreamstime.com

Rock Cycle



Magma
Melting
Cool &
Crystallize
Igneous
(Volcanic)
(Plutonic)
Metamorphic
Heat &
Pressure
Sedimentary
(Clastic)
(Chemical)
(Organic)
Weathering
& Erosion
Compaction
& Cementing
Sediment
Sand, Silt, & Clay

Rock Cycle


Magma
Cool &
Crystallize
Melting
Melting
Igneous
(Volcanic)
(Plutonic)
Metamorphic
Heat & Pressure
Heat &
Pressure
Sedimentary
(Clastic)
(Chemical)
(Organic)
Weathering
& Erosion
Weathering
& Erosion
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& Cementing
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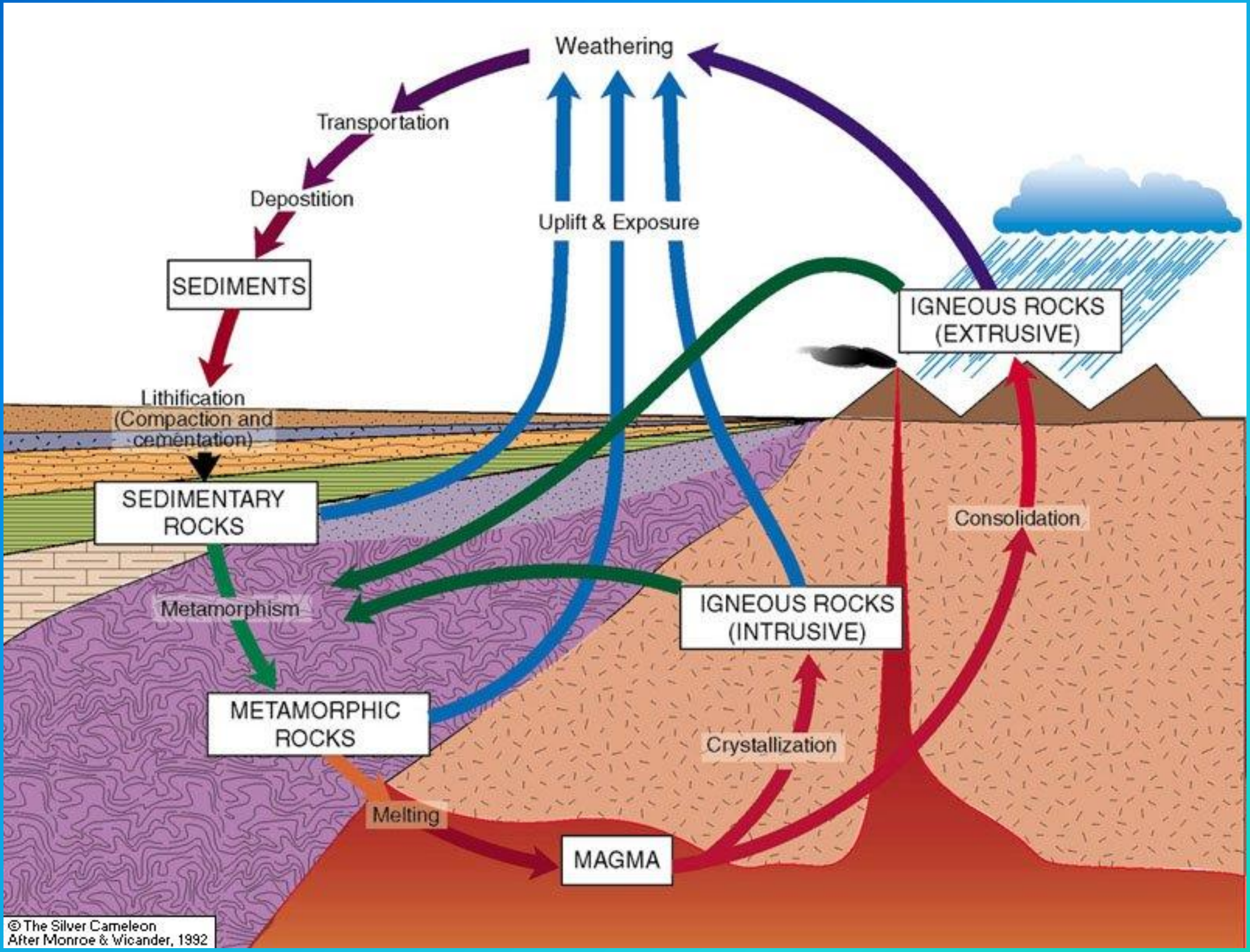
& Erosion
Sediment
Sand, Silt, & Clay

Rock Cycle


Weathering
Transportation
Depostition
SEDIMENTS
Lithification
(Compaction and
cementation)
SEDIMENTARY
ROCKS
Metamorphism
METAMORPHIC
ROCKS
Melting
MAGMA
Uplift & Exposure
IGNEOUS ROCKS
(EXTRUSIVE)
IGNEOUS ROCKS
(INTRUSIVE)
Consolidation
Crystallization
© The Silver Cameleon
After Monroe & Wicander, 1992

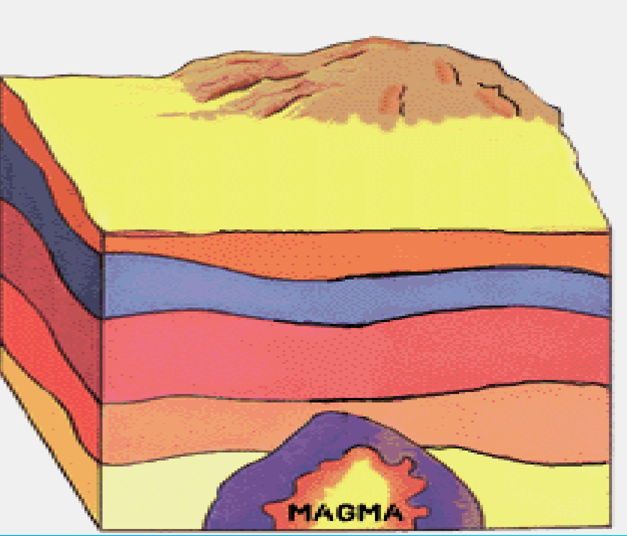
IGNEOUS ROCKS

Definition:

"These are the rocks formed by the solidification of Magma either below surface or above it"

Magma - Hot molten material occurring naturally below the earth surface

Lava – Erupted hot molten material (Magma)



- Magma can exist as a melt **as long as physical and chemical environment** surrounding it remains unchanged
- If there is a change in **temperature and pressure** due to its upward movement – cooling and crystallization takes place.

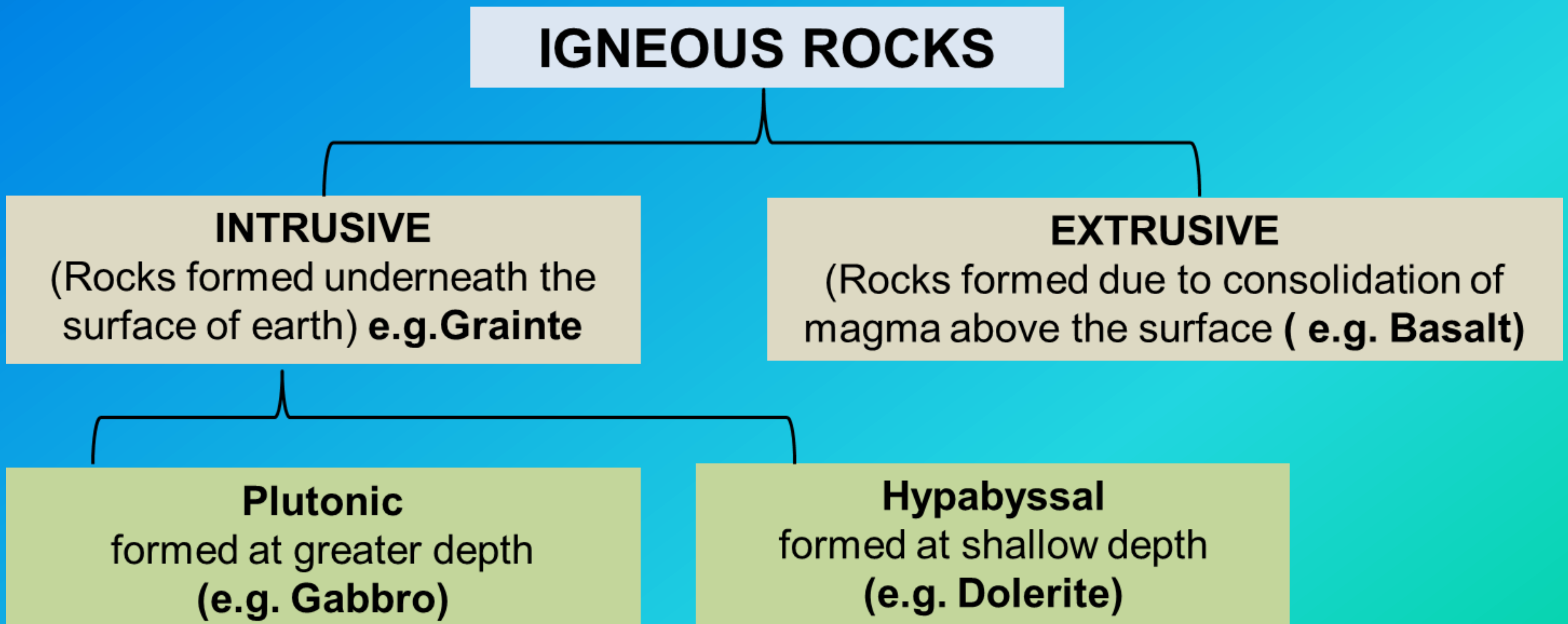
Magma Characteristics:

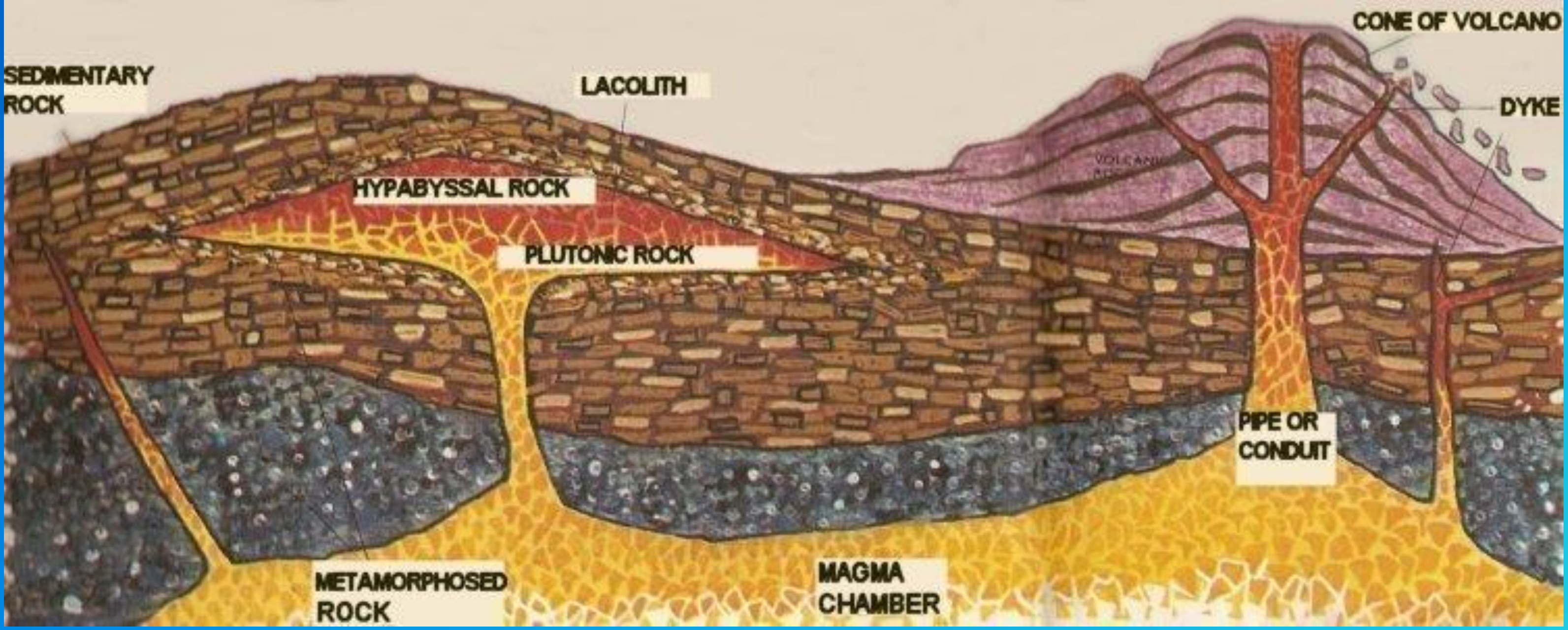
- Rocks are in **hot molten stage**
- Formed at **greater depth**
- Formed due to **high temperature**
    - **Due to rise in temperature with depth**
    - **Radioactive material and related temperature**
- Dominantly of melt with little crystalline or solid fraction and gaseous fraction
- Magma is mobile melt so it is able to move upward and get consolidated.

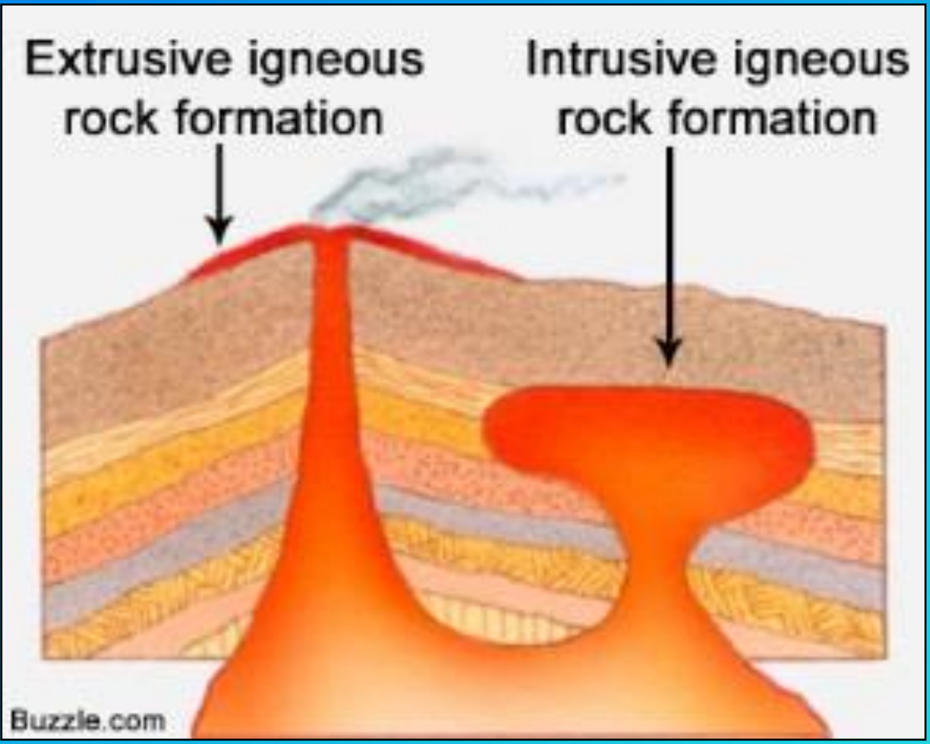
Igneous Rocks

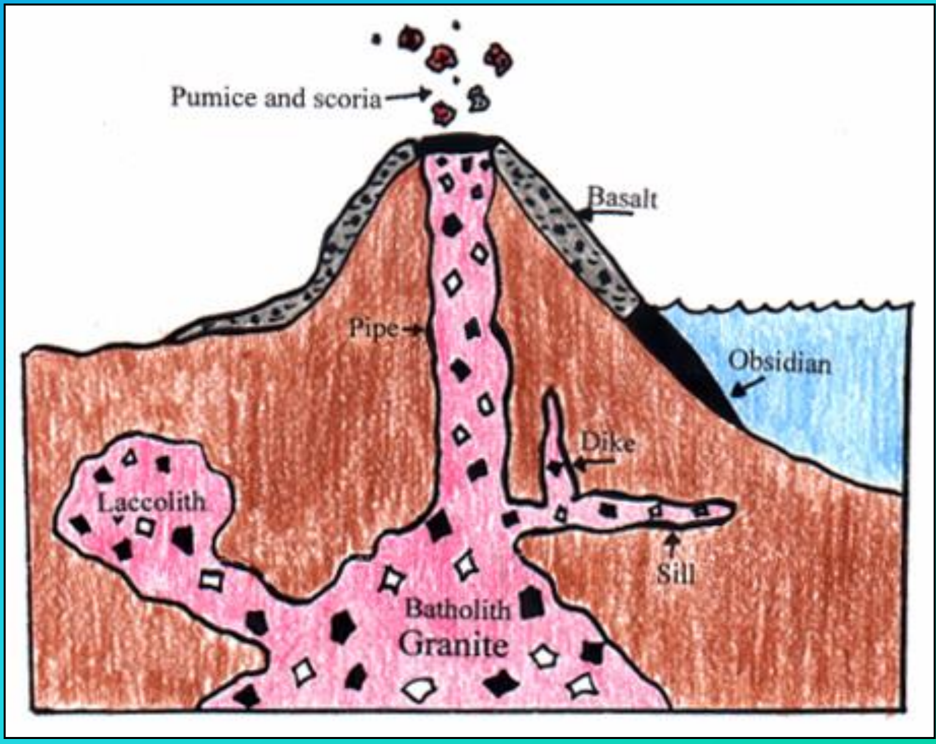
Classifications of Igneous rock;

1) **Intrusive –** forms from magma.
2) **Extrusive –** forms from lava. (Volcanic)




CONE OF VOLCANO
SEDIMENTARY ROCK
LACOLITH
DYKE
HYPABYSSAL ROCK
PLUTONIC ROCK
PIPE OR CONDUIT
METAMORPHOSED ROCK
MAGMA CHAMBER


Extrusive igneous rock formation
Intrusive igneous rock formation
Buzzle.com


Pumice and scoria
Basalt
Pipe
Obsidian
Dike
Laccolith
Sill
Batholith
Granite

Volcanic (extrusive)

- When magma erupts onto the earth's surface, it becomes lava in a volcanic eruption.

- The crystals in the rock don't have much time to form, creating fine-grained rocks with small crystals, such as **basalt**.
- Vesicle are prominent due to release of gases
- Very fast cooling rate because of atmosphere and water contact (sudden chilling)
- So very fine grained or even glassy

Basalt

Obsidian

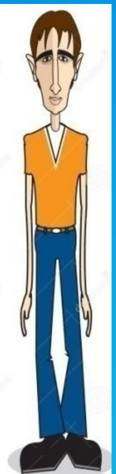
Hypabyssal Rocks : (intrusive)

- Formed at intermediate depth (upto 2 km)
- Rate of cooling is faster than plutonic rock due to low temperature of surrounding rock
- So intermediate grain size, porphyries are common

Dolerite

Plutonic (intrusive)

- When magma cools beneath the surface of the earth it makes intrusive igneous rock (generally 7-10 kms below the surface), such as Granite.
- The magma is insulated by the surrounding rock, and cools slowly.
- This allows the crystals in the rock a long time to form, creating large crystals.
- Exposed at the surface due to erosion of the overlying strata



Granite

Forms of Igneous Rocks

FORMS OF IGNEOUS ROCKS

The forms and shapes attained by the igneous rock as a whole, upon cooling and crystallisations.

Controlling Factors:

- **Structure disposition of the host rock (country rock)**
- **Viscosity of the magma and lava**
- **Composition of the magma and lava**

  Basaltic magma -- SiO_2 45-55 wt%, high in Fe, Mg, Ca, low in K, Na
  Andesitic magma -- SiO_2 55-65 wt%, intermediate. in Fe, Mg, Ca, Na, K
  Rhyolitic magma -- SiO_2 65-75%, low in Fe, Mg, Ca, high in K, Na

- **Environment in which the emplacement take place**

Intrusive igneous body = pluton =

when magma intrudes into and solidifies in the crust.

- 2 types: **Concordant & Discordant Forms**

- **A: Concordant:**
- Boundaries of pluton parallel to layers in country rock.
  - **sills & laccoliths**

A: concordant features: intrusion runs parallel to bedding

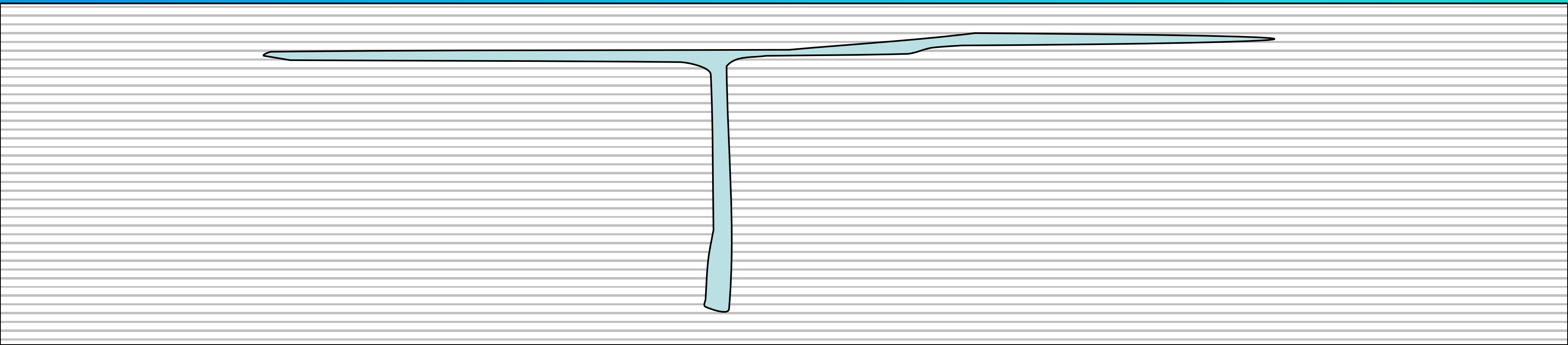
- 1. sill:

➢ Concordant bodies - Parallel to the structure of country rock

➢ Thickness is much smaller than length and width

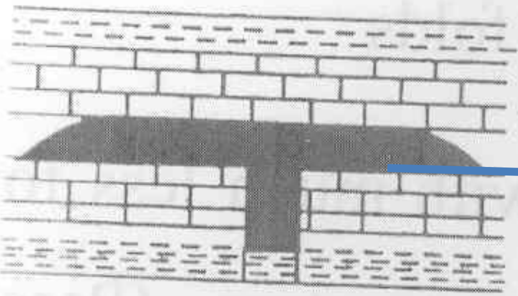
➢ Thinning out at over margins/ends

➢ Core is coarse grained, fine at the margins

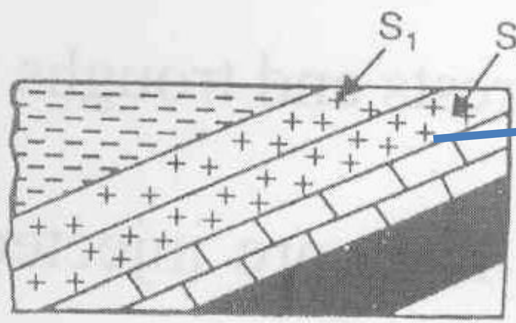


Sills are commonly subdivided into following types:

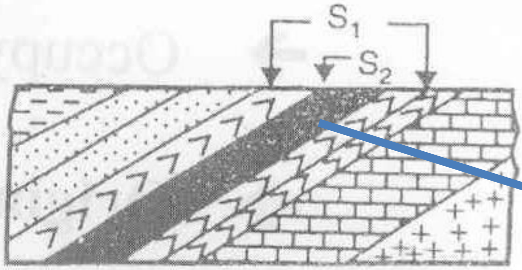
a. **Simple Sills**	:	Formed of a single intrusion of magma or Single sill
b. **Multiple Sills**	**:**	Number of sills of same composition
c. **Composite Sills**	:	Number of sills with different composition
d. **Differential Sills**	:	Large Magma sill with well developed differentiated layers
e. **Interformational Sheets**:		Injected along the plane of Unconformity



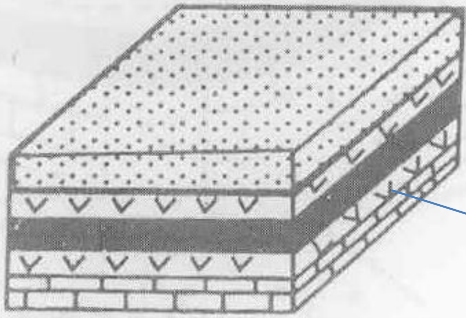
A - Simple Sill



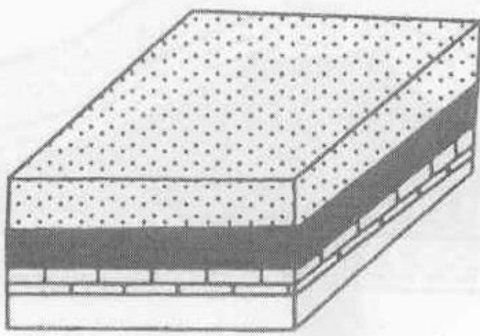
B - Multiple Sill (S_1, S_2)



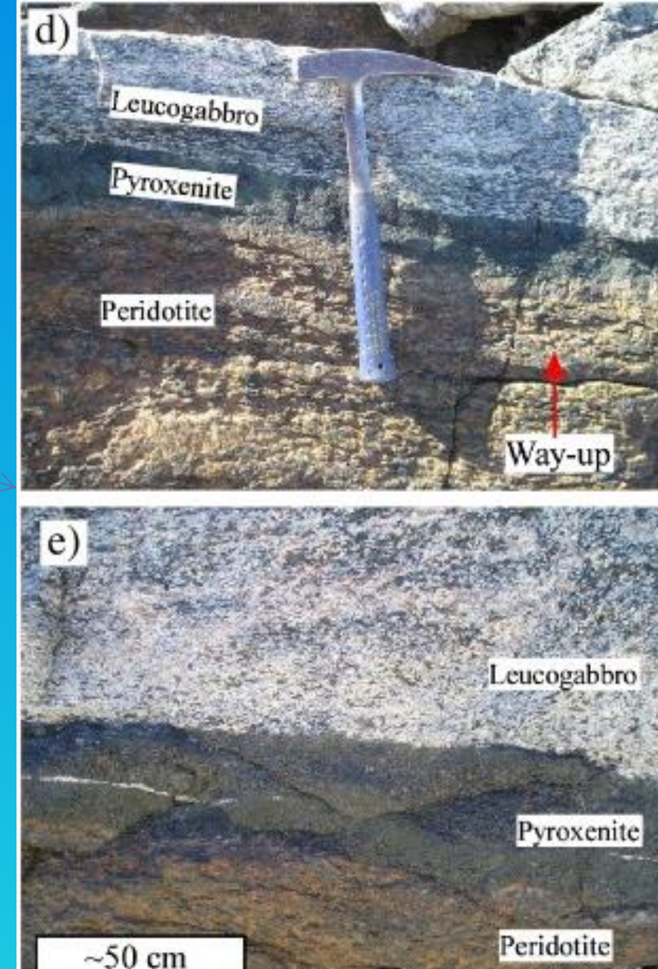
C - Composite Sill (S_1, S_2)



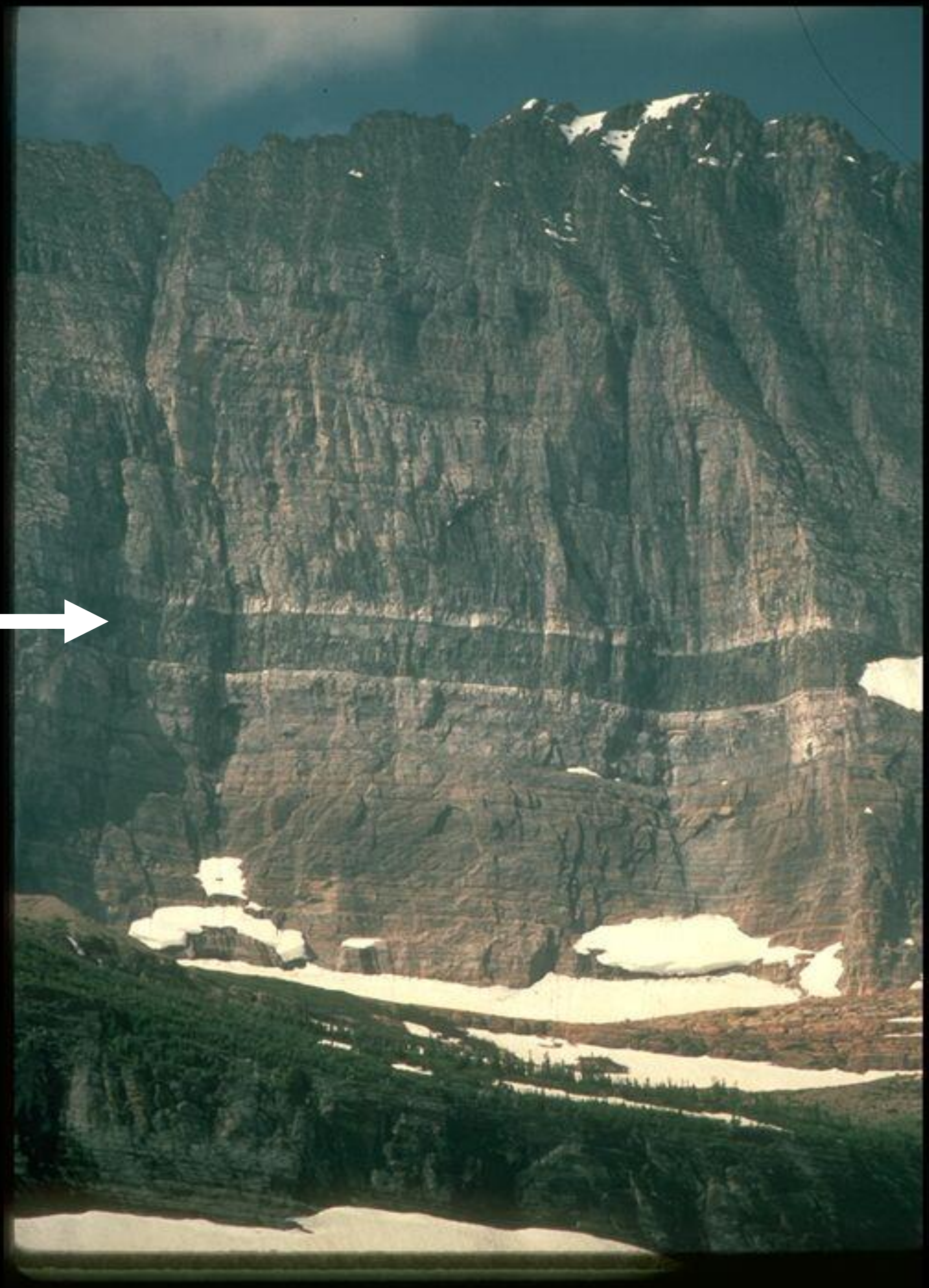
D - Differentiated Sills



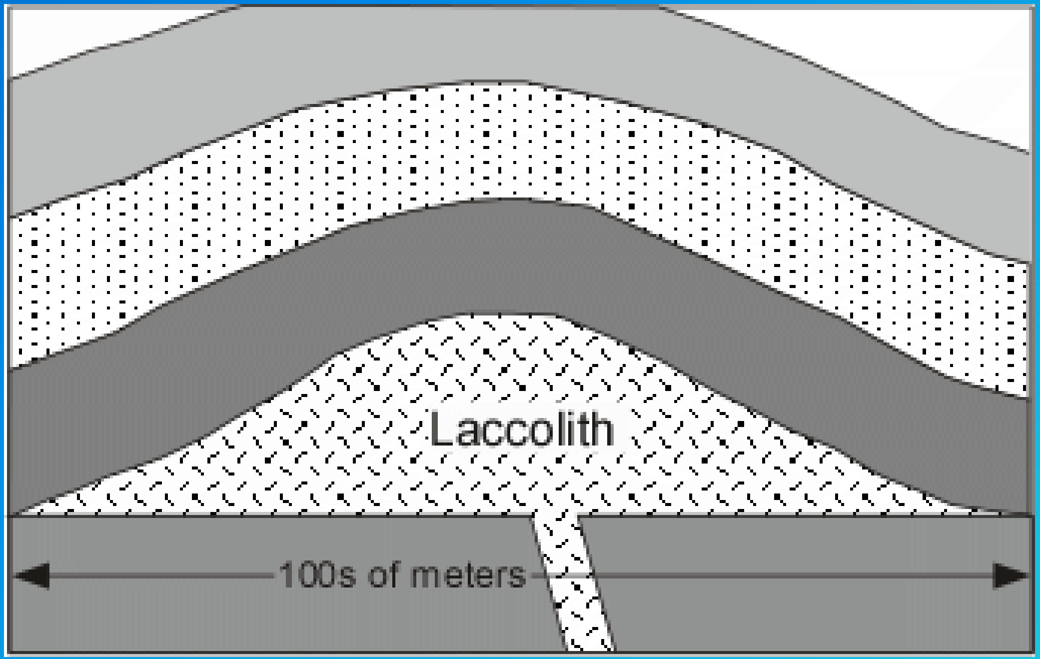
E - Interformational Sills



Sill:



LACCOLITHS: It is a concordant body, with flat bottom and convex upward. It is dome shaped.



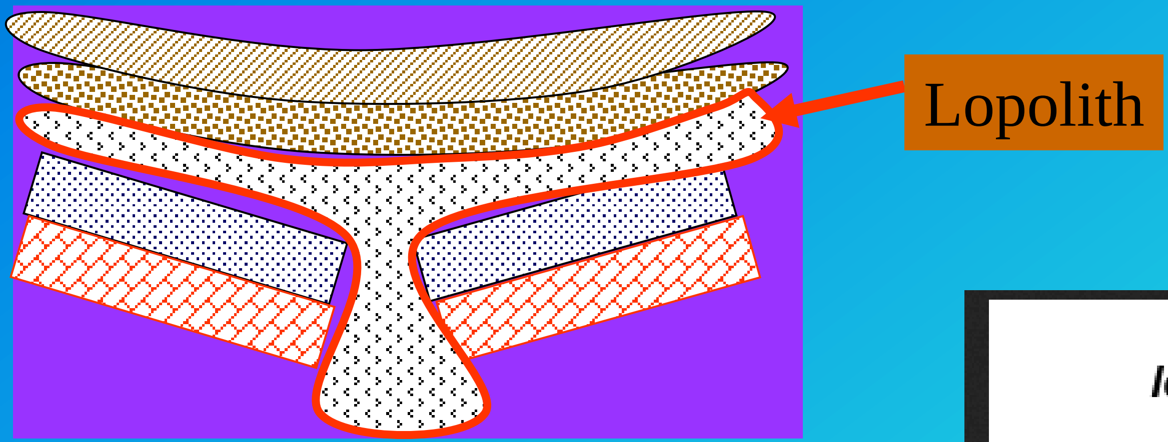
- When viscous magma is injected rapidly along the bedding, as it cannot spreads it pushes up the overlying layers and keep on piling up.

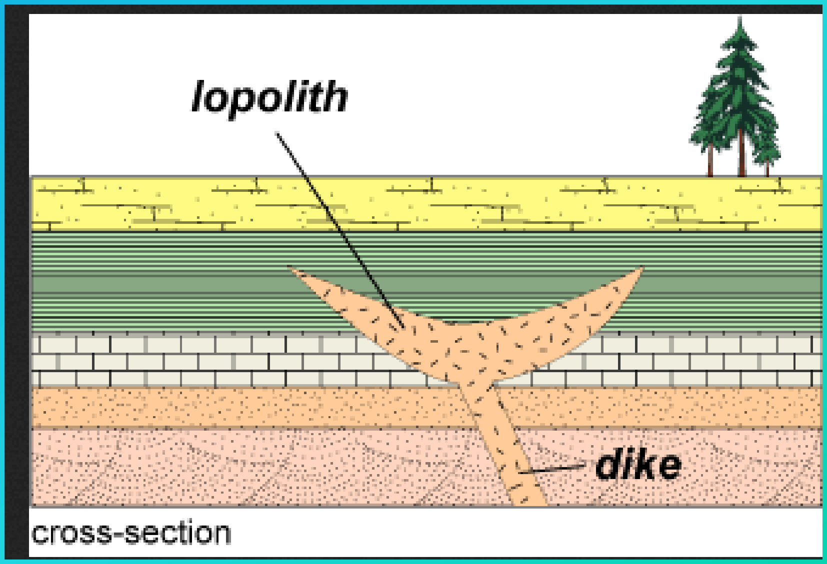
- It causes folding of the overlying rock layers.

Laccolith : concordant

LOPOLITHS:

These are basin or **saucer-shaped** concordant bodies with lenticular shape and are centrally sunken like a basin or sauser.

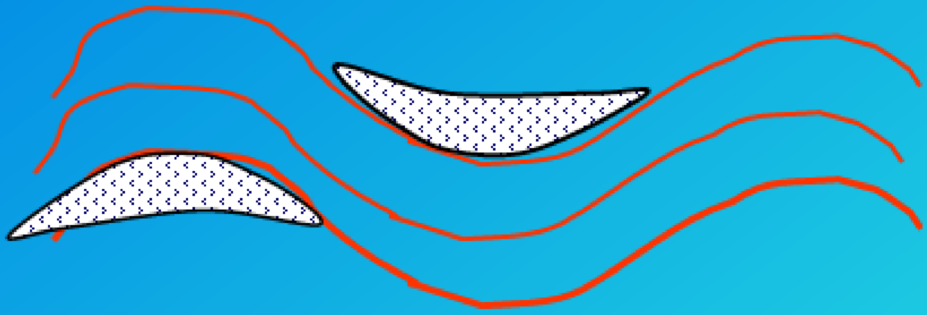


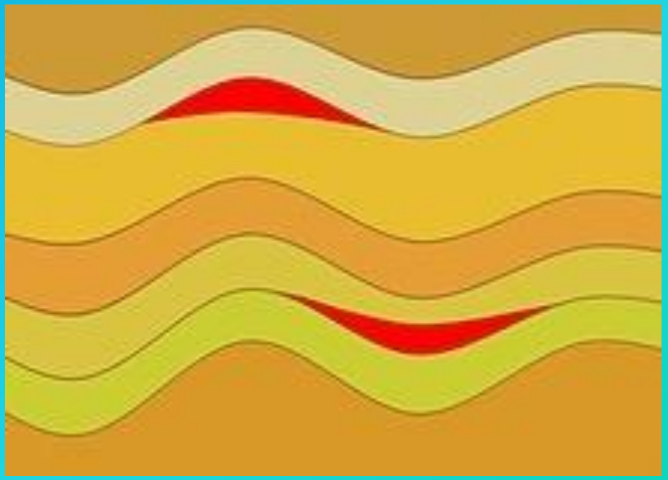


Special Type of Sills

Phacoliths:

- These are concordant, **small sized intrusive** that occupy positions in the **troughs and crests** of bends called folds.
- In outline, these bodies are doubly convex and appear crescents or **half-moon shaped in cross-section.**
- As regards their origin, it is thought that when magma is **injected into a folded sequence of rocks,** it passes to the crests and troughs almost passively

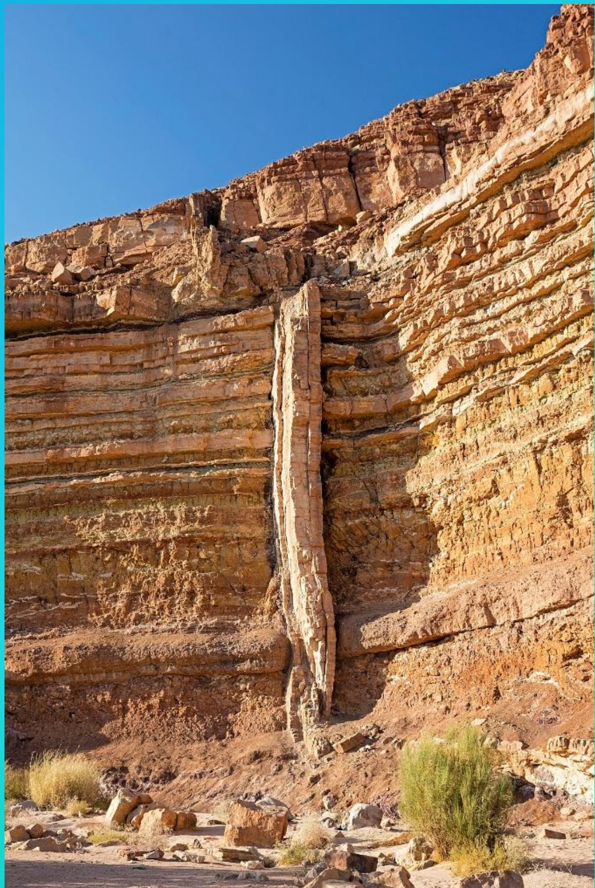




- **B: Discordant:**
  - Boundaries of intrusion cut across layering of country rock.
  - **Dikes, pipes, stocks/batholiths**

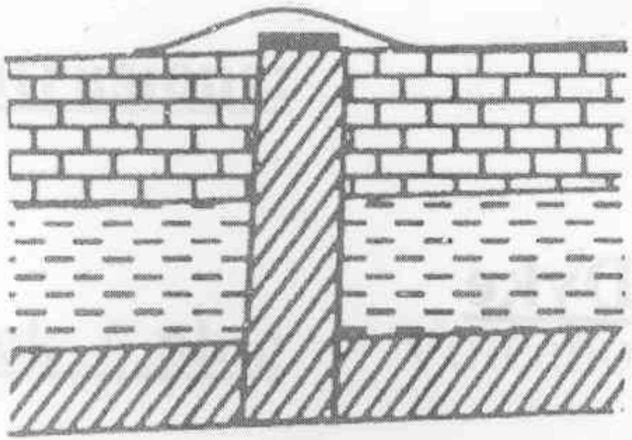
Dykes (Dikes)

- Defined as Columnar bodies of Igneous rocks
- Cut across the bedding plane/unconformities/cleavage plane/any structure plane.
- Intrusion into the pre existing fracture
- They generally occur in groups and sets (Dyke set**)**

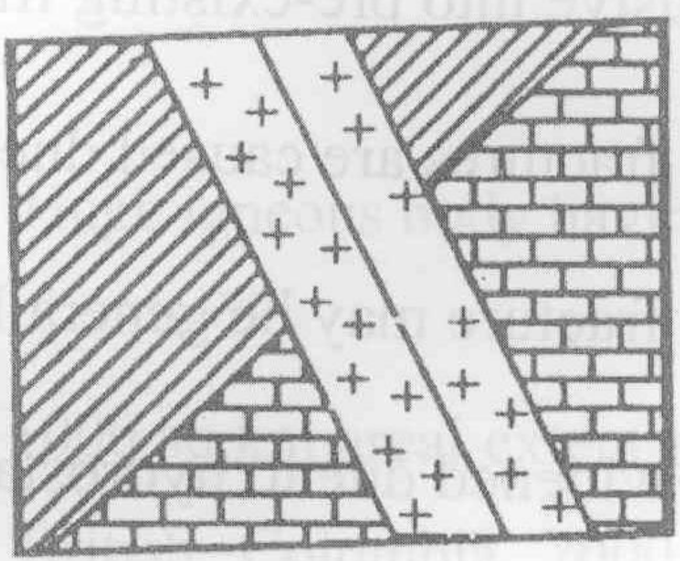


Types of Dykes

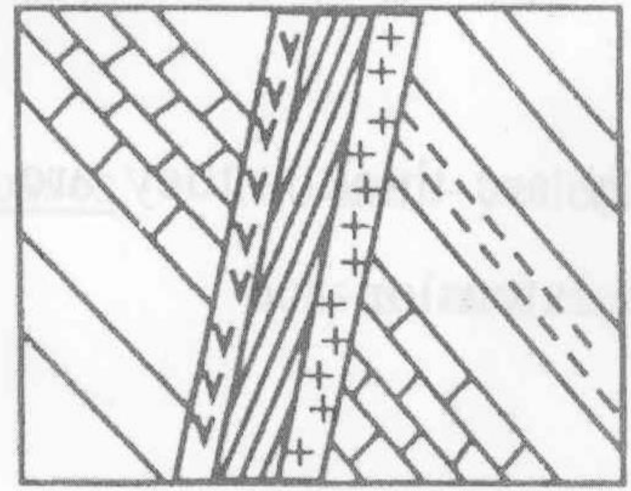
- Simple dykes
- Multiple dykes
- Composite dykes
- Differential dykes
- Cone Sheets
- Ring Dyke



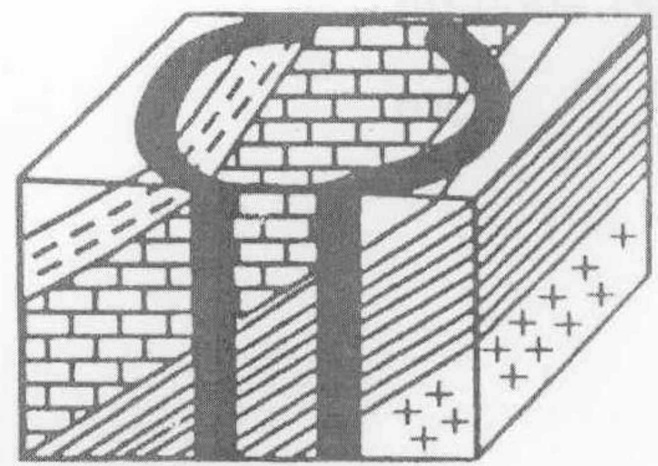
A. Simple



B. Multiple



C. Composite



D. Ring dyke

Composite dykes

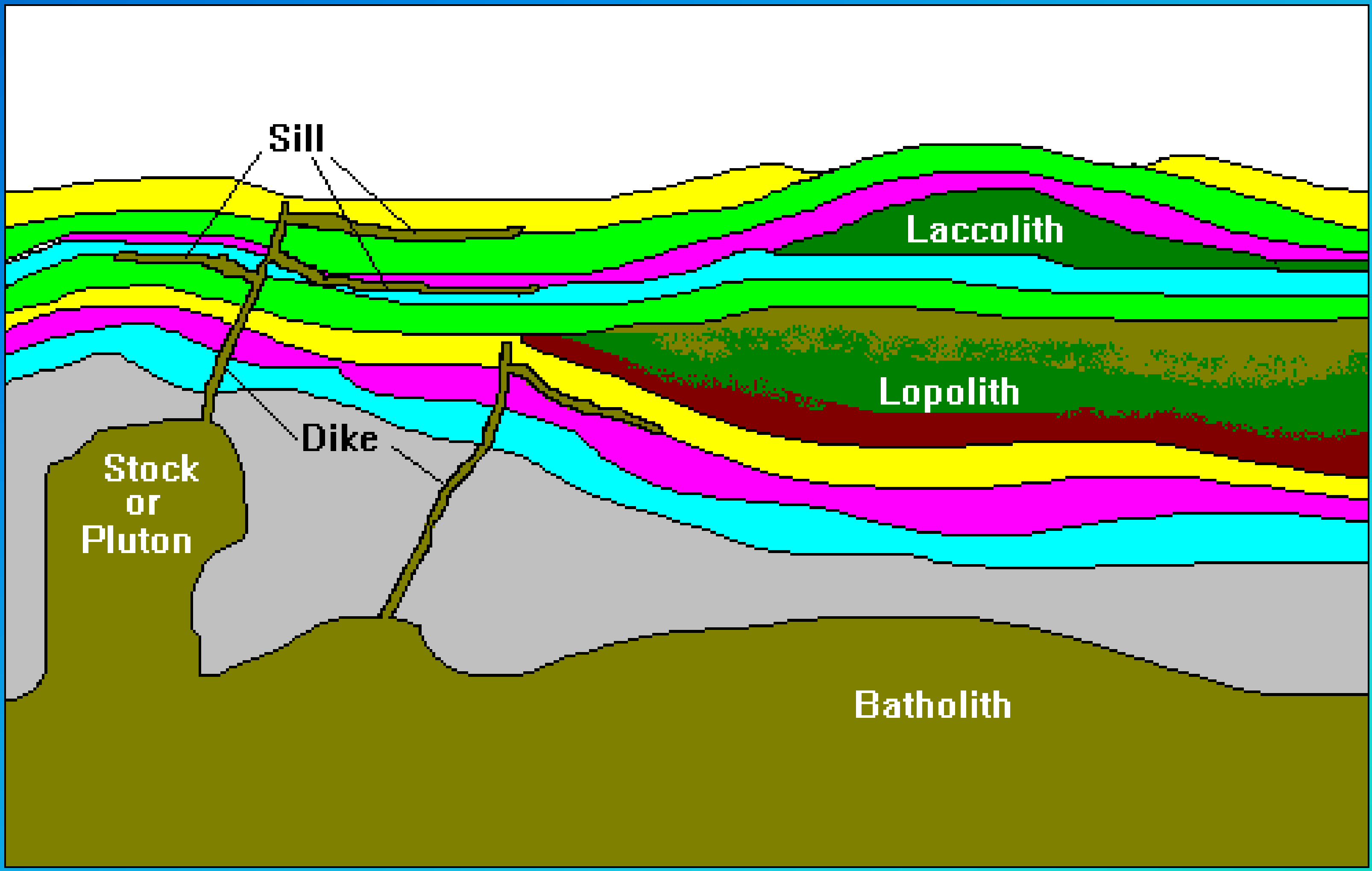
Other Igneous Intrusions

Volconic neck / plug - Volcano mouth closed by successive igneous intrusion

Batholiths - Huge igneous areal extent **e.g. Costa Rica** Brithish Colombia 2000 km long with 40-90 km wide batholith

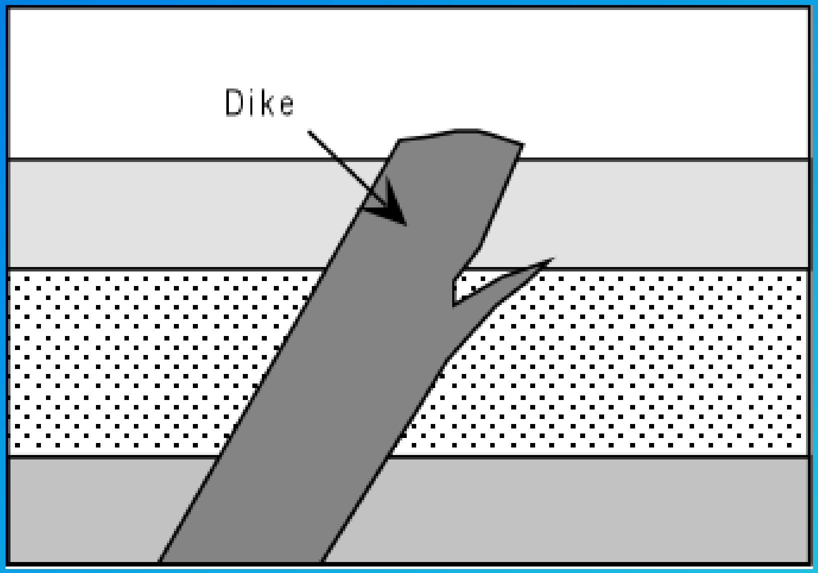
Stocks / Bosses - <100 km - called stock (irregular) / bosses (non circular)

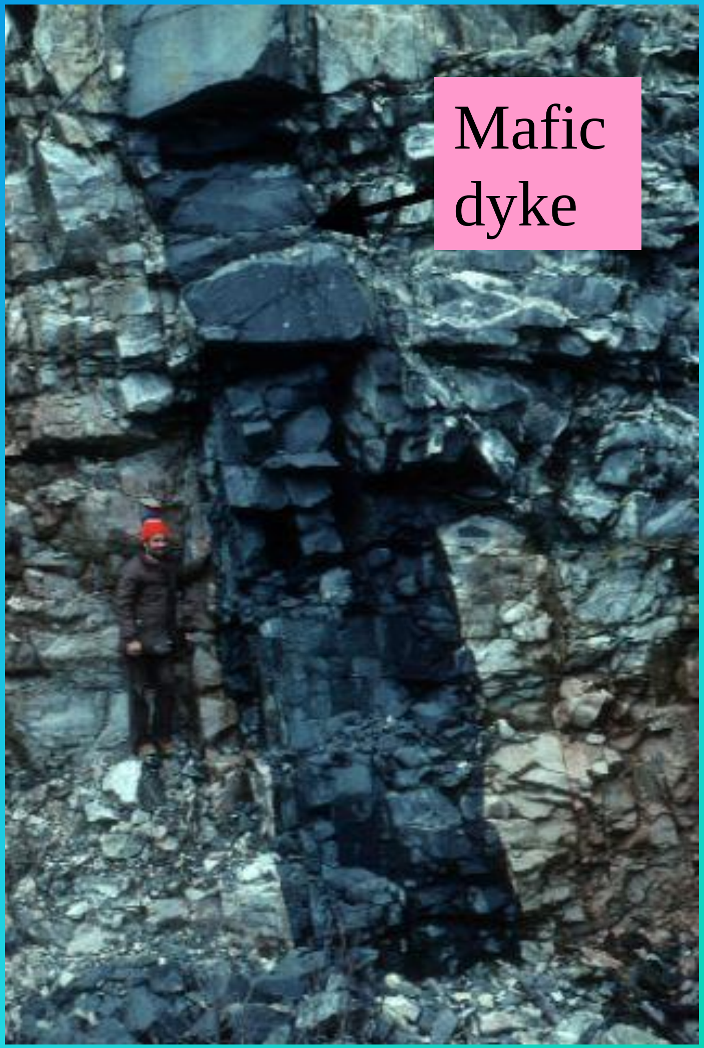
Tongues and Appopysis - Minor projection of igneous batholith into roof rock



Sill
Laccolith
Lopolith
Dike
Stock
or
Pluton
Batholith

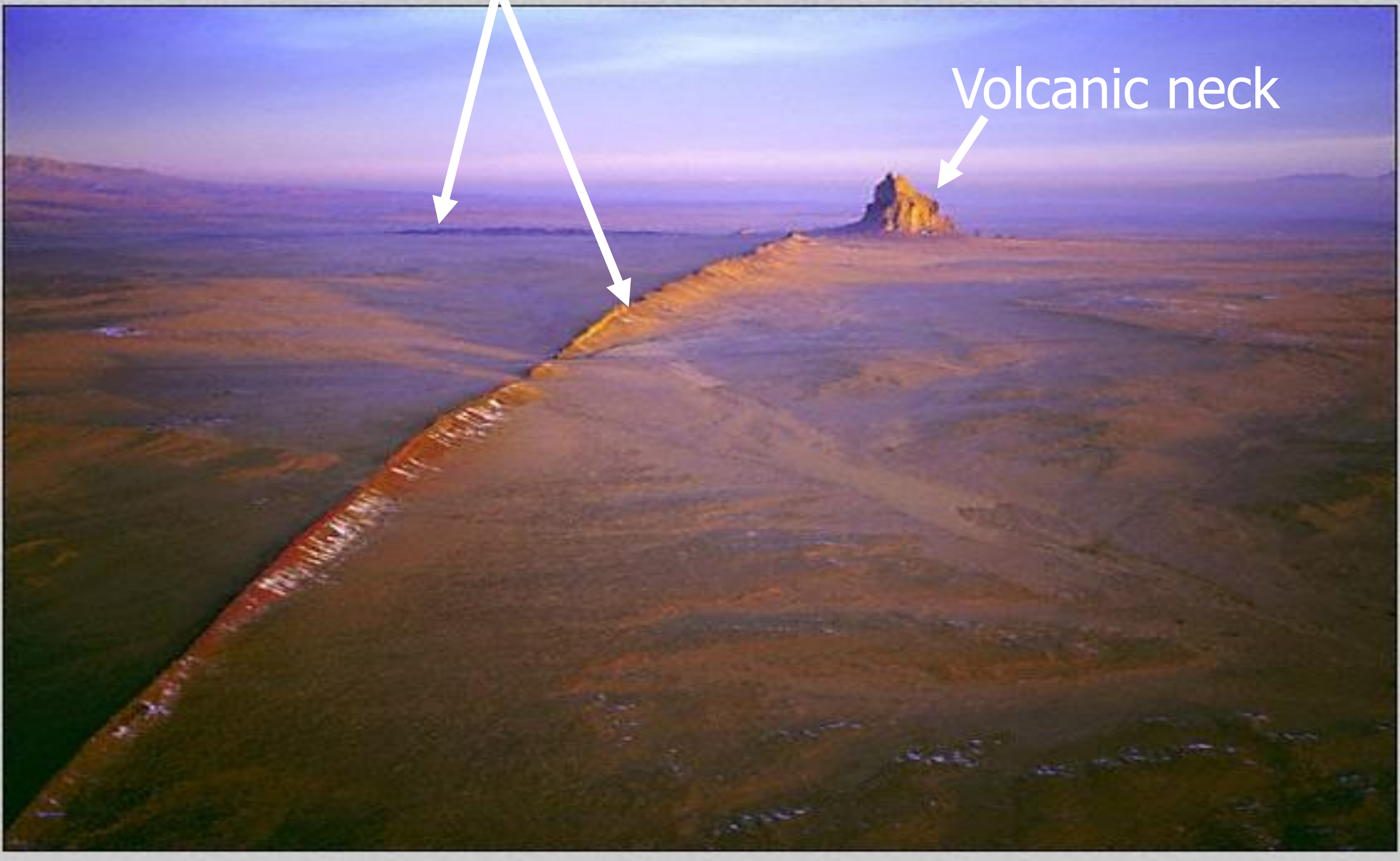
- Quartz-Dolerite dykes of Midland valley of Scotland are about 50-60 km long and upto 30m thick. Few places some dykes are very short upto few meters and as thin as few cm.



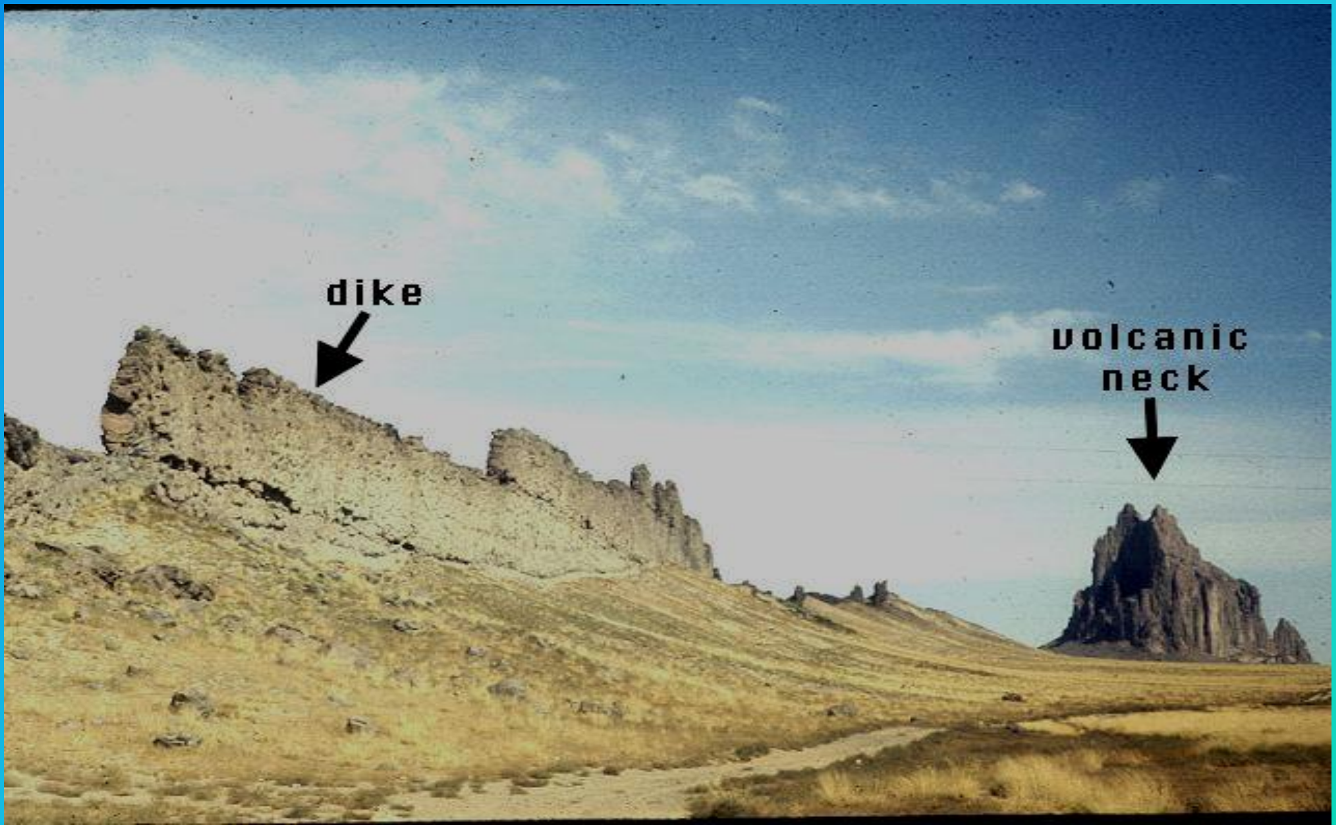


Dike: discordant

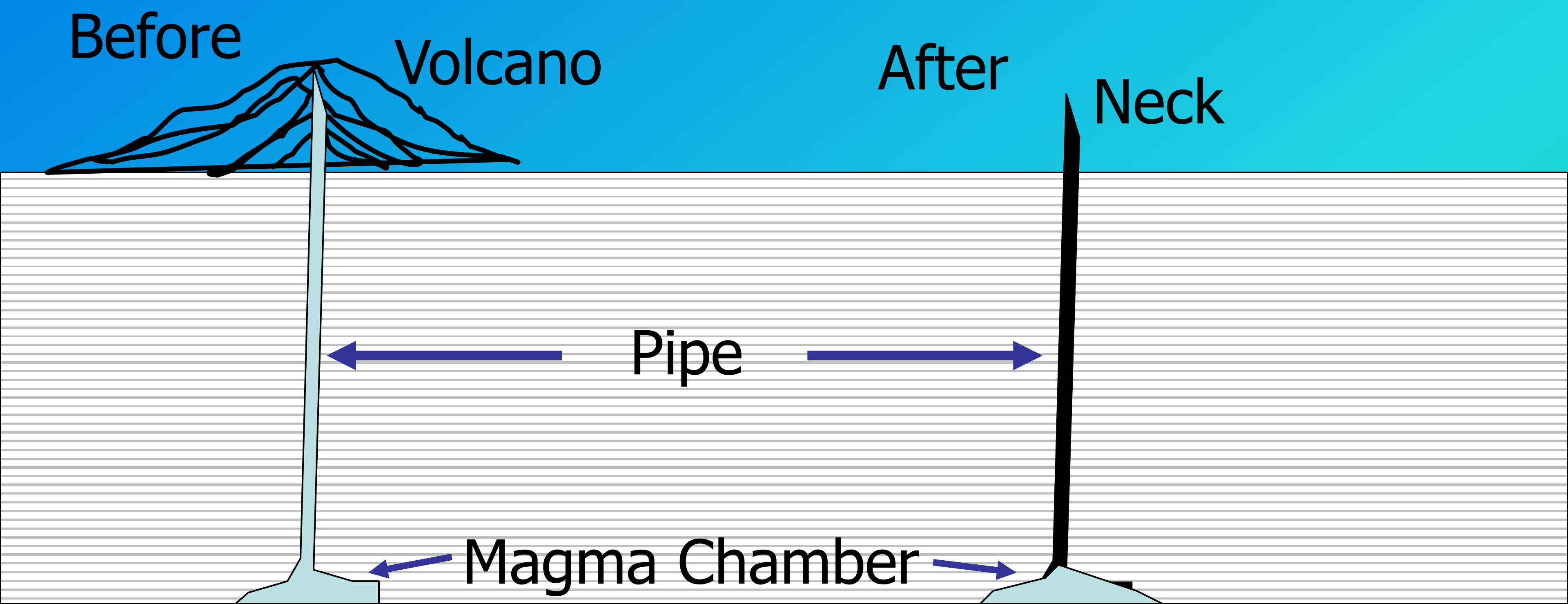
Dike: discordant



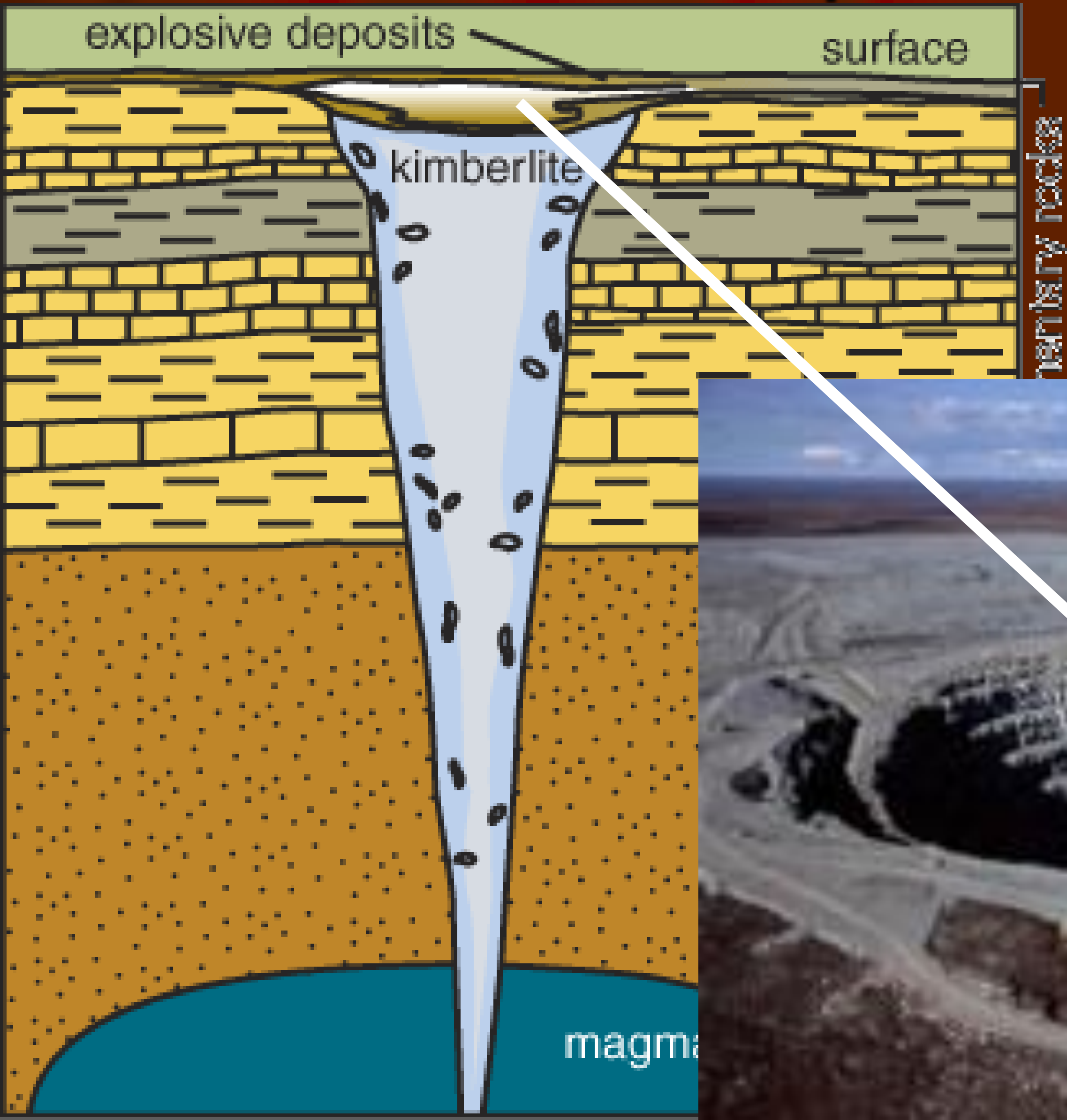
VOLCANIC NECK or VOLCANIC PLUGS: It is cylindrical conduit that fed magma upward to a volcanic vent or it is a conduit of the ancient volcano. Vary in diameter from a few 100s of m to a kilometer or more. These are filled up with crystalline rocks. Shape-circular, elliptical or irregular.



- **2. Volcanic Pipe:** solid lava conduit from magma chamber to surface
  - Mined for diamonds in northern Canada.

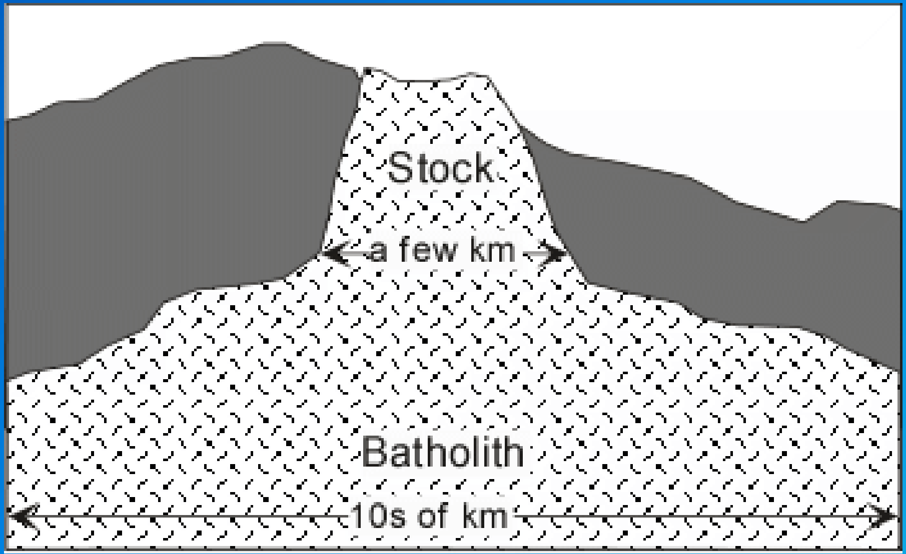


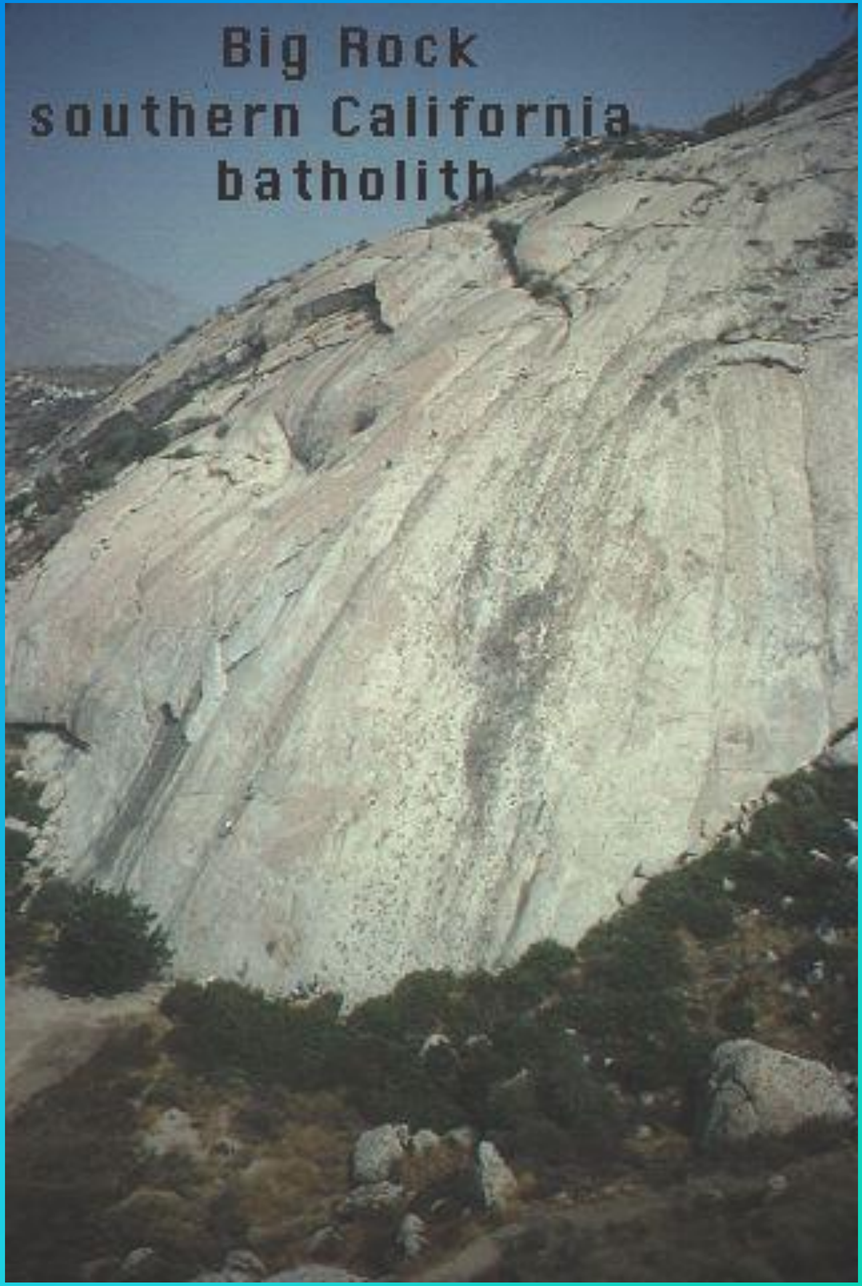
Volcanic Pipe: discordant



BATHOLITHS: are the largest kind of plutons, irregular in shape and occupies large area.

- Their side sloping away from each other which makes them larger and large downwards extending to greater depth
- Their occurrence is commonly associated with the mountain-building process
- These are either granites or granodiorites in composition

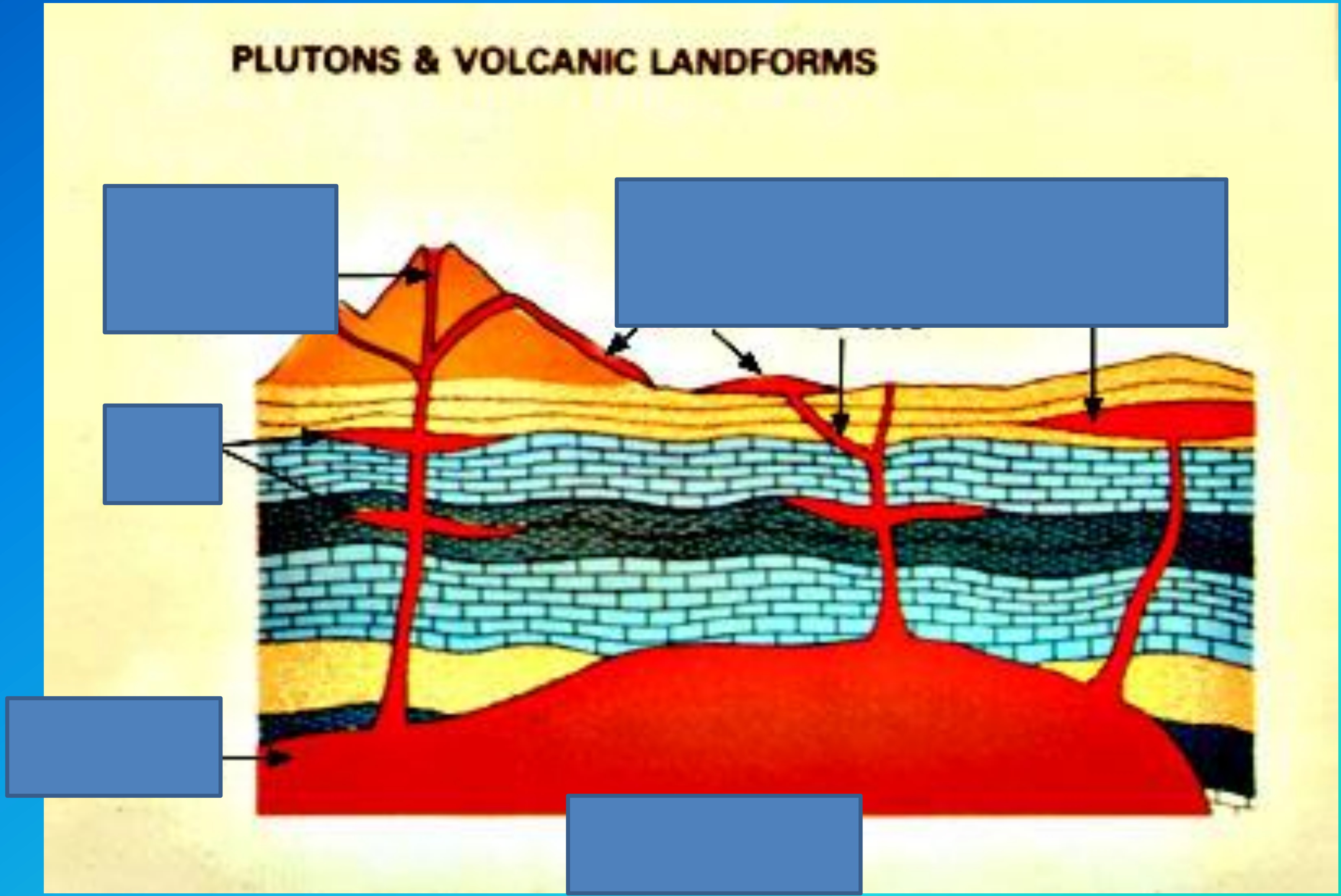


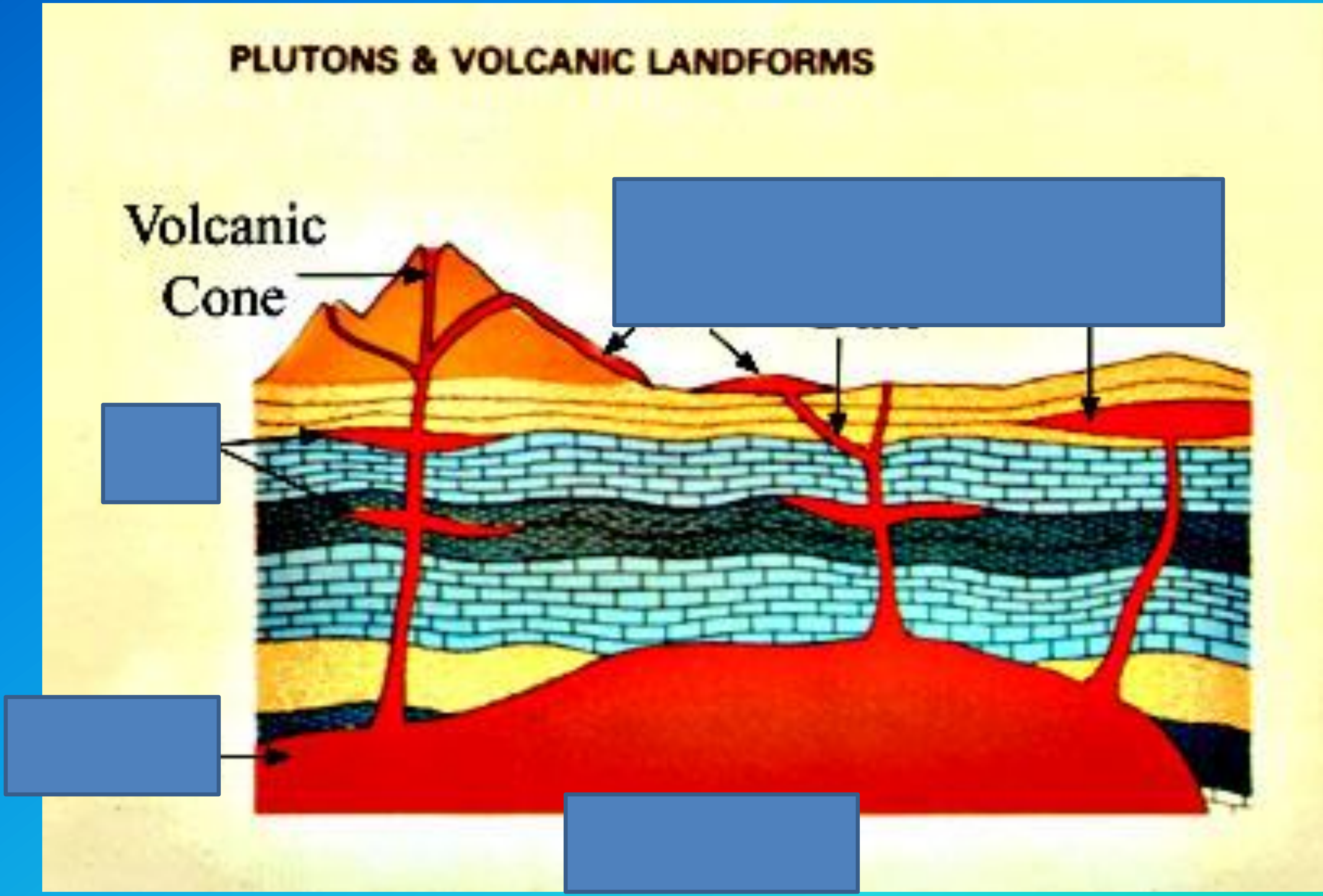


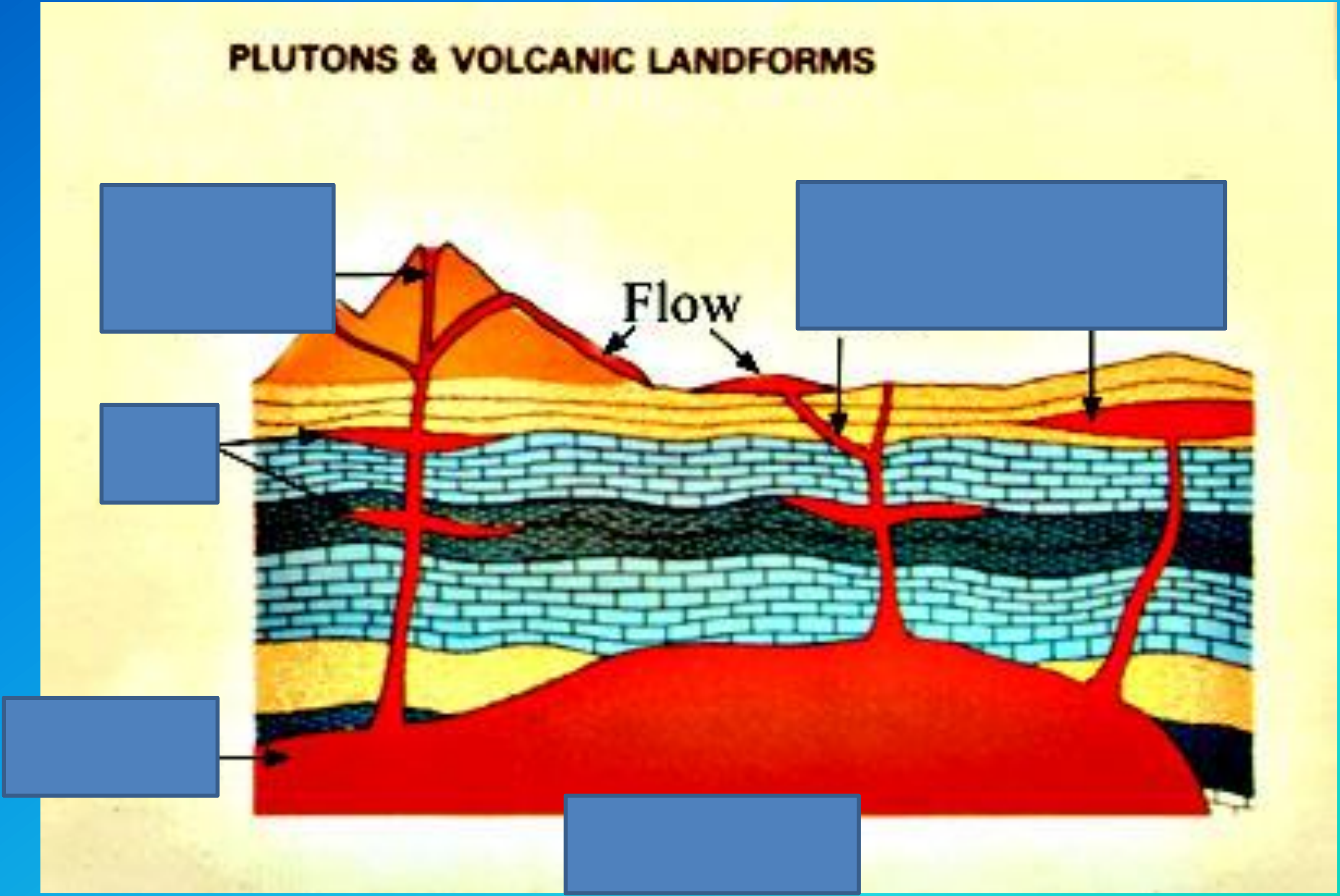
<u>Stocks:</u> ***Are smaller irregular bodies with 10 km in maximum dimension, and are associated with batholiths.***

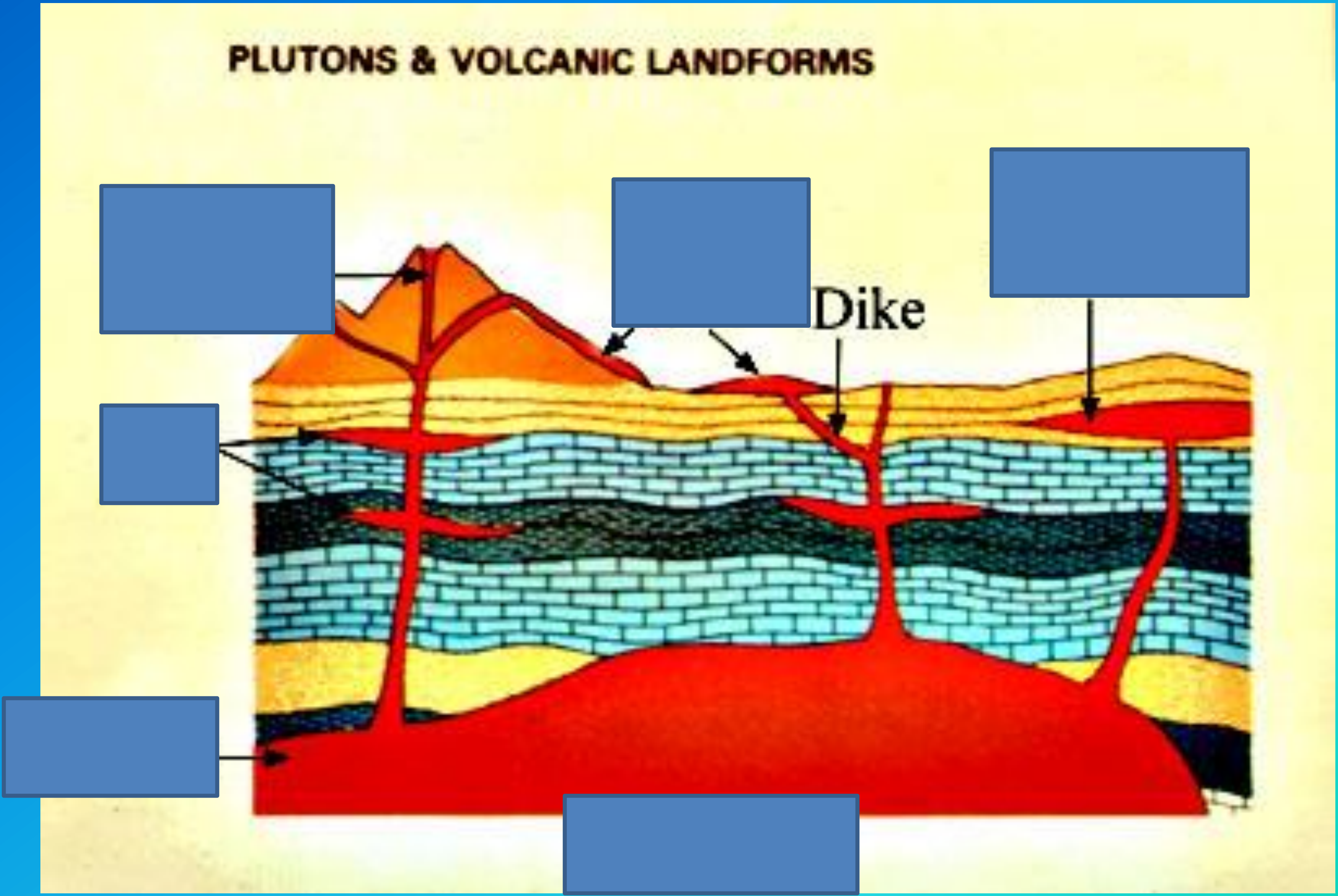
Batholith: discordant

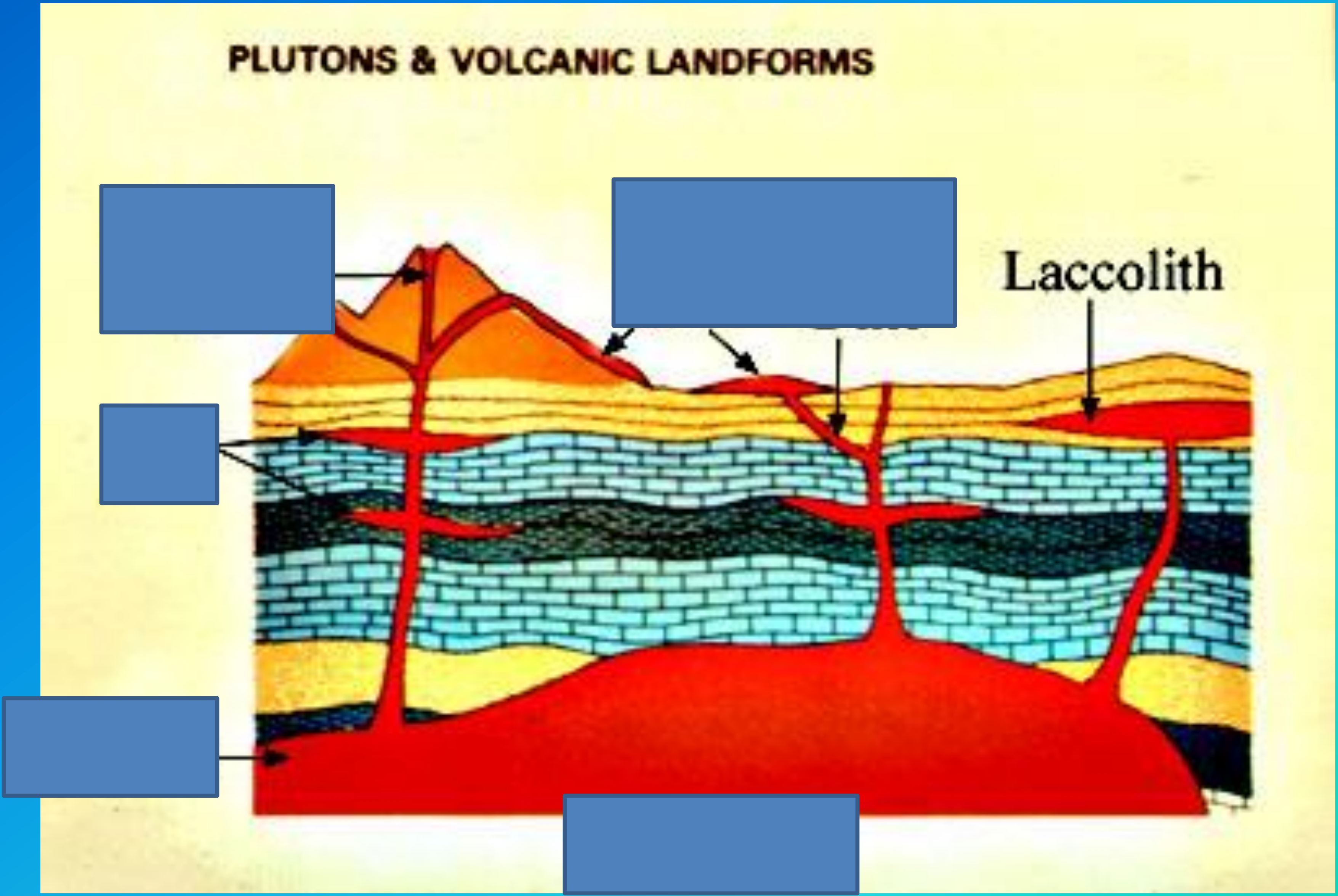
Batholith: discordant

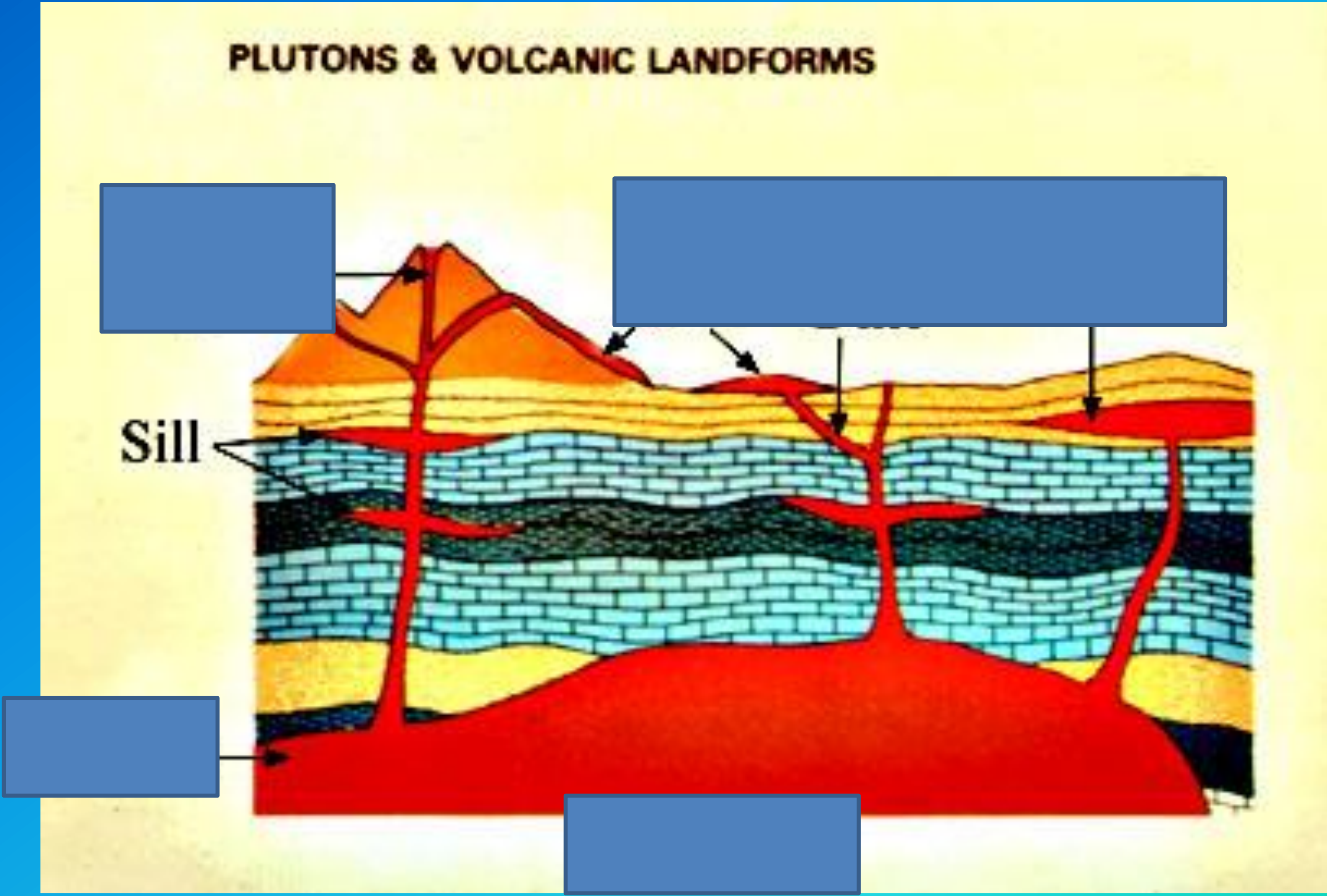

PLUTONS & VOLCANIC LANDFORMS


PLUTONS & VOLCANIC LANDFORMS
Volcanic Cone

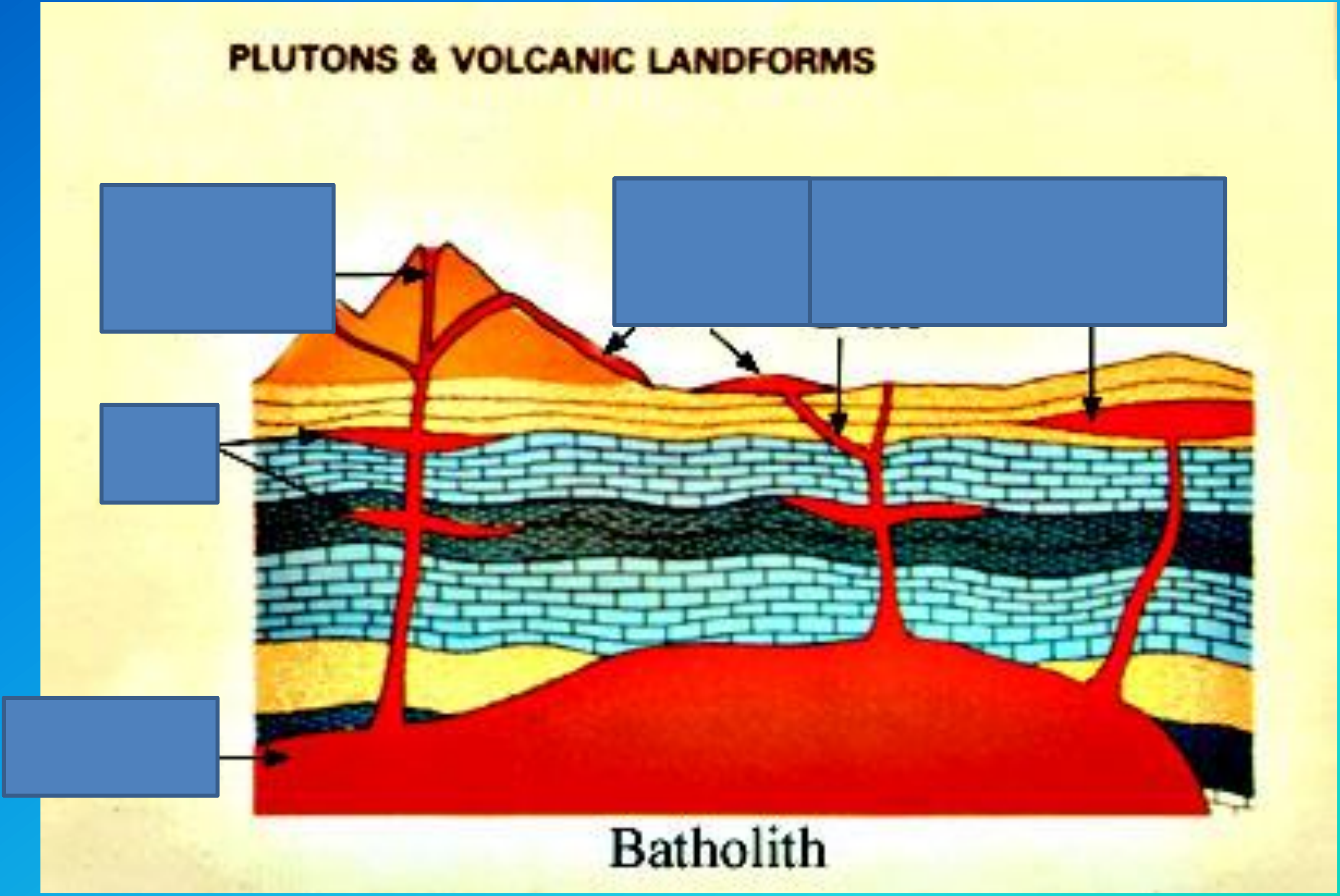

PLUTONS & VOLCANIC LANDFORMS
Flow

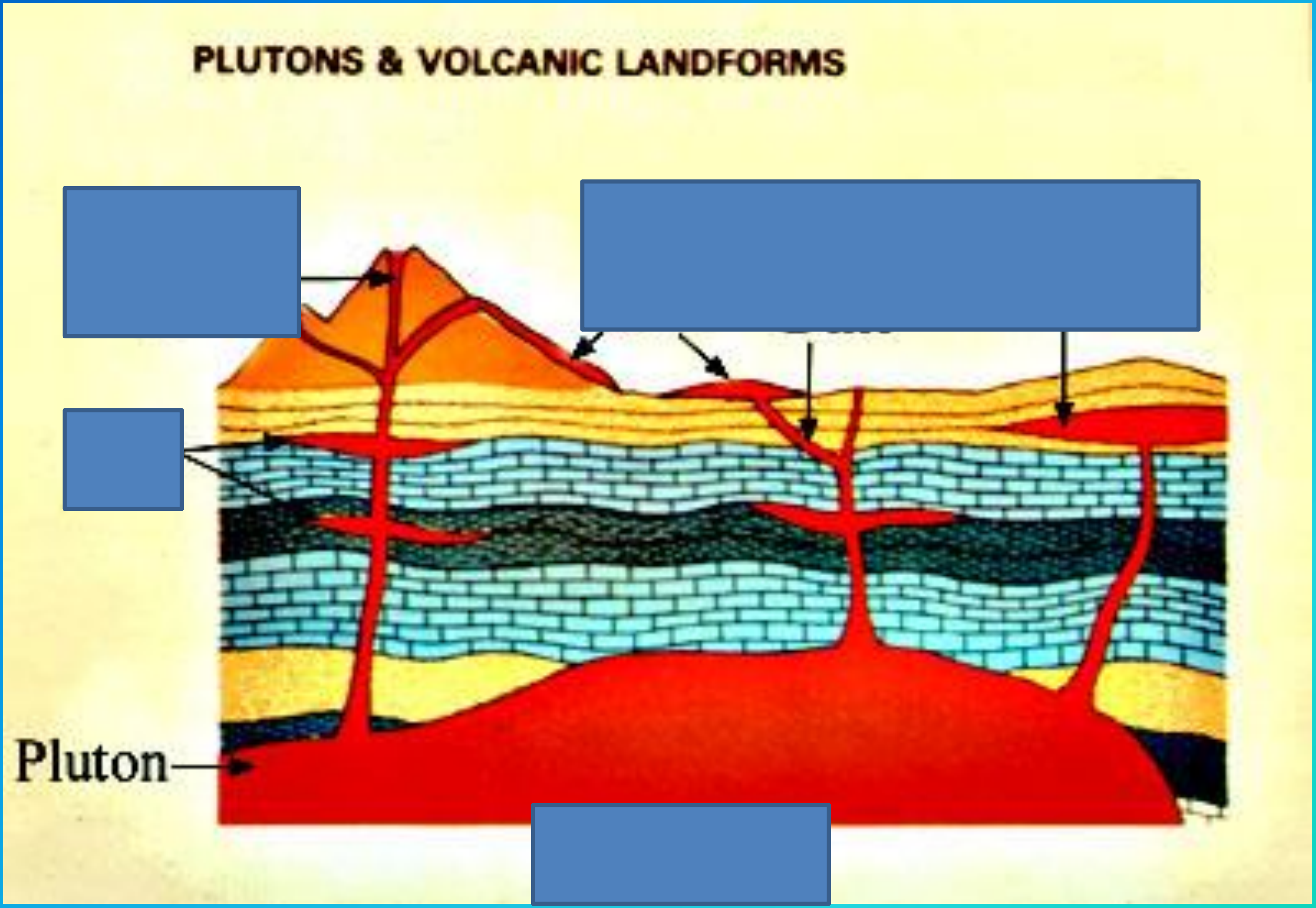

PLUTONS & VOLCANIC LANDFORMS
Dike

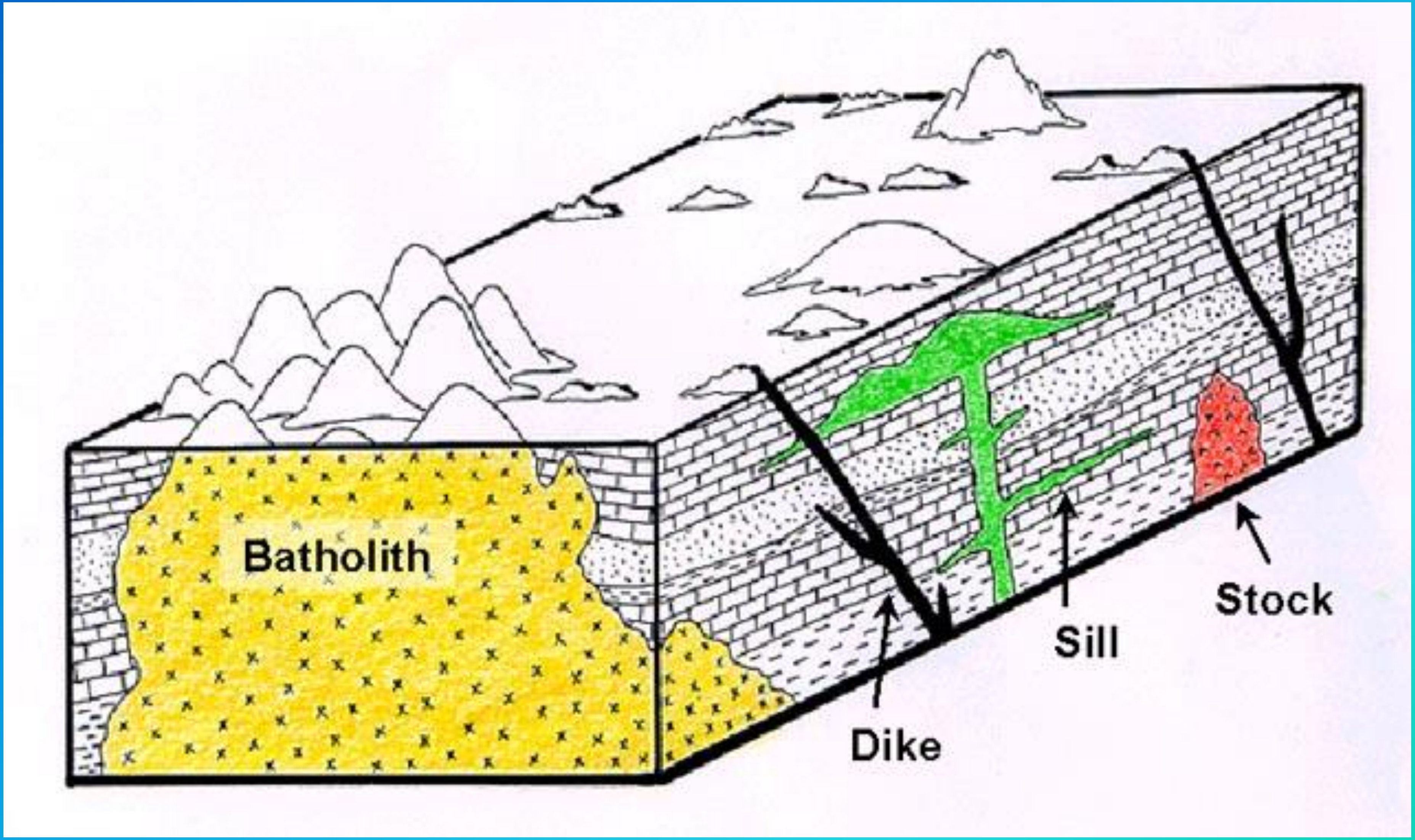

PLUTONS & VOLCANIC LANDFORMS
Laccolith



PLUTONS & VOLCANIC LANDFORMS
Sill


PLUTONS & VOLCANIC LANDFORMS
Batholith


PLUTONS & VOLCANIC LANDFORMS
Pluton


Batholith
Dike
Sill
Stock

Composition and Constitution of magmas

- The hot molten rock matters are conveniently called as Magma.
- It is thick, pasty, porridge-like mass.
- It occurs inside the earth
- When reaches the surface, it is called Lava
- Pyrogenetic Minerals: Minerals which are formed from the igneous magma are called as pyrogenitic. (formed by fire)

➢ Composition of magma

Chemical Composition

Sl.No.	Element	Oxide (%)
1	SiO_2	59.07
2	$AlsO_3$	15.22
3	Fe_2O_3	3.10
4	FeO	3.71
5	CaO	5.10
6	MgO	3.45
7	Na_2O	3.71
8	K_2O	3.11
9	H_2O	1.30
10	P_2O_5	0.30
11	MnO	0.11
12	Rest	0.44

Composition and Constitution of magmas

- The above table shows the average composition of 10 miles in crust
- Igneous rocks are estimated to comprises about 95% of the earth.
- Practically all the known elements have been met with in Igneous rocks.
- Nine elements such as Oxygen, silicon, aluminum, iron, calcium, sodium, potassium, magnesium and titanium are the common rock forming elements.

Chemical Composition By Clark and Washington from over 5000 analyses

1		2	
Oxygen	46·59	SiO_2	59·12
Silicon	27·72	Al_2O_3	15·34
Aluminium	8·13	Fe_2O_3	3·08
Iron	5·01	FeO	3·80
Calcium	3·63	MgO	3·49
Sodium	2·85	CaO	5·08
Potassium	2·60	Na_2O	3·84
Magnesium	2·09	K_2O	3·13
Titanium	·63	H_2O	1·15
Phosphorus	·13	CO_2	·102
Hydrogen	·13	TiO_2	1·050
Manganese	·10	ZrO_2	·039
Sulphur	·052	P_2O_5	·299
Barium	·050	Cl	·048
Chlorine	·048	F	·030
Chromium	·037	S	·052
Carbon	·032	$(Ce,Y)_2O_3$	·020
Fluorine	·030	Cr_2O_3	·055
Zirconium	·026	V_2O_3	·026
Nickel	·020	MnO	·124
Strontium	·019	NiO	·025
Vanadium	·017	BaO	·055
Cerium and Yttrium	·015	SrO	·022
Copper	·010	Rest	·023
Remainder of elements	·034		
	100·000		100·000

Composition and Constitution of magmas

- Volatiles such as hydrogen, fluorine, chlorine and sulphur are often greatest important in the phenomenon of igneous rocks.
- Oxygen and silicon are the most abundant element in magmas.
- Silicates are the most rock forming minerals.
- Silicon is capable of forming several silicates
  - Orthosilicic acids- Ex Olivine (2(Mg, Fe)), SiO2
  - Metasilicic acids – Ex Enstatite (Mg, Fe)O, SiO2
  - Polysilisic acids - Ex Orthoclase (K2O, Al2O3, 6SiO2
- Pyrogenetic silicates fall in to three categories

Composition and Constitution of magmas

- Hence, Pyrogenetic silicates fall in to three groups of orthosilicates, metasilicates and polysilicates.
- Olivine group varying from Forsterite, 2MgO,SiO2 to Fayalite 2Feo, SiO2 forms most important rock forming orthosilicates. Nepheline and anorthite are also comes under this group.
- The Pyroxenes and amphiboles are common examples for metasilicates (Diopside and Hypersthene)

Composition and Constitution of magmas

- Polysilicates are best represented by orthoclase- K_2O, Al_2O_3, $6SiO_2$ and albite - Na_2O, Al_2O_3, $6SiO_2$.
- K and Na forms the most active bases present in igneous magma however calcium is less active. Magnesium and iron are relatively the weakest.
- Iron has weakest affinity for silica hence often it is left out of combination. If there is a considerable deficiency of silica and appears as oxides as Magnetite.

Composition and Constitution of magmas

- If there is a considerable deficiency of silica in magma, potassium and sodium may not be able to combine with sufficient silica to form orthoclase and albite respectively, instead lower silicates of leucite and nepheline will be formed.

Minerals of Low Silication.	Minerals of High Silication.
Leucite.	Orthoclase.
Nepheline	Albite.
Analcite.	Anorthoclase.
Olivine.	Orthorhombic pyroxenes.
	Augite.
Biotite.	Aegirine.
	Hornblende

Mineralogical Composition

Relative abundance of different Minerals (**Clark and Washington**)

Table: Average Mineralogical Composition of Igneous Rocks

Sl.No.	Element	Oxide (%)
i	Feldspars	59.5
ii	Pyroxenes & Amphiboles	16.8
iii	Quartz	12.0
iv	Biotite	3.8
v	Titanium	1.5
vi	Apatite	0.6
vii	Accessory Minerals	5.8

Structure and Texture of Igneous Rocks

- Structures are large scale features like pillow structure, Flow banding, Ropy and Blocky surface of lava.

- Structures denotes also small scale features which are due to juxtaposition of more than one textural aggregate within a rock such as amygdaloidal and spherulitic structures

Structures of Igneous Rocks

- Features of igneous rocks developed on a **larger scale** giving rise to conspicuous shapes or forms

  - **Structure** – Recognition through visual inspection

  - If they are apparent only under microscope they are called **microstructures**

The structures of igneous rocks are large scale features, which are dependent on several **controlling factors like:**

(a) **Composition of magma.**

(b) Viscosity of magma.

(c) Temperature and pressure at which cooling and consolidation takes place.

(d) Presence of gases and other volatiles.

Igneous structures are mostly classified into three major groups, as follows:

1. Mega-structures.

These are usually formed in the flow stage of the magma (i.e., in the extrusive rocks), and include:

- Vesicular and Amygdaloidal structures
- Block-lava and Ropy lava Structures
- Pillow structure
- Flow structure
- Jointing, Sheet and Platy Structure
- Columnar and Prismatic structure
- Rift and Grain Structure

2. Minor structures.

- Primary foliation
- Banding in rocks
- Schlieren

3. Micro-structures.

- Reaction rims
- Myrmekite structure
- Graphic structure
- Xenolithic structure
- Orbicular structure
- Spherulitic structure
- Perlitic-cracks

Vesicular Structures:

When lavas heavily charged with gases and other volatiles are erupted on the surface, the gaseous constituent's escapes from the magma as there is a decrease in the pressure. Thus, near the top of flows, empty cavities of variable dimensions are formed. The individual openings are known as vesicles and the structure as a whole is known as vesicular structure.

Vesicular Structures

Amygdaloidal Structures

Vesicles are subsequently filled with some low-temperature secondary minerals, such as calcite' -zeolite, chalcedony etc., these infillings are called 'amygdales'

Amygdaloidal Structure

Cellular or scoriaceous structure:

By the bubbling out of the gases, from lava heavily charged with volatile and gaseous constituents, numerous cavities are formed with the solidification of the lava. When the cavities are very much abundant, the term 'pumice' or 'rock-froth' is applied. Such structures are known as cellular or scoriaceous structures and are characteristic of highly siliceous lavas.

Block Lava:

Since lavas of acidic composition, due to their high viscosity, do not flow to greater distances, they after solidification are found to offer a very rough surface. Such lava flows are known as block lava. It is also known as 'aa' structure.

Block Lava

Ropy Lava

Lavas of basic composition are quite mobile because of their low viscosity and they can flow to greater distances and after solidification offers very smooth surface. Such lava flows are known as ropy lava and are also known as 'pahoehoe' structure.

Pillow Structures (Ellipsoidal Structure):

It consists of isolated pillow shaped masses piled one upon another... These are produced by extrusion of lava into rain-soaked air, beneath ice-sheets, under water logged sediments or in sea water. Spilite, a lava rich in albite (i.e., sodium rich) characteristically exhibits pillow structure.

Pillow Structures

Flow Structure

Subsequent to eruption of lava upon the surface the viscous, varieties flow from one place to the other with great difficulty and in their attempt to do so, the dissimilar patches within the lava are drawn out in the form of elongated lenticels. Sometimes the already ciystallised particles within the magma are: arranged parallel to the direction of flow pf the lava. They naturally indicate the direction of flowing of the mass, prior to its consolidation. These are also known as directional structure or more commonly flow structure.

b). Structure due to cooling of Magma

Jointing Structures

- **Sheet Joints (Parallel layers)** **(Quarry surfaces)**
- **Normal Joints (Cubical block)** **(Granite)**
- **Columnar Joints (Polygonal block)** **(Basalt)**

Sheet structure:

- The development of one set of well defined joints sometimes brings about a slicing effect on the massive igneous rock body. If all such slices are horizontal, the structure is said to be sheet structure.
- The horizontal joint planes are some times so closely spaced as to produce a sheet structure

Platy structure:

- This is also due to the development of different sets of joints, which gives rise to only plates of the rock mass, on striking the rock. Such a feature is known as platy structure.

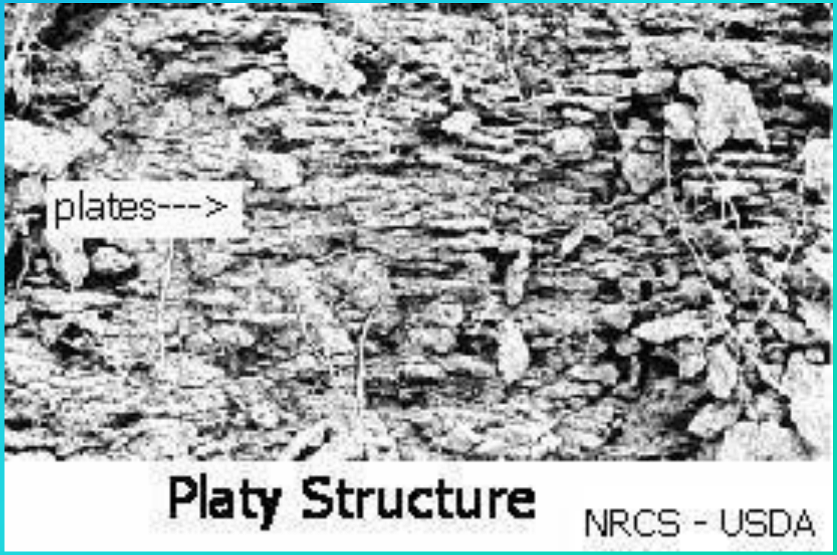
Columnar structure:

- With uniform cooling and contraction in a homogeneous magma the parting planes tend to take on a regular columnar or prismatic form.
- A few sets of vertical joints developed and such joints bring about the formation of columns, which may be square, rectangular, rhombic or hexagonal in outline.

Columnar Structures

Sheet Structures

Platy Structures



Columnar structure:

As a consequence of contraction due to cooling, a few sets of vertical joints develop. Such joints bring about the formation of columns, which may be square, rectangular, rhombic or hexagonal in outline.

Columnar Joints

Rift and Grain Structures

These are due to jointing. In granites, three mutually perpendicular, equally spaced joints, which are taken into advantage while producing cubical blocks, are known as 'mural jointing. But for processing of the blocks down to smaller dimensions, the mutually perpendicular closely spaced joints (one horizontal and the other vertical) are taken into advantages. These joints are known as rift and grains.

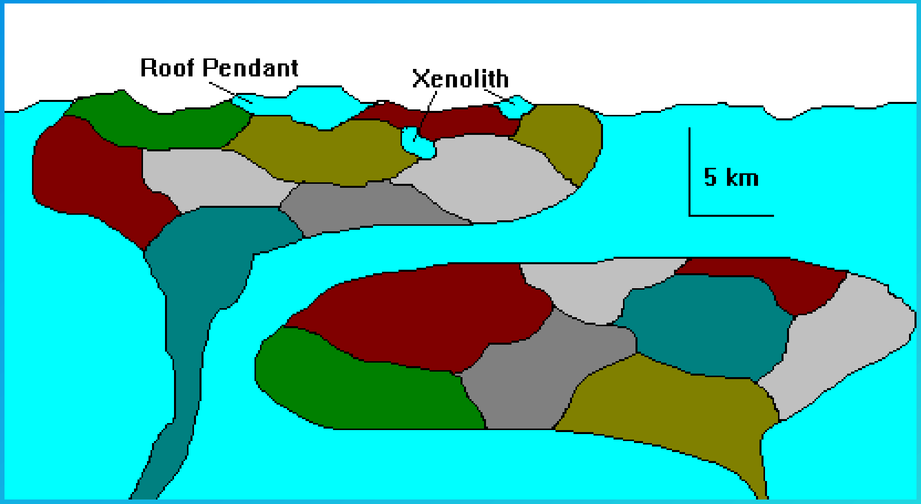
c). Miscellaneous or Micro Structures

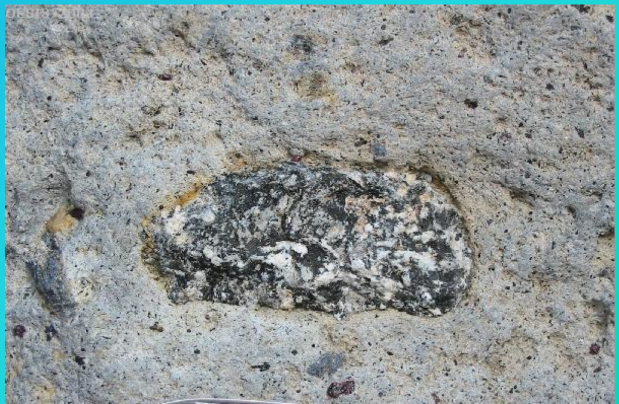
Reaction Structures - Partly altered material encircling a batholith mass

- The reaction may be partly or complete

- Form reaction rim

Xenolithic Structures - Presence of foreign material in magma. Foreign fragments are called Xenoliths.



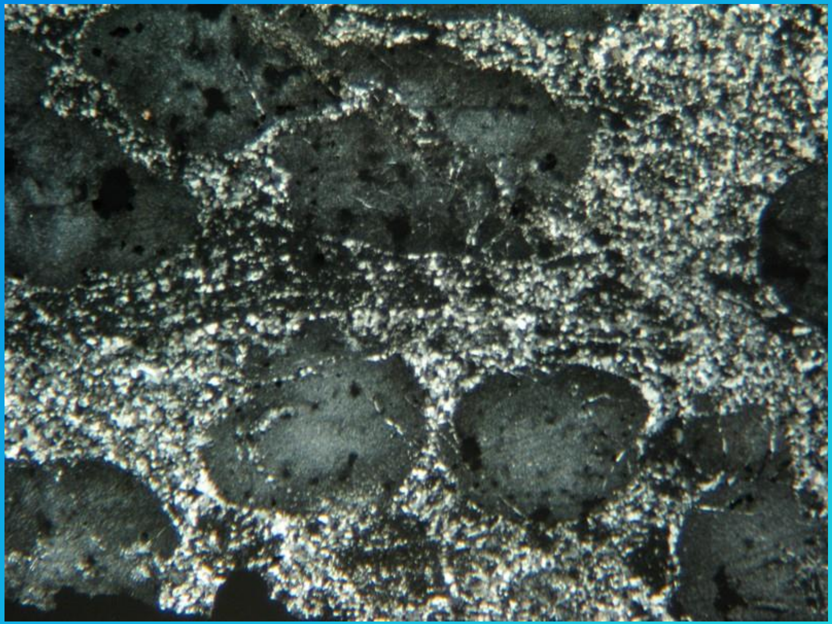


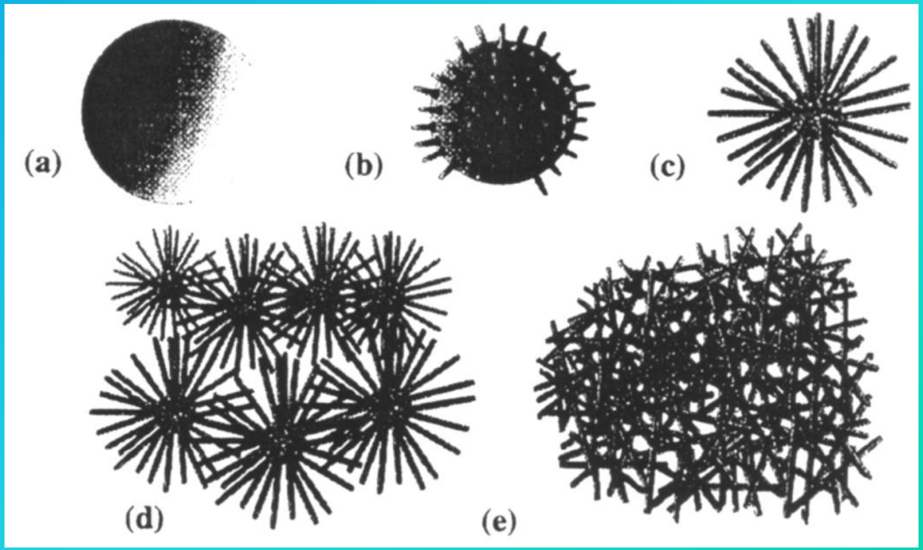
Spherculitic Structures

- **Spherulite**, spherical body generally occurring in **glassy rocks, especially silica-rich rhyolites.**

- Spherulites frequently have a radiating structure that results from an intergrowth of quartz and orthoclase.

- These spherical bodies are thought to have formed as a consequence of rapid mineral growth after nucleation, possibly on an accumulation of volatiles.





Orbicular Structures

- These are spherical segregations consisting of **concentric shells of different mineral composition and texture**, which occasionally occurs in **granitic rocks**.

Textures of Igneous Rocks

Definition:

The term texture is defined as the mutual relationship of different mineralogical constituents in a rock. It is determined by the size, shape and arrangement of these constituents within the body of the rock.

- Majority of textures can be recognized / studied only under microscope.

Controlling Factors:

- **Crystallisation slow or rapid**
- **Magma rich in one constituent poor in other constituent.**
- **It may be highly viscous or quite mobile**

All these above leads to

- **Various shapes, sizes and arrangements – hence number of textures.**

TYPES OF TEXTURES :

FACTORS:

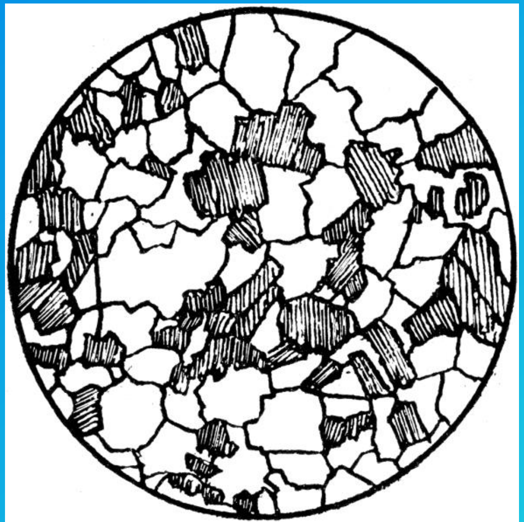
- **Degree of Crystallization**
- **Granularity**
- **Fabric & Grain Size**

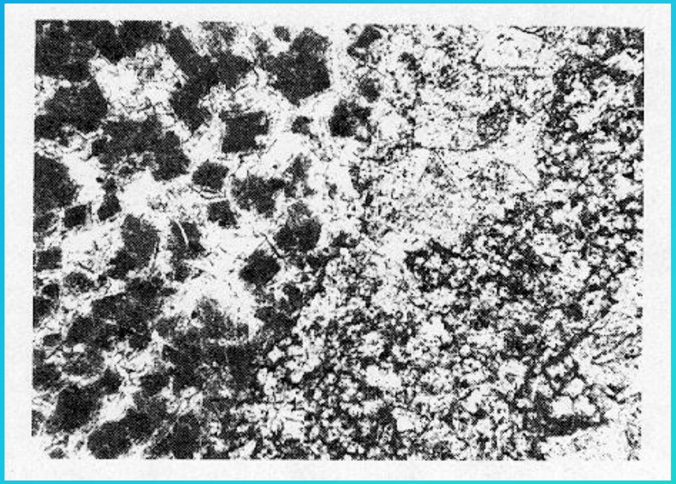
Degree of Crystallization

Holo Crystalline - Constituent minerals are distinctly Crystalline

Meso Crystalline - Partly crystalline and partly glassy

Holo Hyaline - very fine, non crystalline in nature or glassy





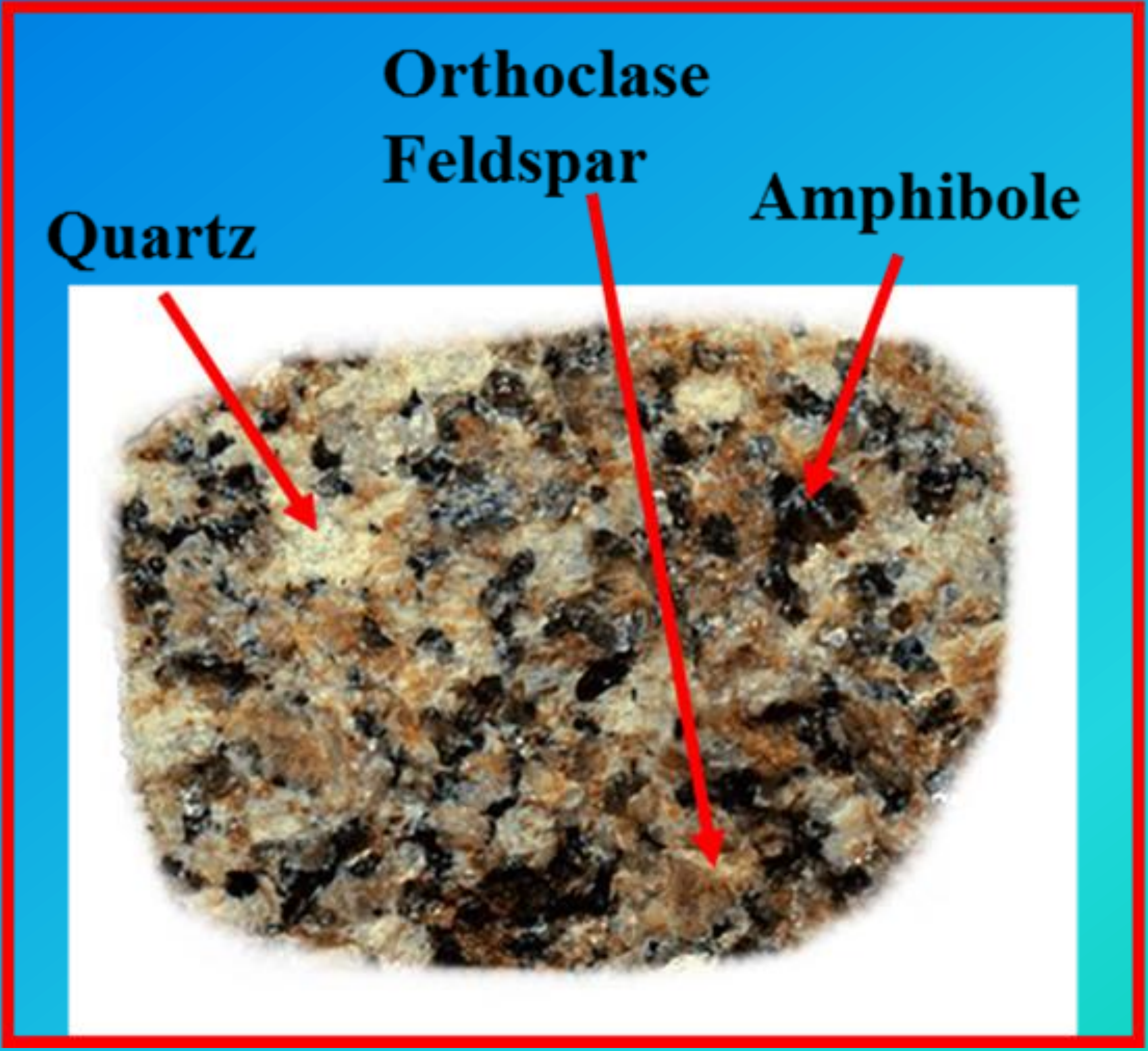
Degree of Granularity

The absolute size of crystal in igneous rock ranges from phaneric to aphanitic

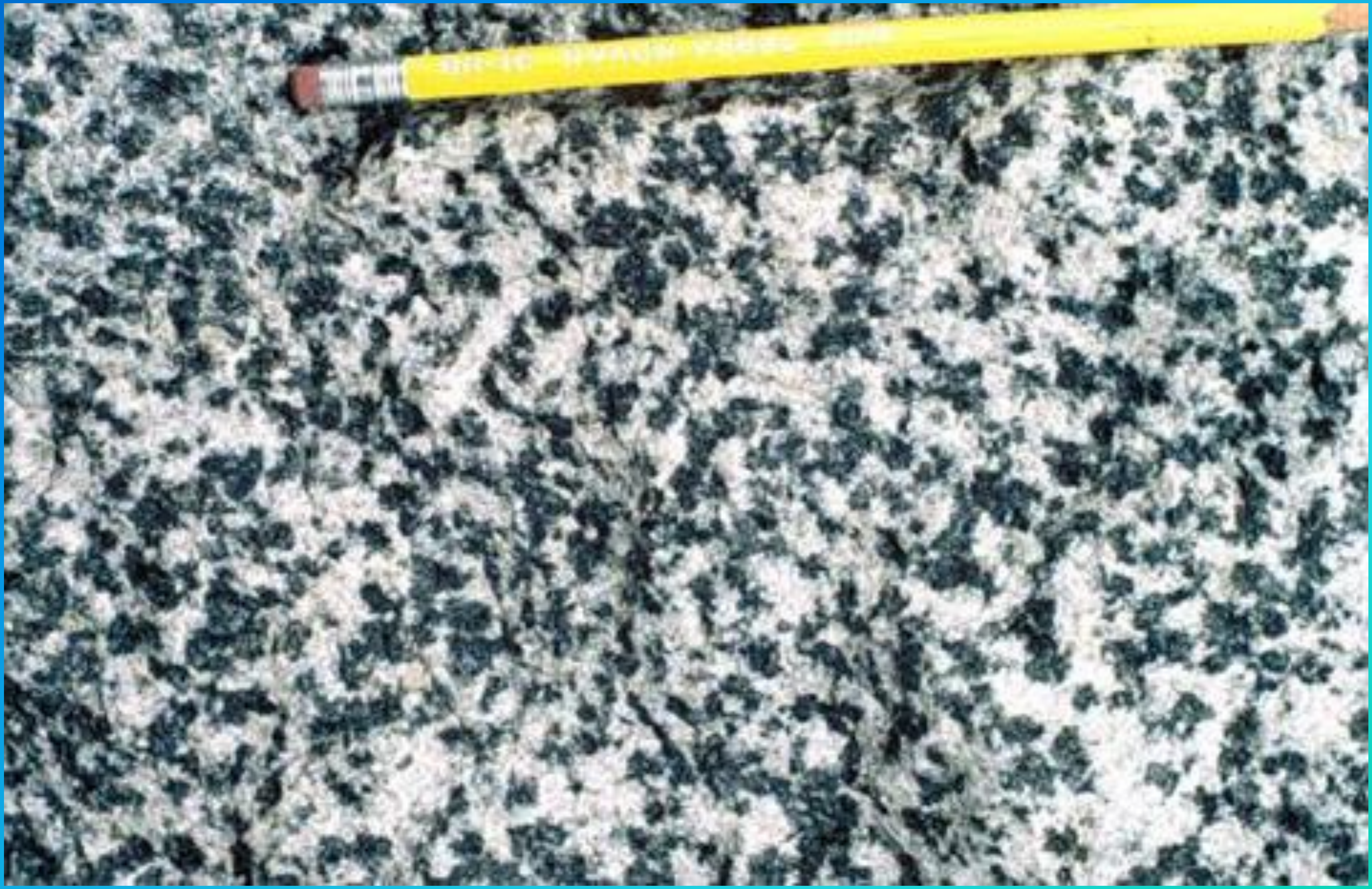
Coarse grained	-	Average grain size in above 5mm ***(visible to naked eye)***
Medium grained	-	5mm to 1mm ***(need lens)***
Fine grained	**-**	below 1mm ***(with the help of microscope)***

Granite –Coarse grained

- Minerals can be identified with the unaided eye.



Diorite – Medium grained



Basalt – Fine grained

- Minerals are not identified with the unaided eye.

SHAPE OF THE CRYSTAL

The fabric or pattern of a rock depends on the shapes, size and relative arrangement of crystals.

Crystal forms described based on the development of their faces.

Euhedral: Completely crystal faces

Subhedral: Intermediate stage

Anhedral: Crystal faces are absent

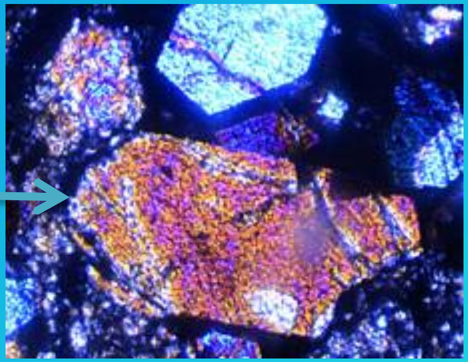
Fabric & Grain Size

1. **Degree of perfection of the forms and crystals of individual minerals**

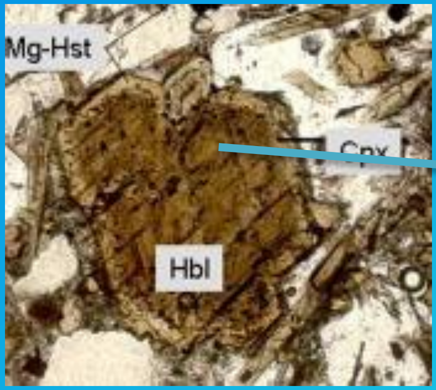
   - Can be recognized well in thin section under microscope
   - Euhedral, Subhedral and anhedral

❑ Panidiomorphic -	Majority in euhedral crystals
❑ Hypidomorphic -	All shapes – Euhedral, subhedral and anhedral
❑ Alotriomorphic -	Majority is anhedral crystals

euhedral



subhedral



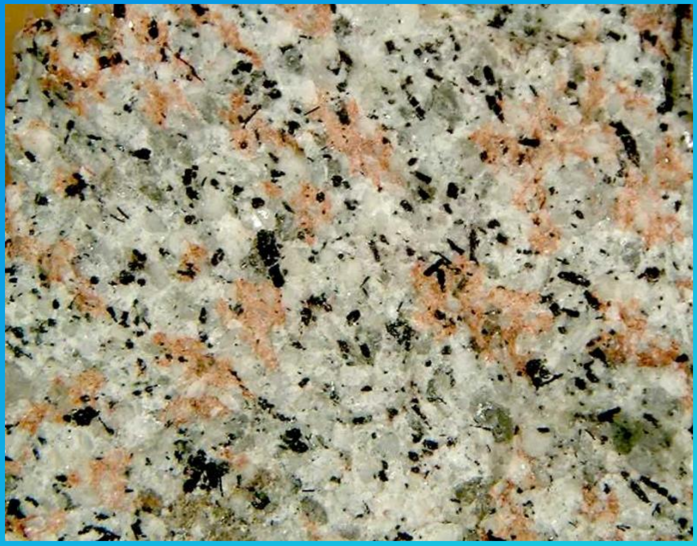
anhedral

2. Grain Size:

- Relative grain size of constituent minerals

- Equigranular - All constituent minerals have nearly dimension
- Inequigranular - not is equal dimension

Equigranular



Inequigranular

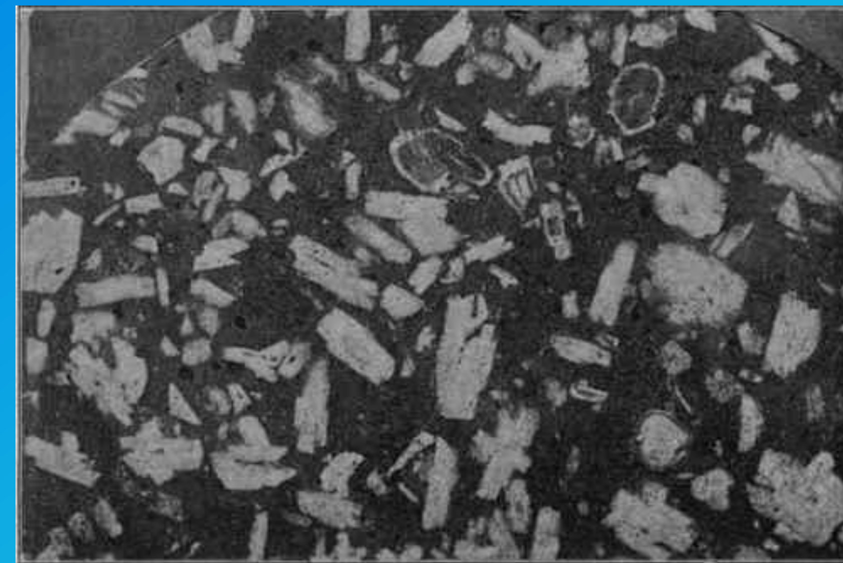
TYPES OF TEXTURES:

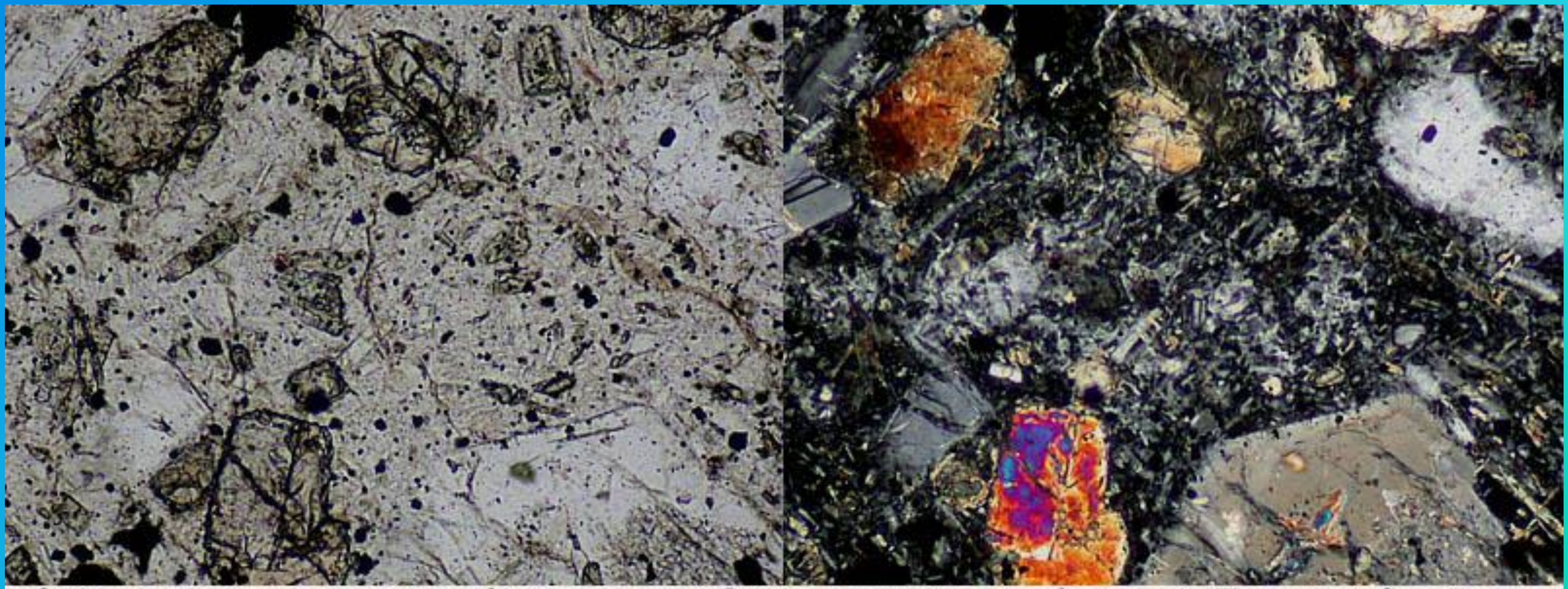
Equigranular:

Granitic Texture	-	Constituents minerals are either coarse grained or medium grained with euhedral to subhedral outlines.
Orthophyric Texture	-	Individend grains are fine in size but not microgranular
Felsitic Texture	-	Grains are microscopic crystals with perfect crystal shape (equigranular, panidiomorphic texture)

Granite-texture

Felsitic Texture





Orthophyric texture (variety of intergranular) for the groundmass of a basalt. Texture defined by the random orientation of tabular feldsapr microlites and some Cpx.

Equigranular Texture - Igneous Rock Textures

Rocks with equigranular texture have mineral grains that are generally the same size.

This example is a Granite.

Inequigranular:

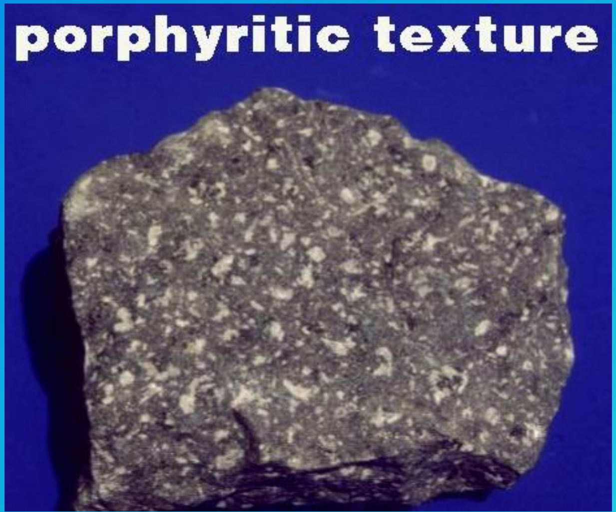
Majority of grains show marked difference in their relative grain sizes.

Porpheritic Texture: Few large sized crystals (Phenocrystals) embedded in fine grained ground mass or matrix.

(Mega Porphyritic and Microporphyritic)

Factors:

- **Difference in molecular concentration**
- **Change in physico-chemical conditions**
- **Relative in solubility**



Porphyritic Texture - Igneous Rock Textures

Rocks with porphyritic texture like this Andesite have larger mineral grains, or phenocrysts, in a matrix of smaller grains.

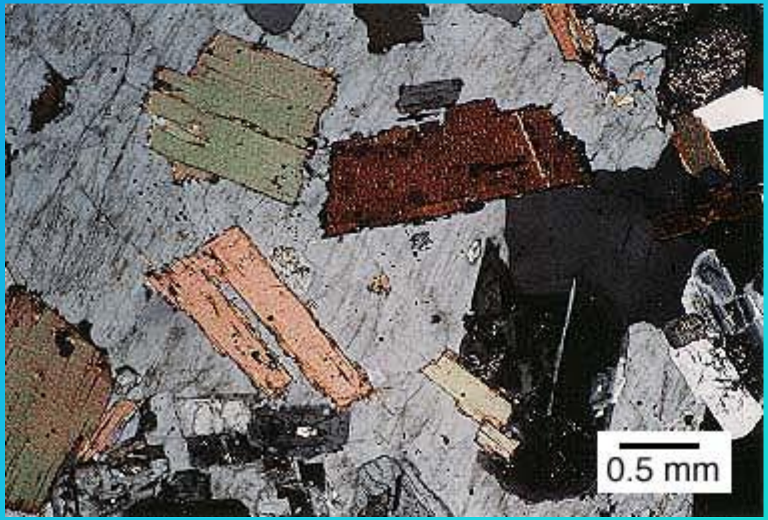
Poikilitic Texture :

Fine grained crystals within / embedded large sized crystals.

Eg. Augite large blocks consists of Plagioclase feldspar – Ophitic texture

Poikilitic Texture - Igneous Rock Textures

Poikilitic texture is one in which large crystals, like this feldspar grain, contain small grains of other minerals scattered inside them.

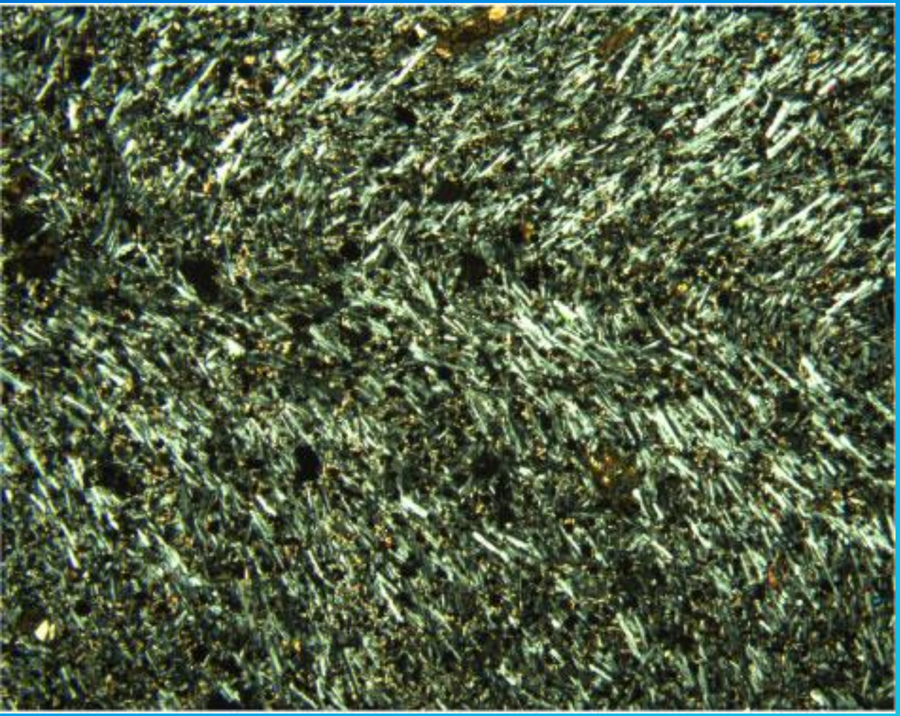


In this photomicrograph, euhedral to subhedral biotite and plagioclase crystals are surrounded by optically-continuous, gray-colored K-feldspar

Directive Texture :

- **Result of flow magma**
- **Parallel arrangement of crystals in the direction of flow**

E.g. Trachytic and Trachytoid Textures

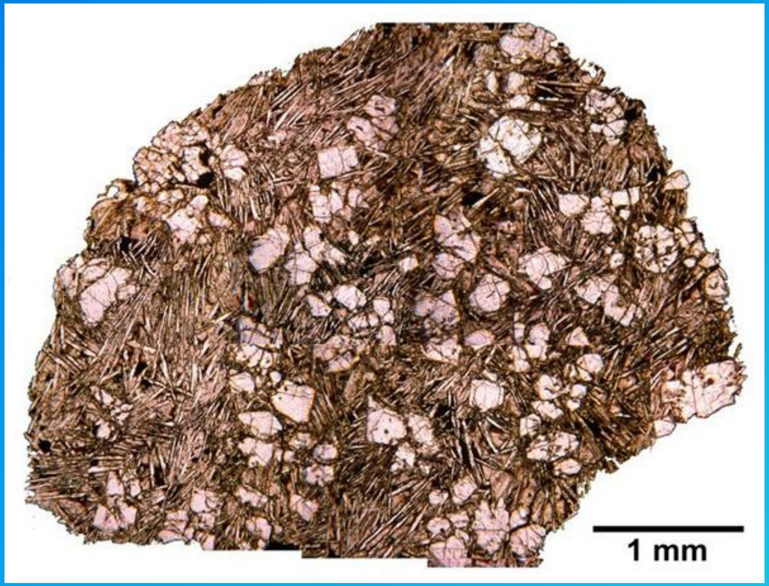


Photomicrograph showing strain bands in **trachytic texture**

Intergrowth Texture :

- **Two or more minerals grow simultaneous due to space constrain these get mixed up.**
- ***E.g.* Graphic Texture –** *(regular growth of quartz and feldspar) and*

  Granophyric Texture - *(irregular growth of quartz and feldspar)*



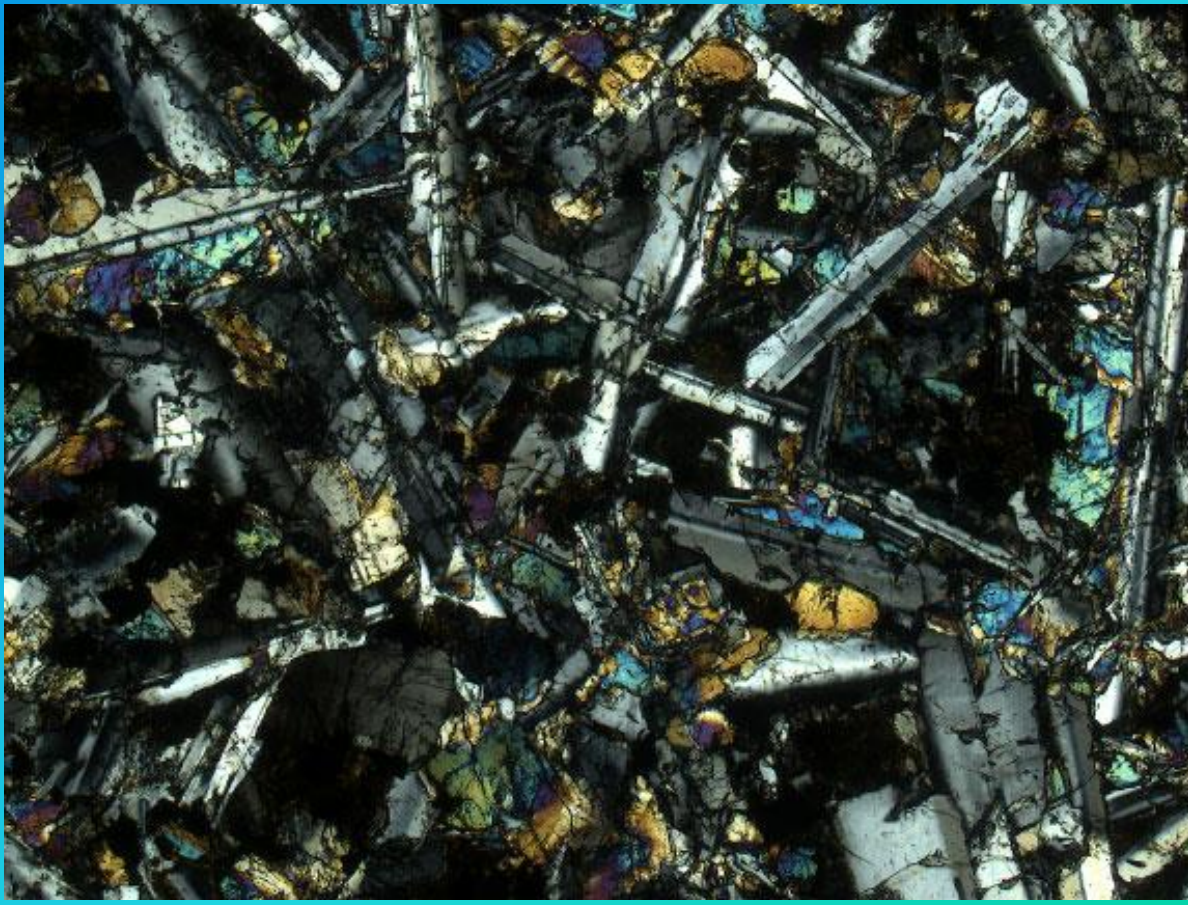
Graphic Texture

Pegmatite in medium-grained granite, displaying graphic **intergrowth granophyric texture**

Intergranular :

- **The intergranular spaces later filled with later formed crystals or glass**
- ***E.g. Intersertal texture***

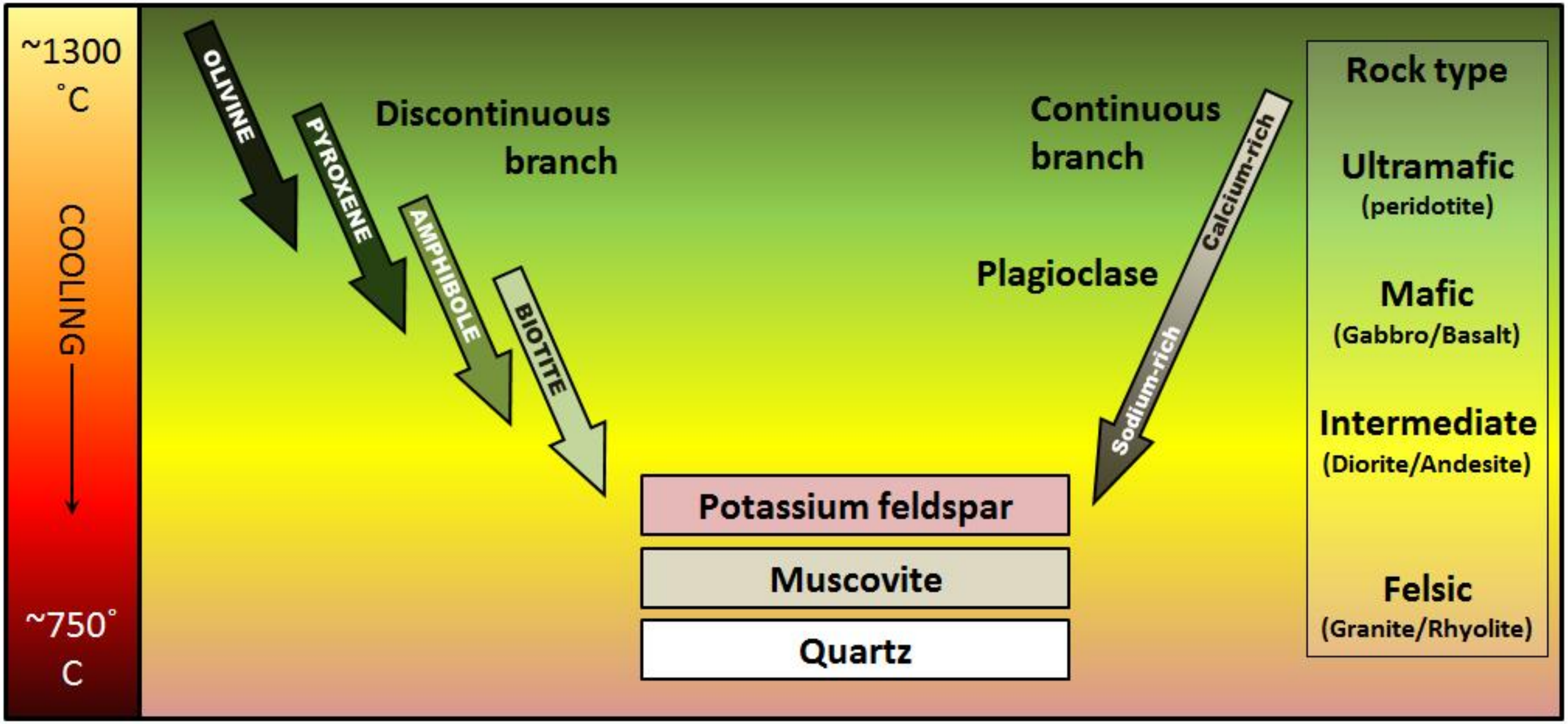
Intergranular texture in massive fine-grained basalt



Crystallisation of Magmas

- **Bowen's Reaction Series.**
  - Mafic minerals and the discontinuous reaction series.
  - Plagioclases and the continuous reaction series.
- **Understand phase diagrams:**
  - Diopside – Anorthite system.
  - Anorthite – Albite system.

Bowen's Reaction Series



In the discontinuous branch, olivine is typically the first mineral to form. As the temperature continues to drop, olivine becomes unstable while pyroxene becomes stable.

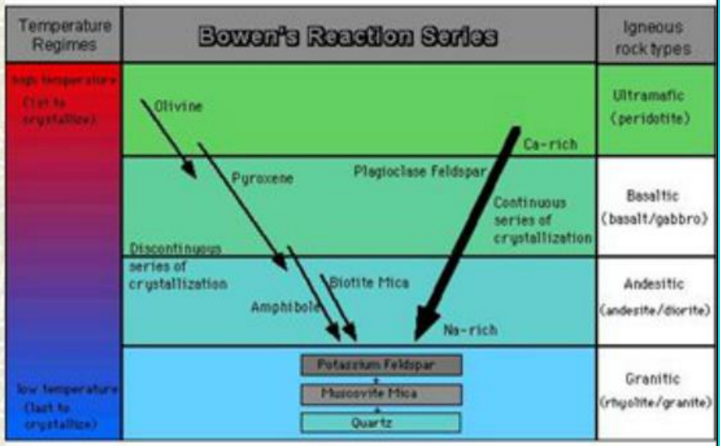
The early-forming olivine crystals *react* with silica in the remaining liquid magma and are converted into pyroxene, something like this:

$Mg_2SiO_4 + SiO_2 \longrightarrow 2MgSiO_3$

olivine pyroxene

Bowen’s Reaction Series.

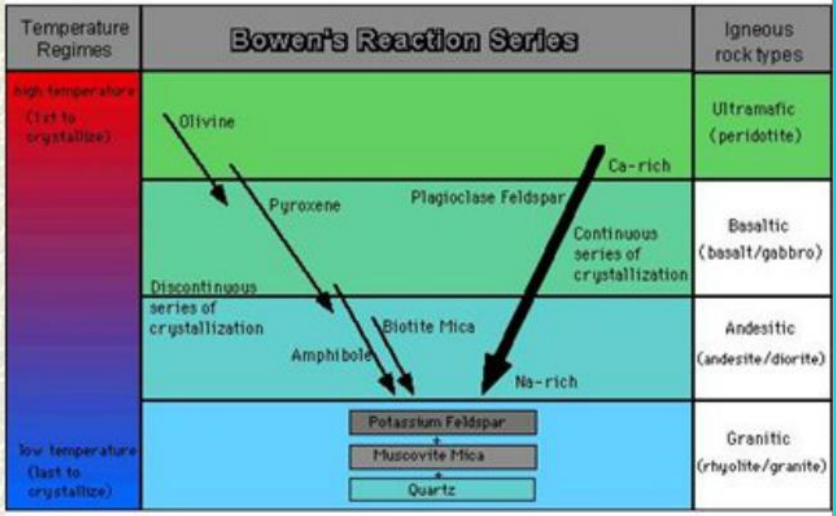
- This reaction series is based on laboratory experiments by Bowen.
- He realised that as a magma cooled not all the minerals that would eventually form the rock crystallised at the same time/temperature.
- Some minerals always formed at high T and others at low T.
- He experimented with different types of magma from ultrabasic to acid.



Adapted from *Earth Science*, 7th Edition by Tarbuck and Lutgens

Bowen's Reaction Series.

- His first findings were that Olivine formed at the highest T followed by pyroxenes (augite), amphiboles (hornblende) then followed by biotite mica.
- These are the mafic/ferromagnesian minerals.
- They form the discontinuous reaction series.



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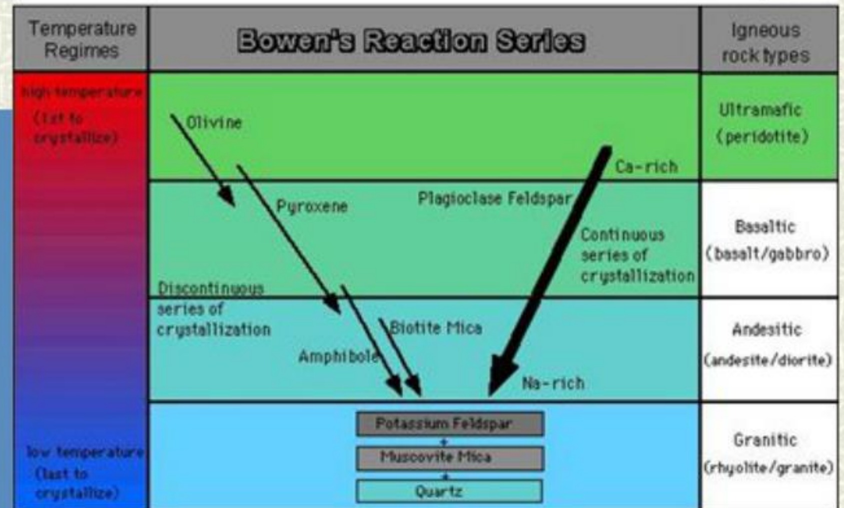
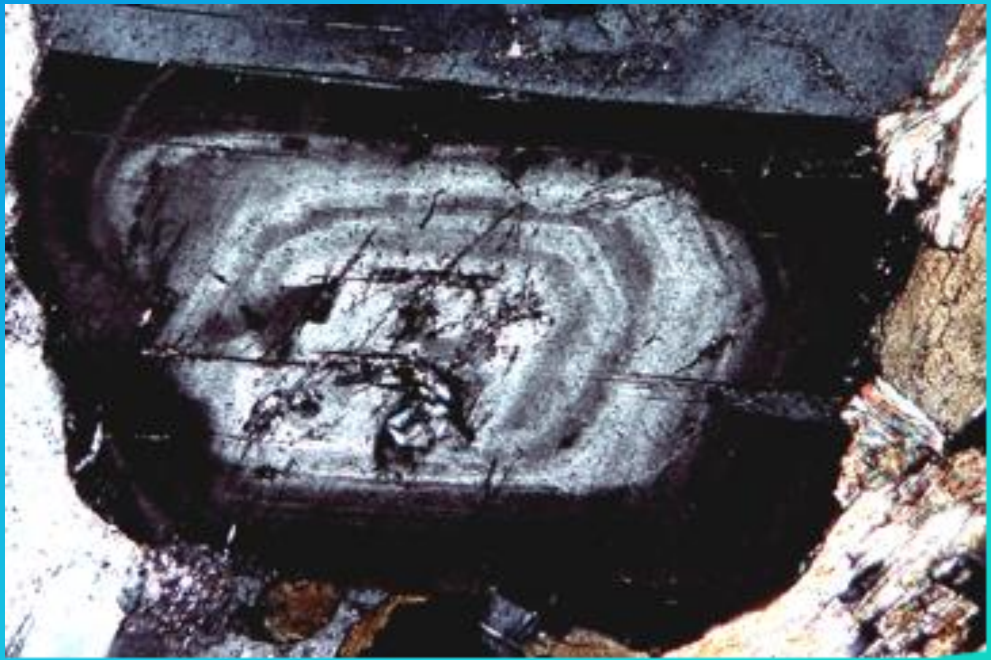
Bowen's Rection Series.

- **At a lower T will be other minerals Orthoclase / potash feldspar followed by muscovite mica and finally quartz.**

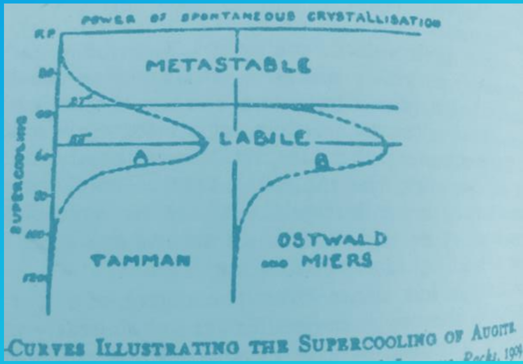


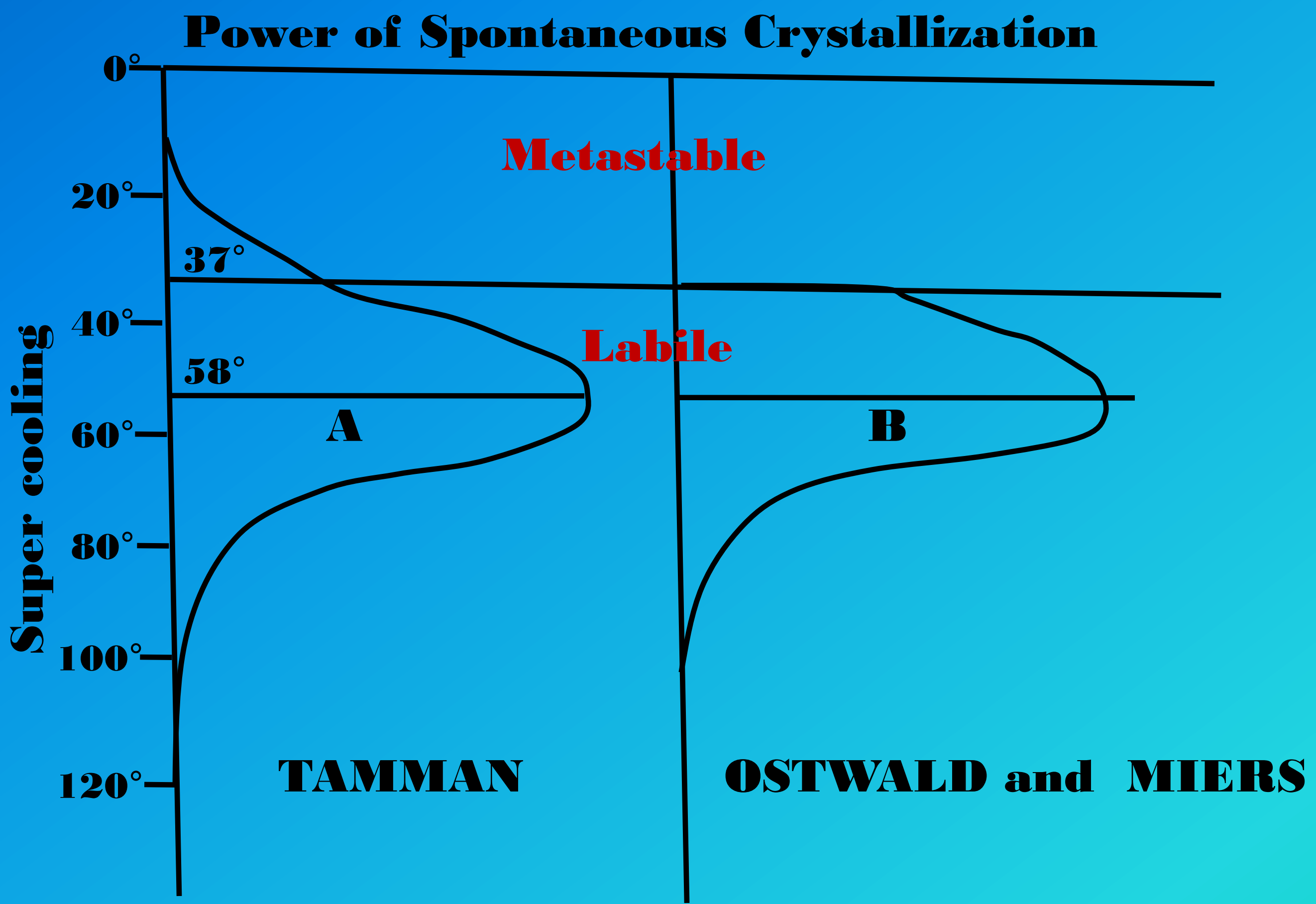
- In some cases, individual plagioclase crystals can be zoned from calcium-rich in the centre to more sodium-rich around the outside.
- This occurs when calcium-rich early-forming plagioclase crystals become coated with progressively more sodium-rich plagioclase as the magma cools.
- Finally, if the magma is quite silica-rich to begin with, there will still be some left at around 750° to 800°C, and from this last magma, potassium feldspar, quartz, and maybe muscovite mica will form.



Crystallization of Unicomponent Magma

- Augite has been taken up for this unicomponent study.
- The diagram given below indicates the crystallization of Augite
- Abscissa (X-axis) represents the power of spontaneous crystallization.
- Ordinate (Y-axis) represents the temperature below the freezing points.
- According to Tamman, the curve A represents the the mode of crystallization.
- Crystallization begins at the freezing point but the rate of crystallization is extremely slow.
- Temperature between 30 ° and 55°, rate of crystallization increases and reaches maximum at 55° and then degreases rapidly until crystallization ceases at a temperature 120° below freezing point.

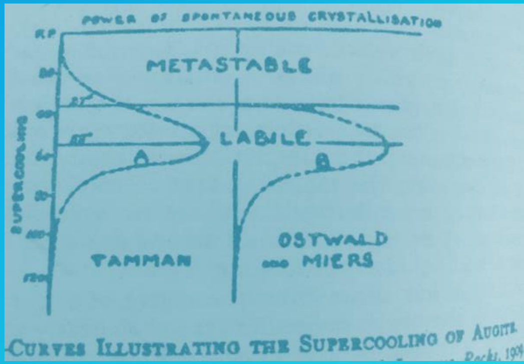




Curve Illustrating the Super cooling of Augite

Crystallization of Unicomponent Magma

- **The temperature region where the generation of crystals is slow is called the Metastable region.**
- **The region where the crystallization is rapid called Labile region.**
- **According to Ostwald and Miers, no crystallization occurs at freezing points but their concept was not accepted by the geologist.**
- **They believed that crystallization never develop unless some dissolved substances inculcated to the solution.**
- **The above unicomponent concept leads to the grain size variations in the Igneous rocks. Large crystals are developed when the crystals are crystallized at the metastable region.**
- **If the cooling is rapid, it quickly Pass over the metastable region and bulk crystallization started at the labile region resulting fine grained Igneous rocks**

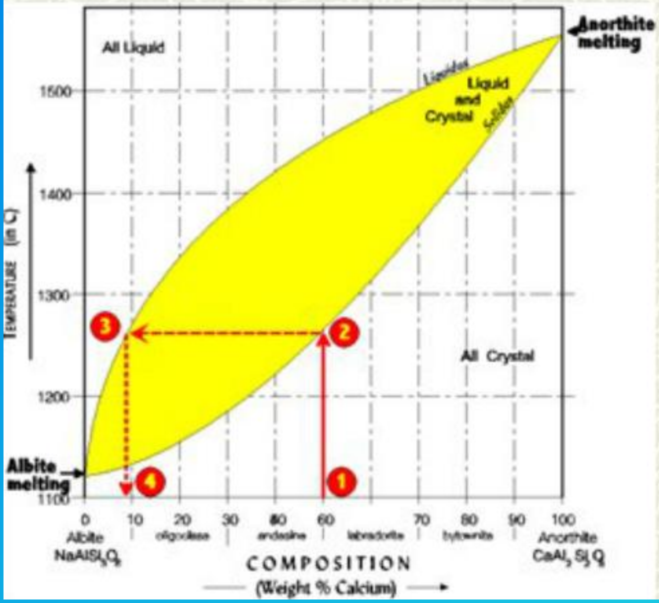


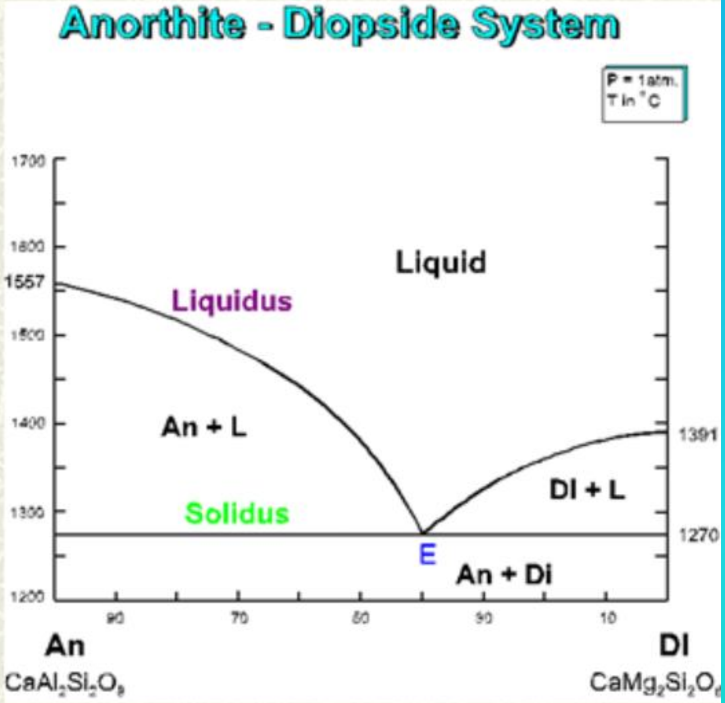
Curves Illustrating the Supercooling of Augite

CRYSTALISATION OF BINARY MAGMAS

Understanding phase diagrams:

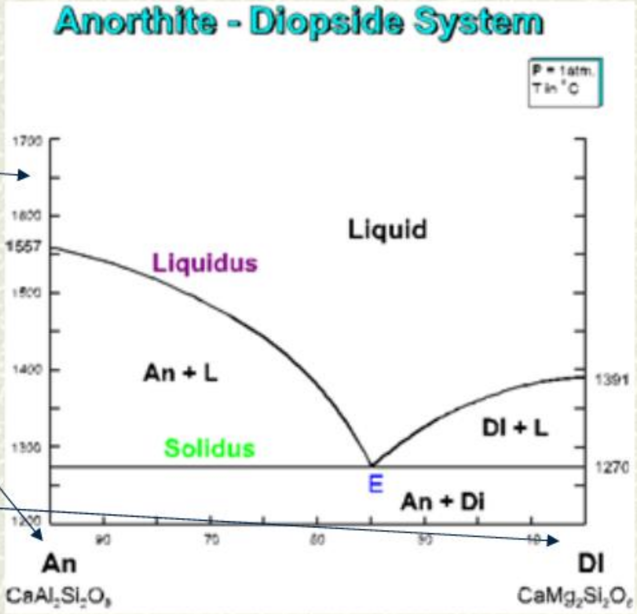
- Diopside – Anorthite system.
- Anorthite – Albite system.





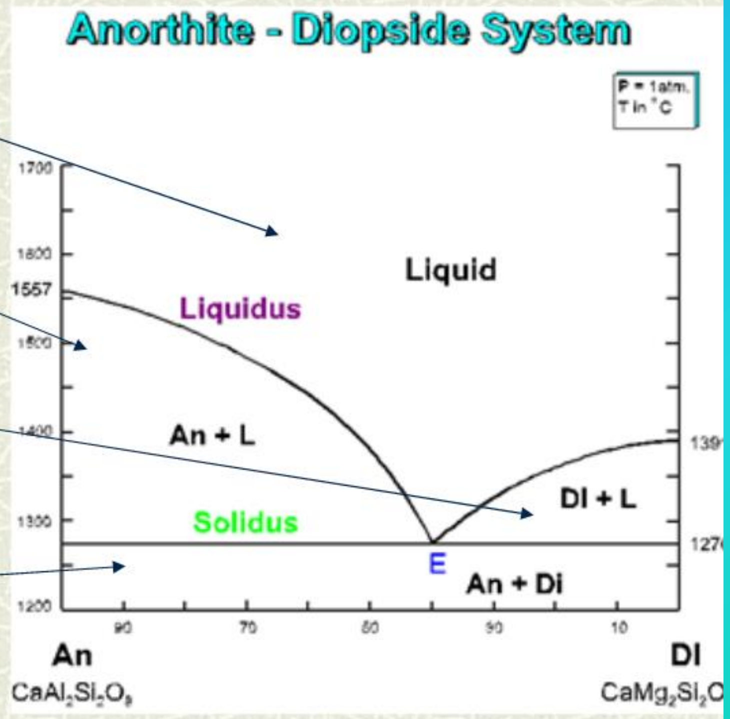
Diopside – Anorthite system.

- **The axes:**
  - **Vertical:** shows you the temperature (T).
  - **Horizontal:** has 100% anorthite (Ca rich plagioclase) at one end and 100% diopside at the other.



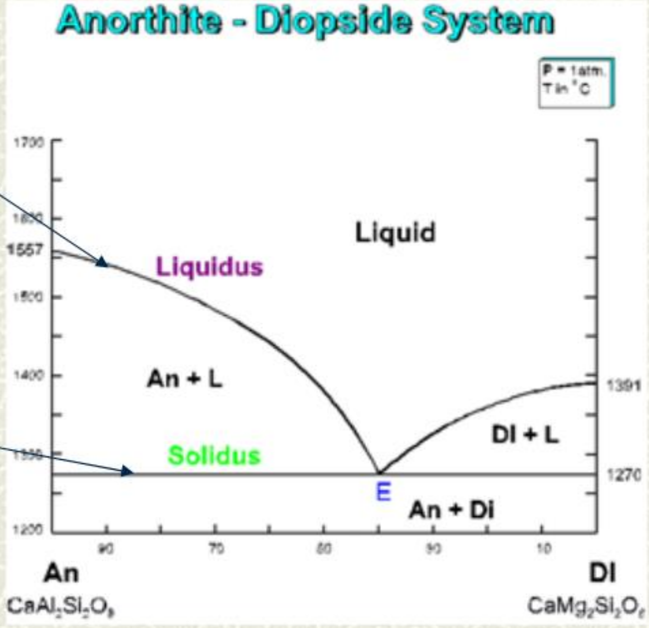
Diopside – Anorthite system.

- The fields: these are the various areas of the phase diagram:
- **Liquid field:** This is where the magma is completely liquid.
- **Anorthite + liquid field:** this is where both liquid and crystals of anorthite occur.
- **Diopside + liquid field:** this is where liquid and crystals of diopside occur.
- **Anorthite + Diopside field:** this is where crystals of both anorthite and diopside occur.



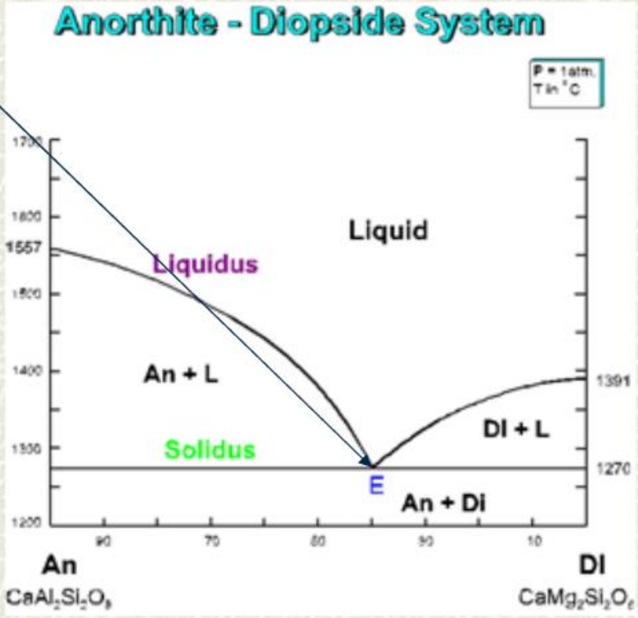
Diopside – Anorthite system.

- **The Lines:**
- **The Liquidus:** Liquid only above, liquid + solid below.
- **The Solidus:** Solid only below, liquid and solid above.



Diopside – Anorthite system.

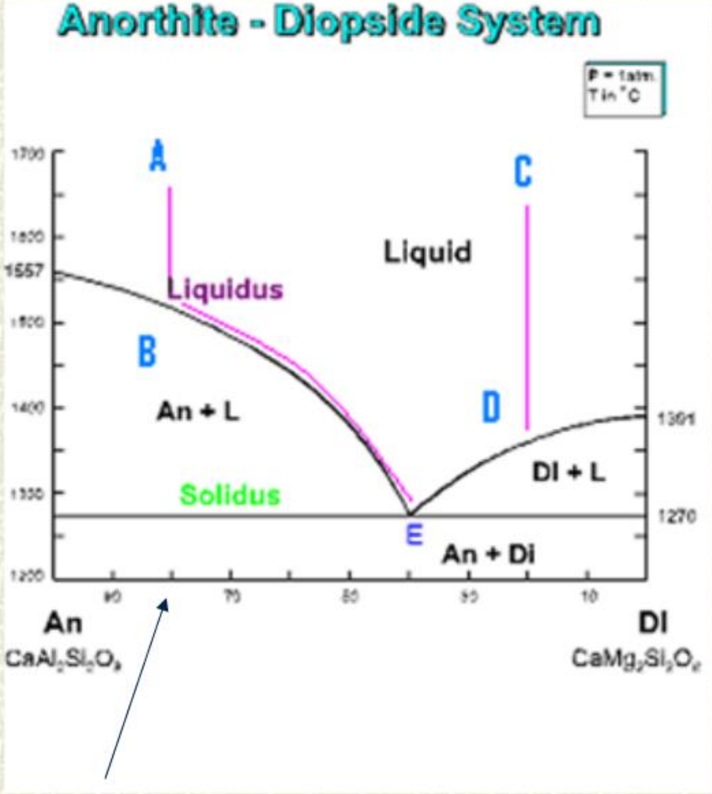
- **The Eutectic: This is the lowest possible cooling (or melting point). (E)**



Diopside – Anorthite system.

Cooling of a liquid (magma) of composition A.

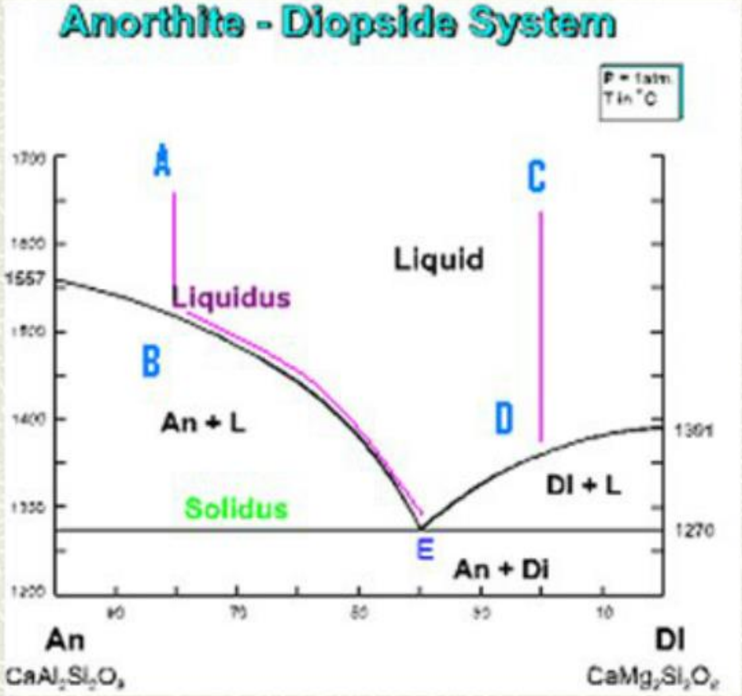
- This has a composition of 80% anorthite and 20% Diopside.
- The liquid of composition A will cool (straight down) until it meets the Liquidus at B.
- This touches the Anorthite + liquid field so only (pure) Anorthite will start to crystallise.
- What will removal of Anorthite from the melt do the relative amount of Diopside left in the melt?
- It will increase.



80% An 20% Di

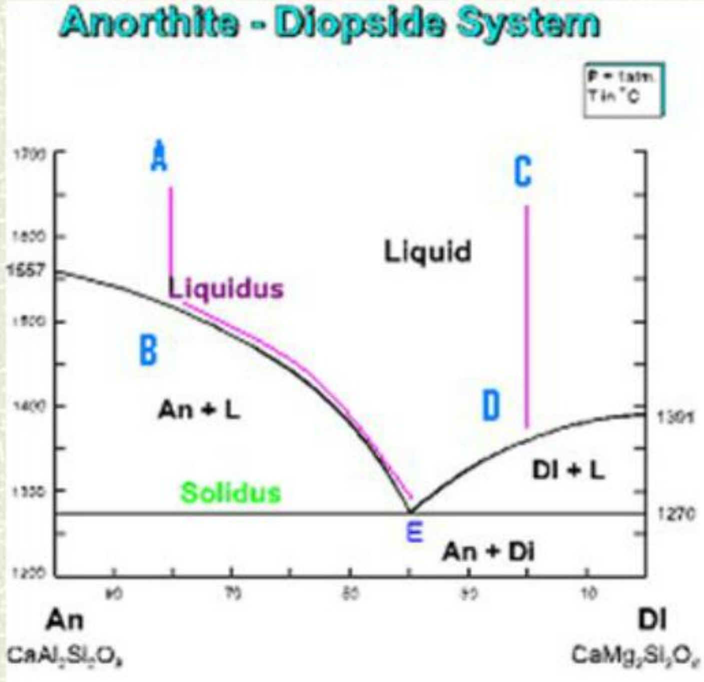
Diopside – Anorthite system.

- In order to continue crystallisation the **T must drop** and move **down the liquidus** to the right **towards Diopside**.
- **Anorthite** will continue to crystalise and the magma move down the liquidus until the **eutectic** is met.
- At the **Eutectic** point **anorthite + Diopside** will crystalise together at about 1275º.



Diopside – Anorthite system.

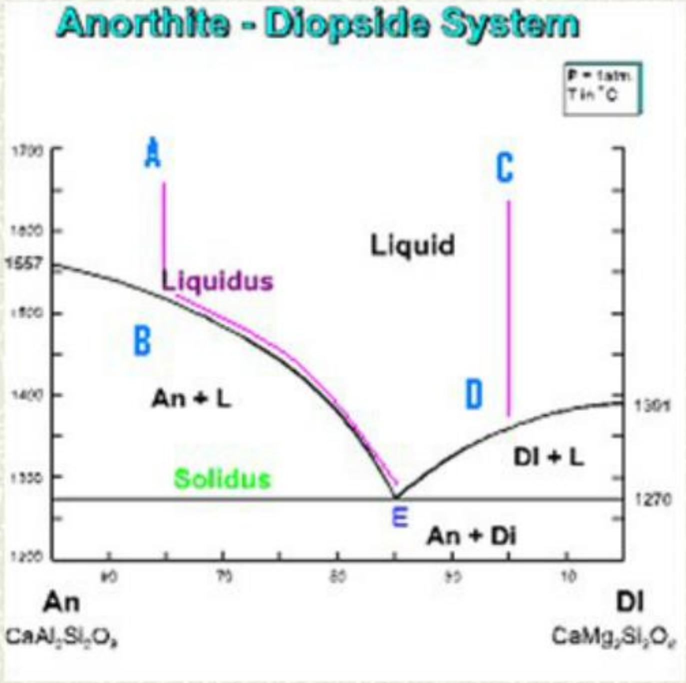
- At the eutectic the magma will have what composition?
- Di = 58% and An 42%
- This proportion of minerals will now continue to crystalise (no further cooling is required).
- This eutectic proportion of minerals will be added to all the previously formed Anorthite crystals.
- The final composition of the rock will be (unsurprisingly) the same as the original magma (80% An and 20% Di).



Diopside – Anorthite system.

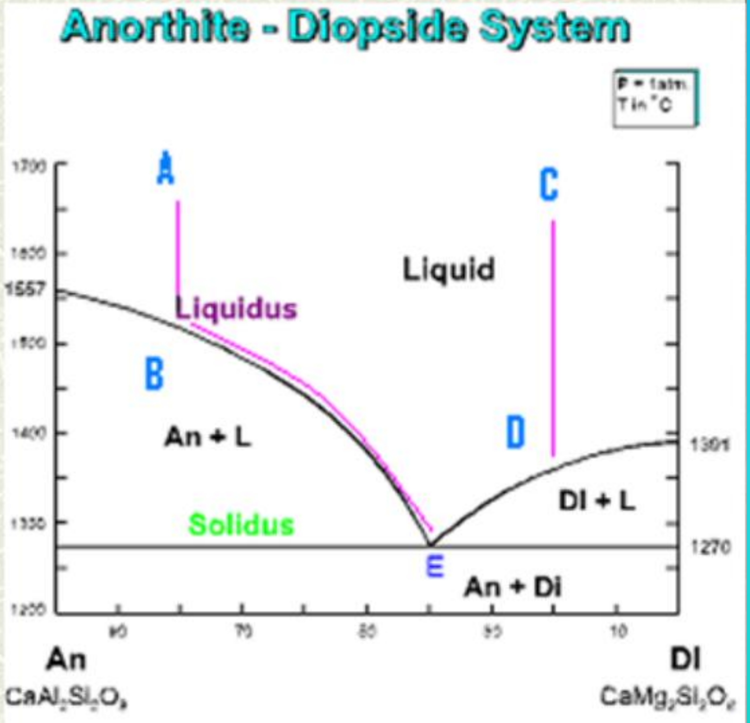
Cooling of a liquid (magma) of composition C.

- **What is it's composition?**
- **20% anorthite and 80% Diopside.**
- **The liquid of composition C will cool (straight down) until it meets the Liquidus at D.**
- **This touches the Diopside + liquid field so only (pure) Diopside will start to crystallise.**
- **What will removal of Diopside from the melt do the relative amount of Anorthite left in the melt?**
- **It will increase.**



Diopside – Anorthite system.

- In order to continue crystallisation the T must drop and move down the liquidus to the left towards Anorthite.
- Diopside will continue to crystalise and the magma move down the liquidus until the eutectic is met.
- At the Eutectic point anorthite + Diopside will crystalise together at about 1275º.



Diopside – Anorthite system.

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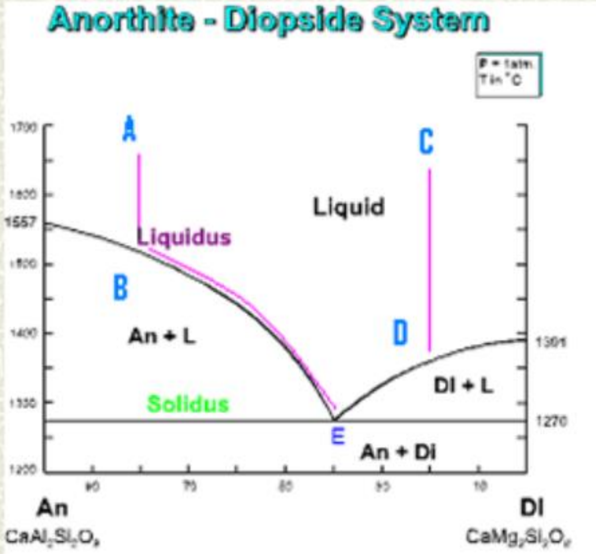
- Di = 58% and An 42%
- This proportion of minerals will now continue to crystalise (no further cooling is required).
- This eutectic proportion of minerals will be added to all the previously formed Diopside crystals.
- The final composition of the rock will be (unsurprisingly) the same as the original magma (20% An and 80% Di).



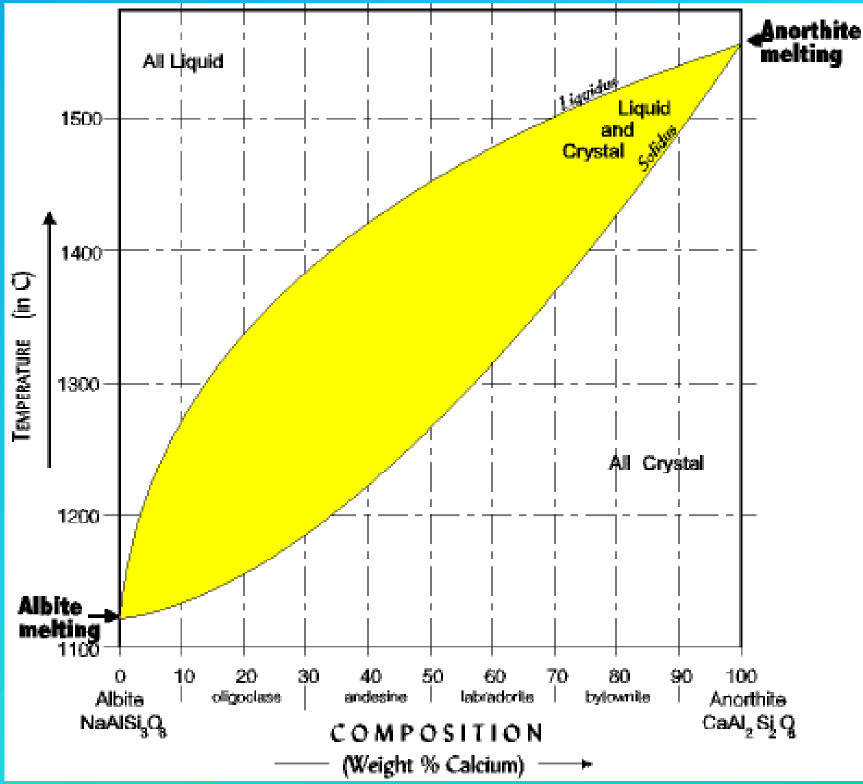
CRYSTALISATION OF BINARY MAGMAS

Low temperature, sodic plagioclase (Albite) is on the left; high temperature calcic plagioclase (anorthite) is on the right.

The diagram is divided into three fields, all liquid, liquid + crystal, all crystal. The ***liquidus*** line separates the *all liquid* phase from the *liquid+crystal* phase. The ***solidus*** line separates the *liquid+crystal* phase from the *all crystal * phase.

The solidus and liquidus lines are experimental, they have been determined by melting and cooling many melts at different percents anorthite.

Plagioclase Feldspar (Mix-Crystal System)

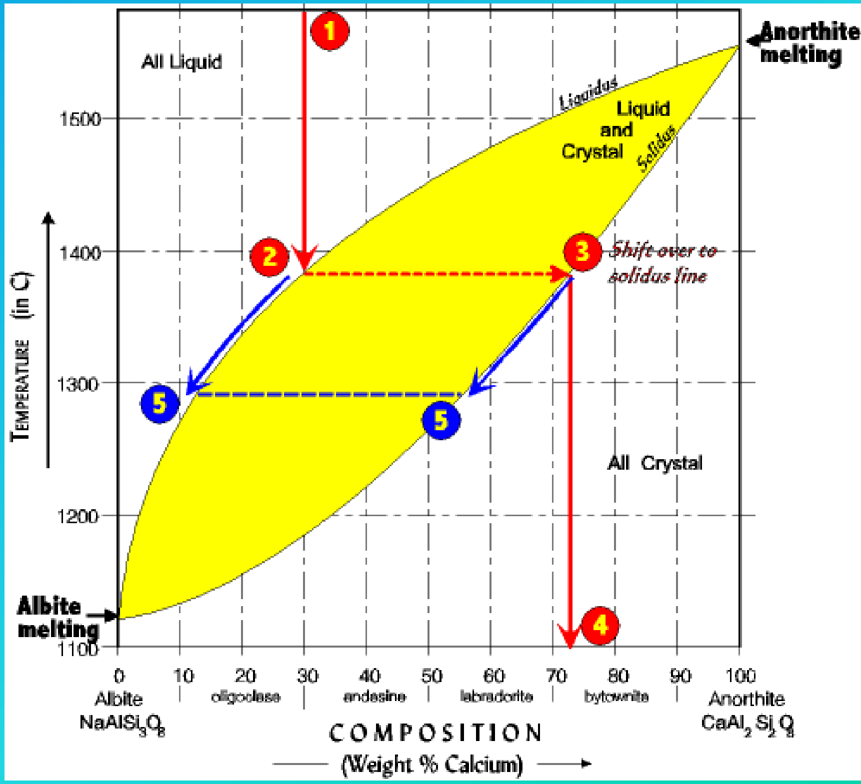


1. As an example, begin with a hot melt of 30% anorthite.

2. Cool melt to liquidus line. First crystal begins to form at about 1380°.

3. To determine the composition of the first crystal move horizontally across the diagram to the solidus line. The solidus always indicates crystal composition.

4. Then drop from the solidus straight down to the bottom scale. The first crystal is 72% anorthite. The diagram is always read in this manner, *down-across-down* regardless of starting composition.

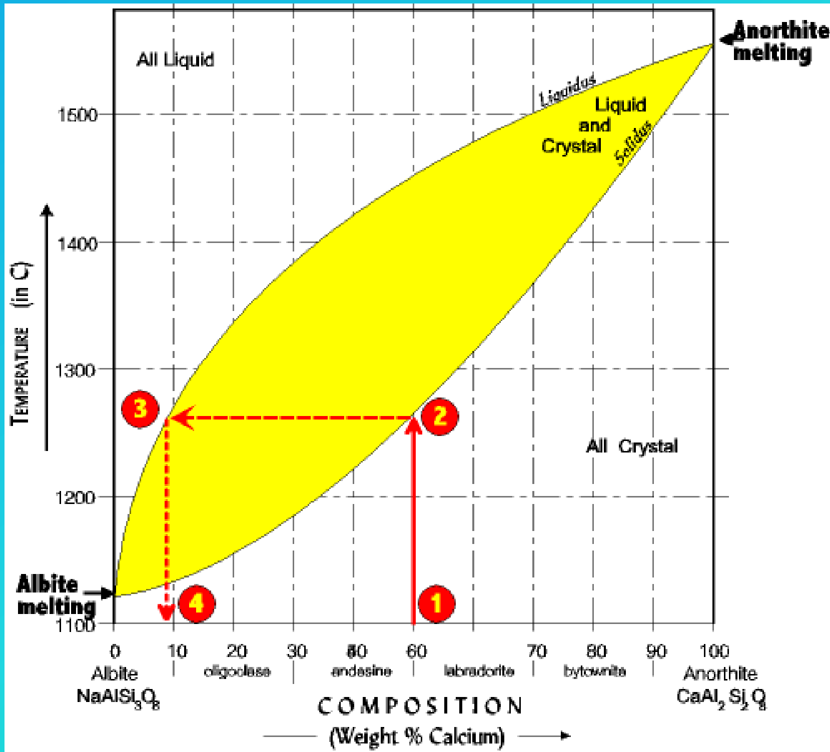


1. Imagine a plagioclase crystal which is 50 % anorthite (50% Ca and 50% Na). It is slowly heated until it begins to melt. The crystal does not melt uniformly. Rather the Na rich fraction (lower in the reaction series) begins melting before the Ca rich fraction (higher in the reaction series).

2. The composition of the first melt is found by drawing a vertical line up to the solidus line (at about 1260°). . .

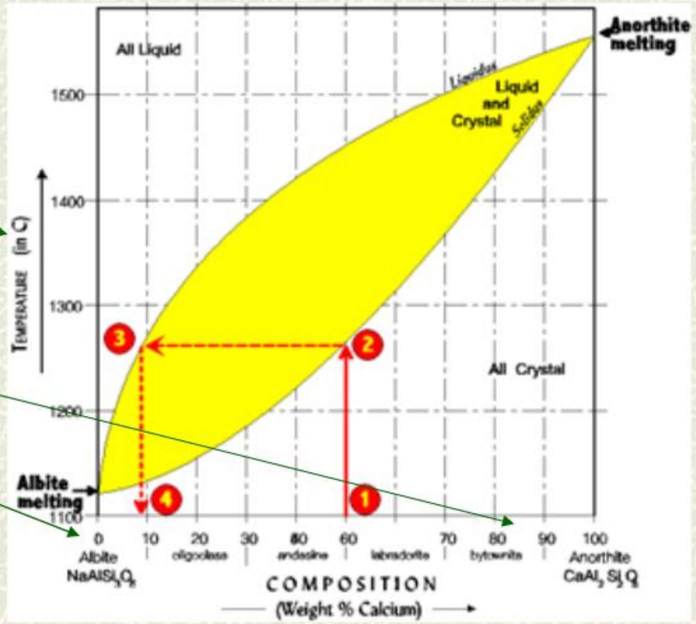
3. Then across to the liquidus line . . .

4. And back down to find the composition of the first melt, about 9% anorthite (91% albite).



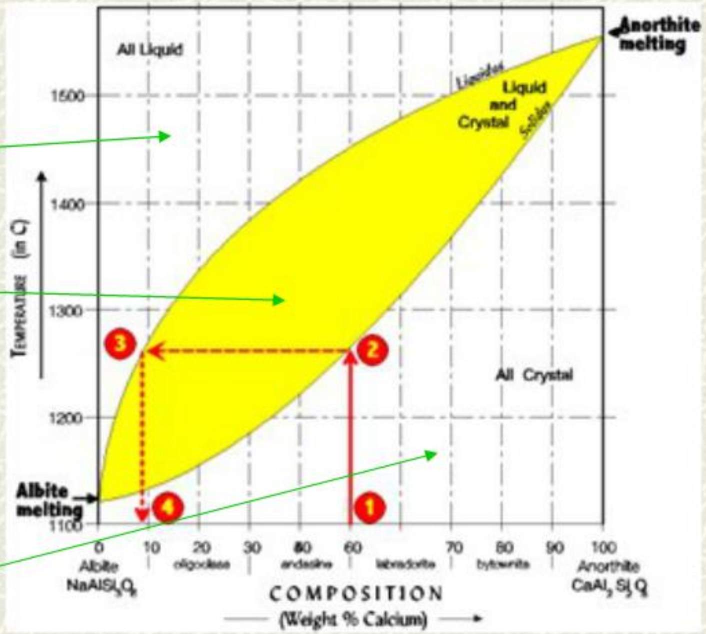
Albite - Anorthite

- **The axes:**
  - **Vertical:** shows you the temperature (T).
  - **Horizontal:** has 100% anorthite (Ca rich plagioclase) at one end and 100% albite (Na\rich plagioclase) at the other.



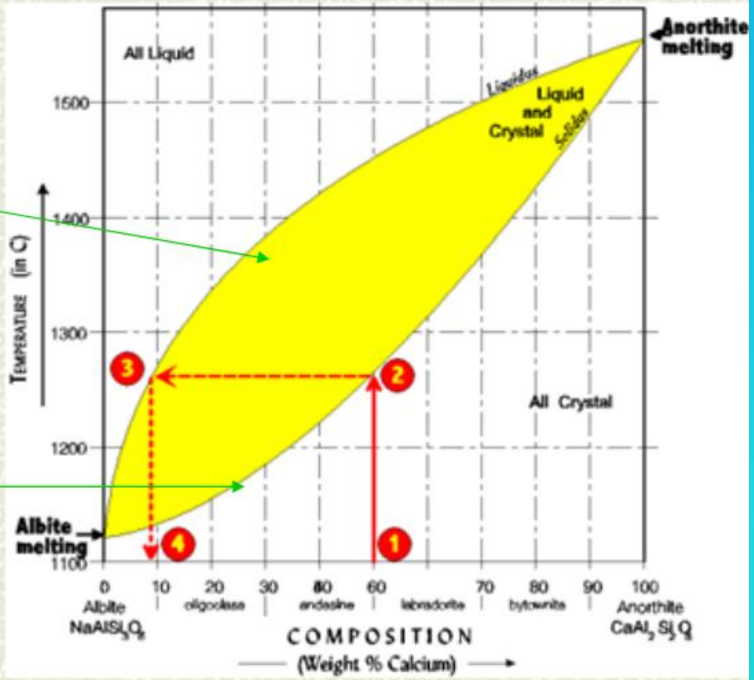
Albite - Anorthite

- The fields: these are the various areas of the phase diagram:
- **Liquid field:** This is where the magma is completely liquid.
- **liquid + crystal field:** this is where both liquid and crystals of plagioclase occur.
- Remember that this is a solid solution series so the crystals that form are mixtures of albite and anorthite.
- **Crystal field:** Totally solid. Only crystals of plagioclase occur.



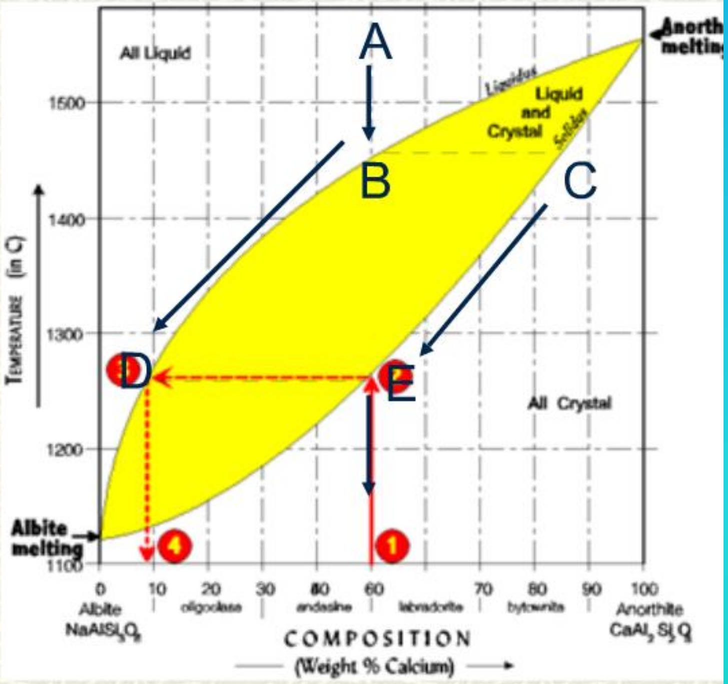
Albite - Anorthite

- The Lines:
- The Liquidus: Liquid only above, liquid + solid below.
- The Solidus: Solid only below, liquid and solid above.



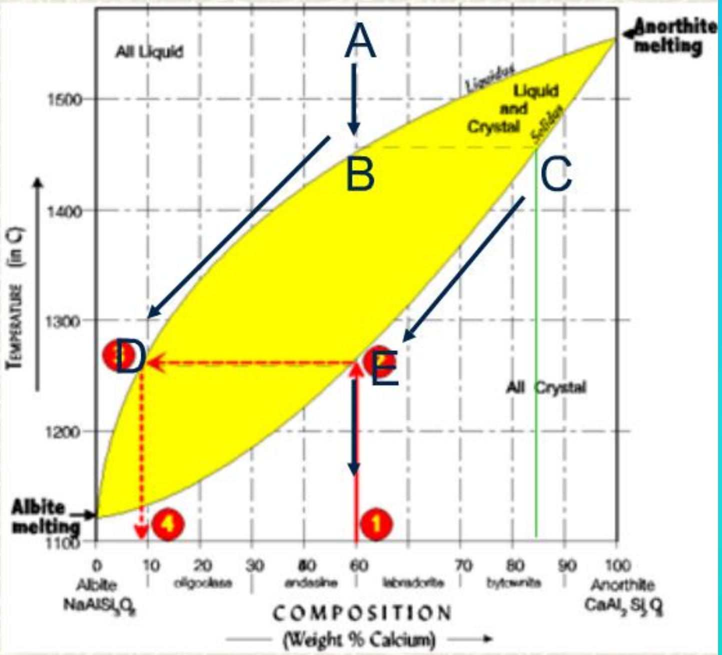
Albite - Anorthite

- The **diopside - anorthite** system has minerals of **fixed compositions**.
- Where **solid solution** exists the crystallisation takes a different pattern.
- Lets look at melt A as an example.



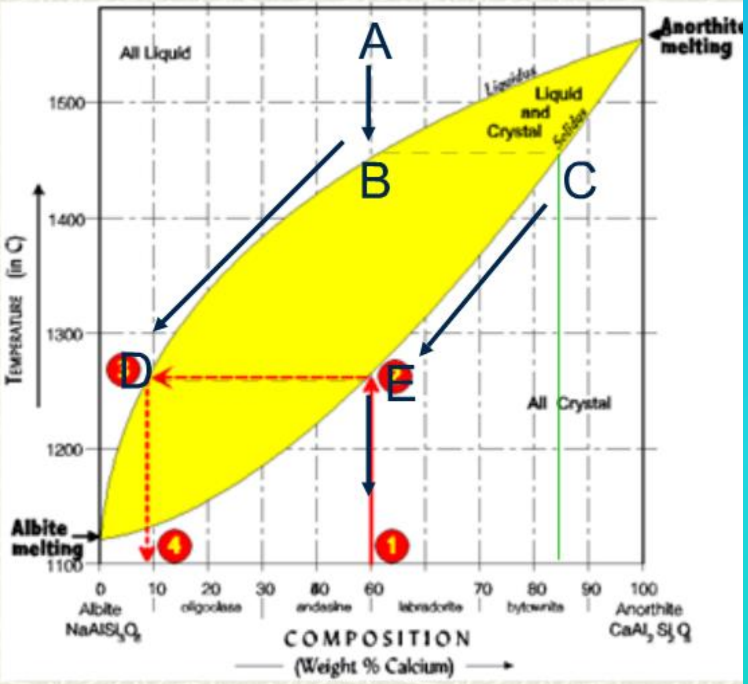
Albite - Anorthite

- What is the initial composition of magma A?
- 50% albite 50% anorthite.
- A cools to meet the liquidus at B.
- Solid of composition C begins to crystallise.
- What is this composition?
- 15% albite 85% anorthite
- C is much richer in anorthite than the liquid it is in.



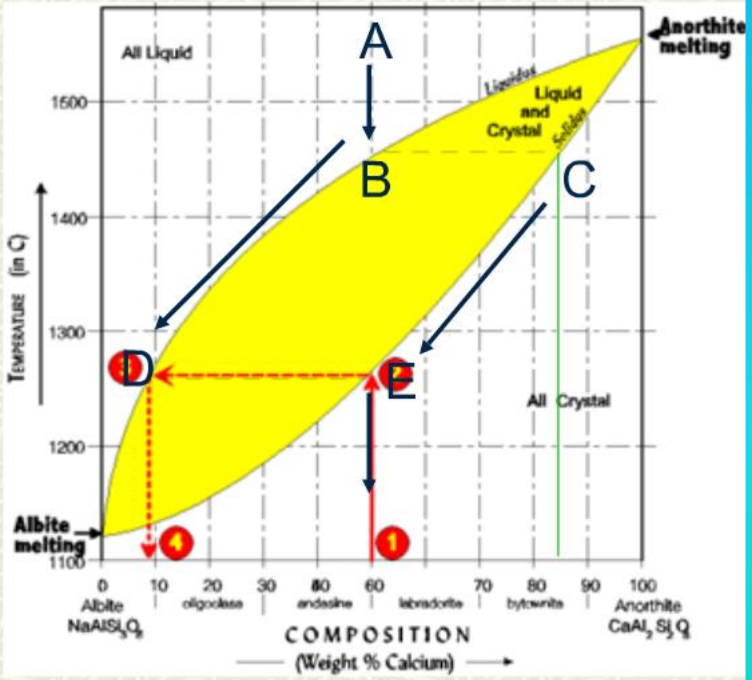
Albite - Anorthite

- The liquid has also been depleted in anorthite and so moves towards the albite end (D).
- In order to continue crystallising the T must drop and the magma moves down towards D.
- The solid reacts with the liquid, constantly changing its composition and moves towards E where crystallisation is complete.



Albite - Anorthite

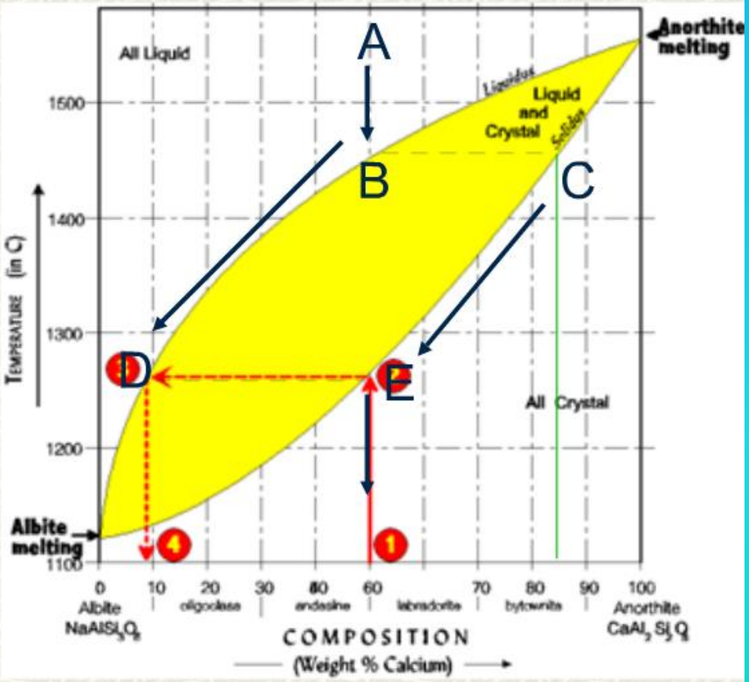
- The last liquid to crystallise (D) is much richer in **albite** than the original melt.
- But because the solid and liquid continuously react the composition of the final solid has the same composition as the original melt (50% albite 50% anorthite).



Albite - Anorthite

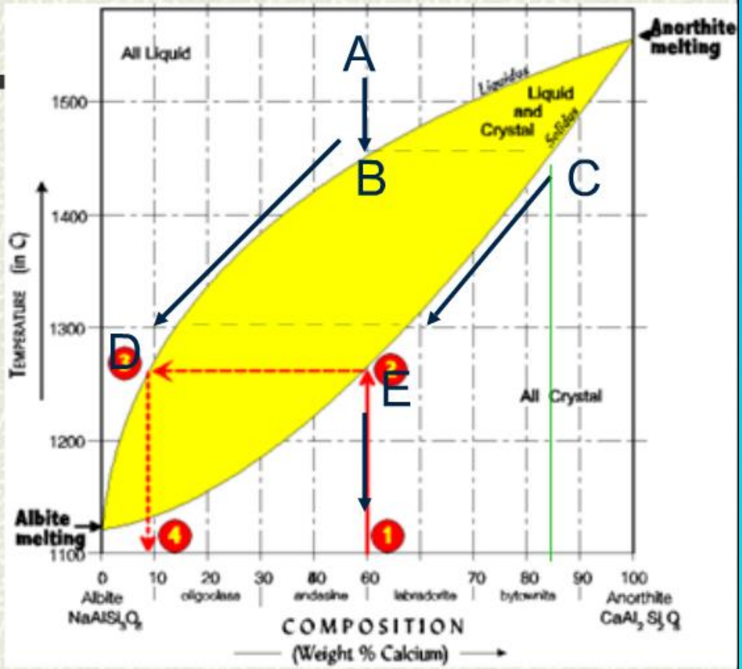
- So the final plagioclase crystal will eventually have the same composition as the original magma as long as it is able to react with the liquid.
- Why might it **not be able to react**.

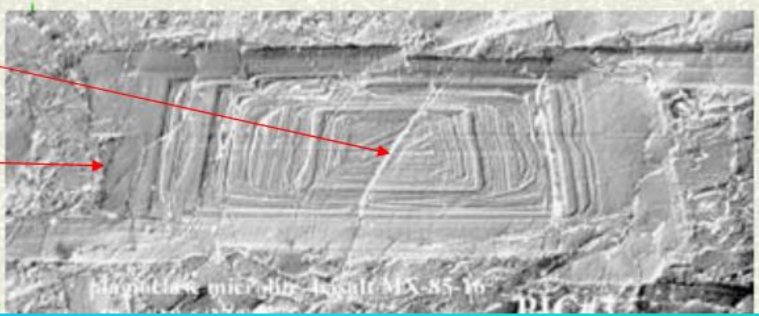
1. It **separates** from the magma.
2. It **cools too quickly** to be able to reach equilibrium.



Albite - Anorthite

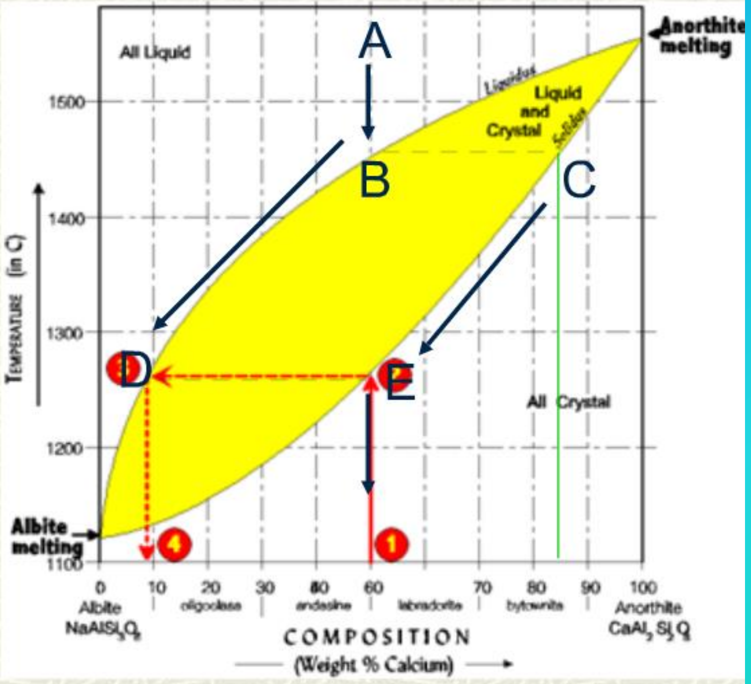
1. This will produce layers that start off with plagioclase that is initially **An rich** then each layer of rock will be more **albite rich**.
2. With this situation the crystals of plagioclase may be zoned with **An rich in the core** and **albite rich at the rim**.





Albite - Anorthite

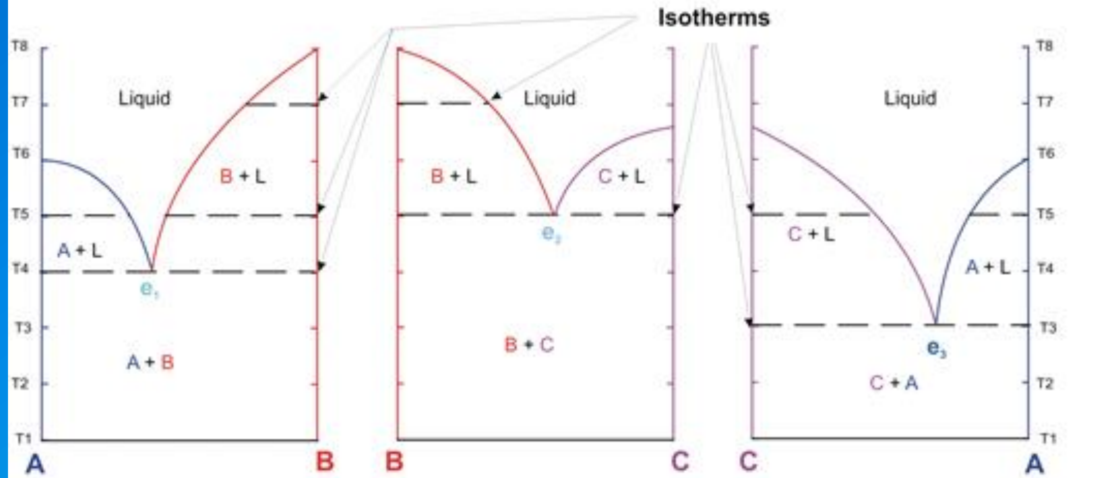
- What does this phase diagram have that the diopside – anorthite had?
- A eutectic point.
- Why doesn't it have one?
- Because there is only one mineral.

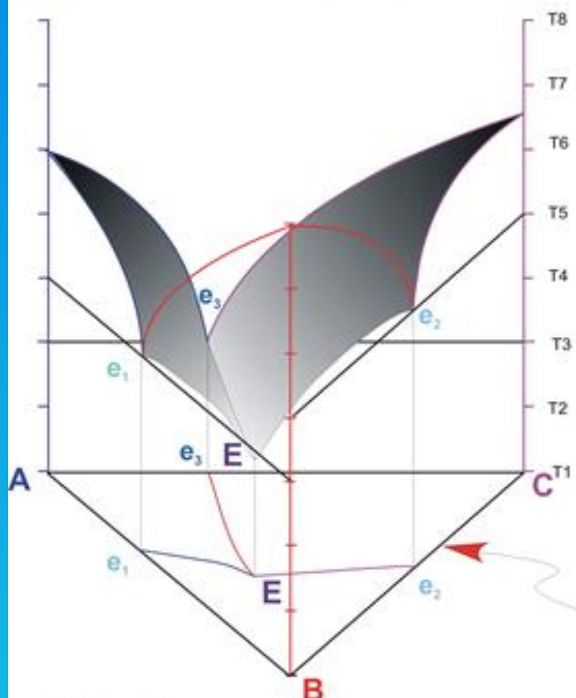


TERNARY DIAGRAM

- **Ternary phase diagrams are 3 component systems.**
- **To <u>Construct a Ternary Diagram</u> it is necessary to know the three binary systems for the three components.**
- **Ternary diagrams have a vertical temperature axis.**

ERSC 3P21 - TERNARY DIAGRAMS





The ternary diagram is constructed by joining together the three binary diagrams along the component axes **A**, **B** and C. The ternary diagram is defined in terms of the three components which define the system - **A**, **B** and C.

The ternary diagram represents the projection of the liquidus surface, its contours and the boundary curves, onto the base of the triangle formed when the binary diagrams are joined together. The three components which define the ternary system are located at the corners of the triangle.

This surface is contoured with the temperature interval representing the contour interval.

The projection of the three dimensional liquidus surface onto the base of the triangle to present a two-dimensional view of the surface.

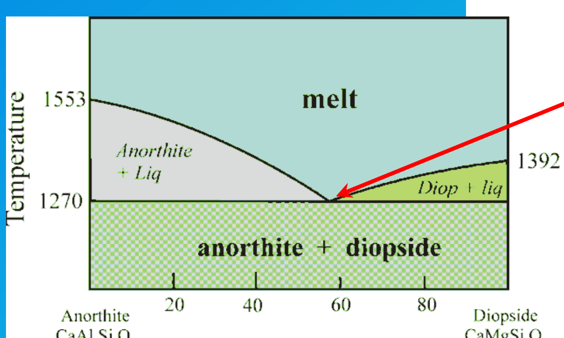
e_1, e_2 and e_3 - Represent the three binary eutectics in the three binary diagrams

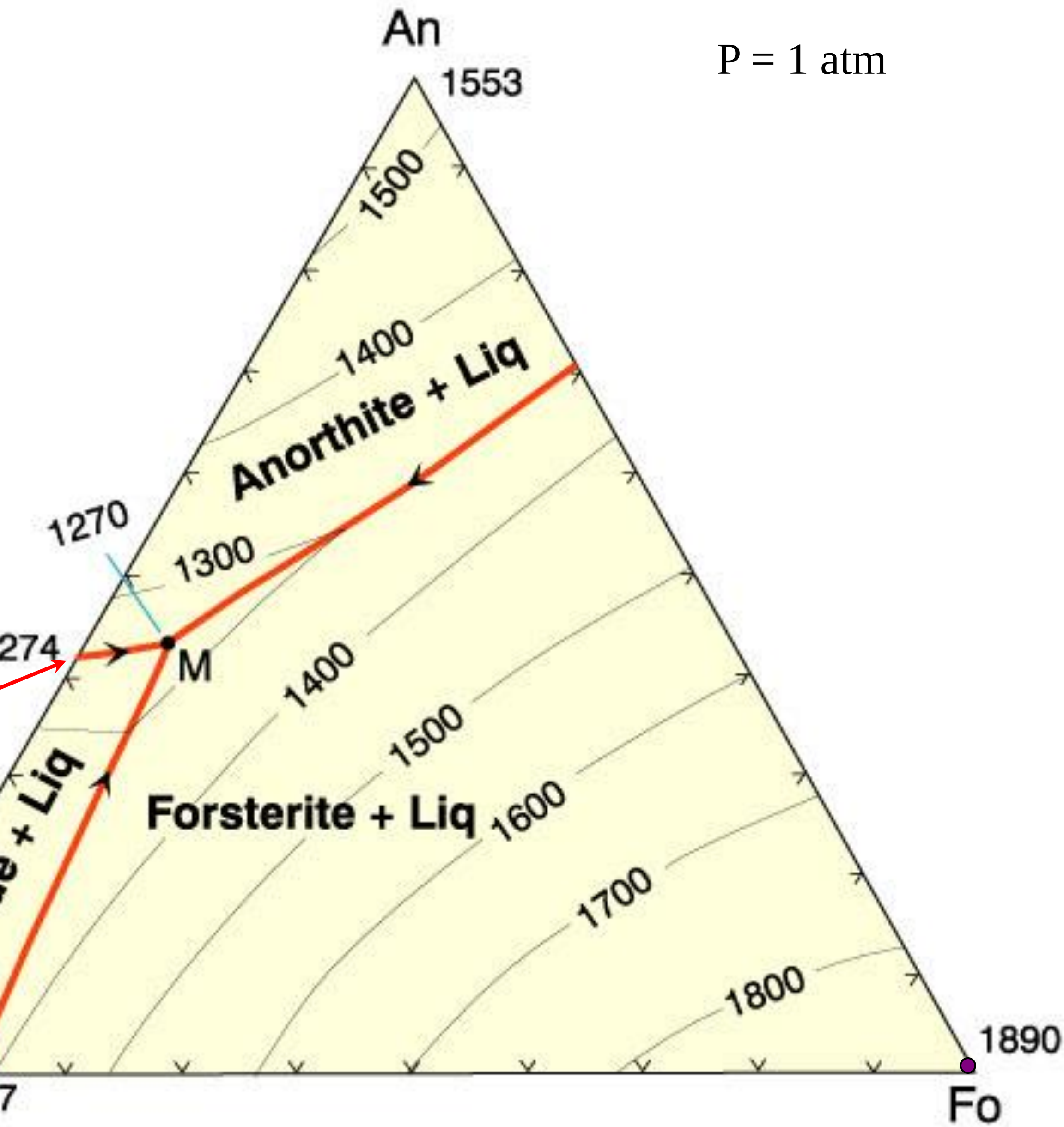
E - Represents the ternary Eutectic

Ternary Systems: Forsterite – Diopside – Anorthite Liquidus Projection

In order to portray the magmatic phase relations of systems with more than two chemical components, we need to develop specialized projection schemes.

Three component systems can be represented on a two dimensional sheet of paper, if we project only those phase relationships for which a magmatic liquid is present.

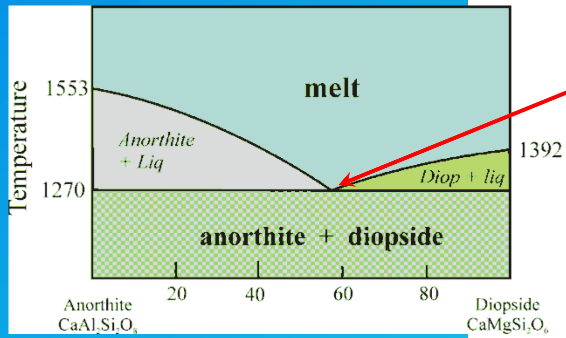


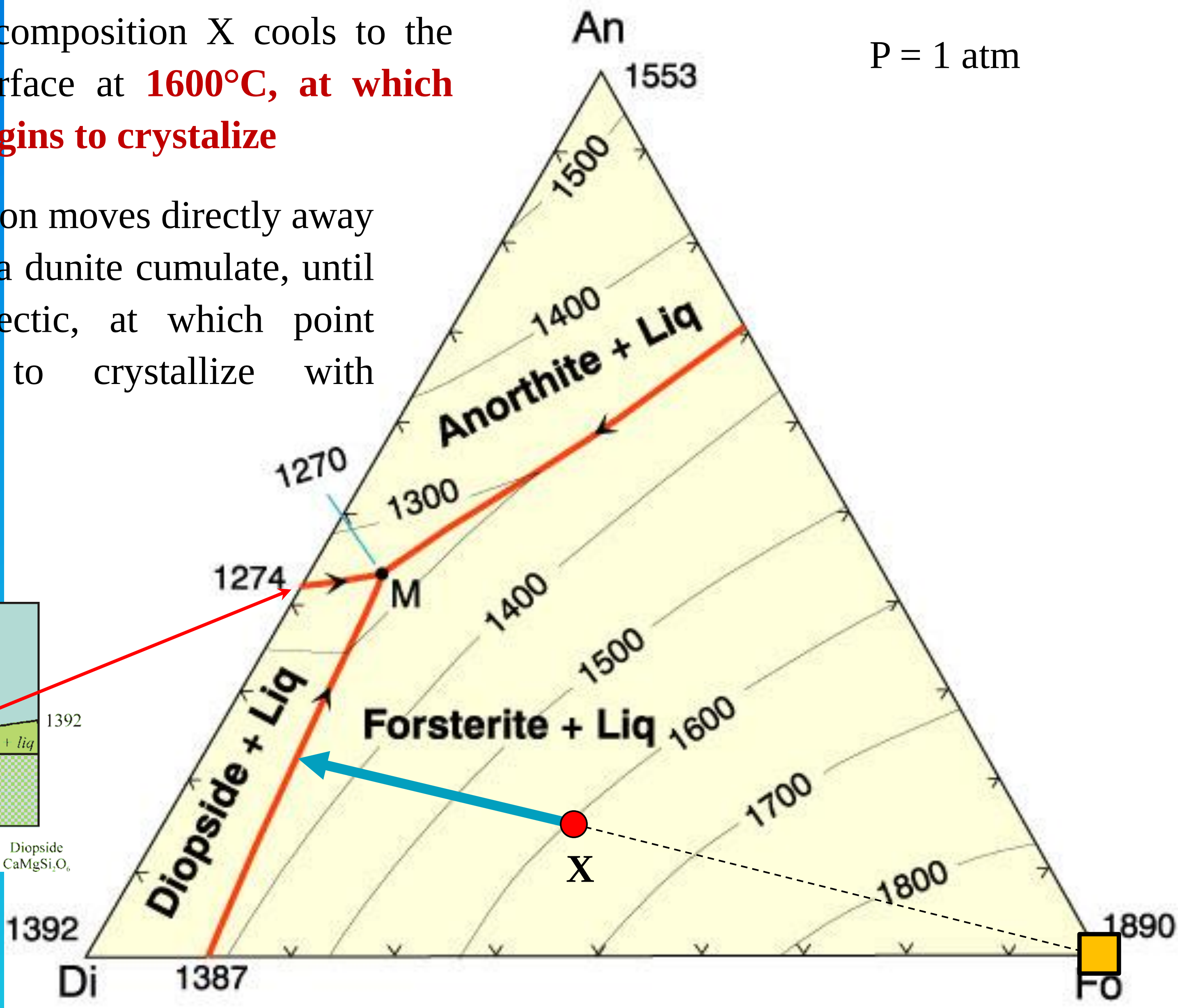


Ternary Systems: Forsterite – Diopside - Anorthite

A Liquid of bulk composition X cools to the olivine liquidus surface at **1600°C, at which point Forsterite begins to crystalize**

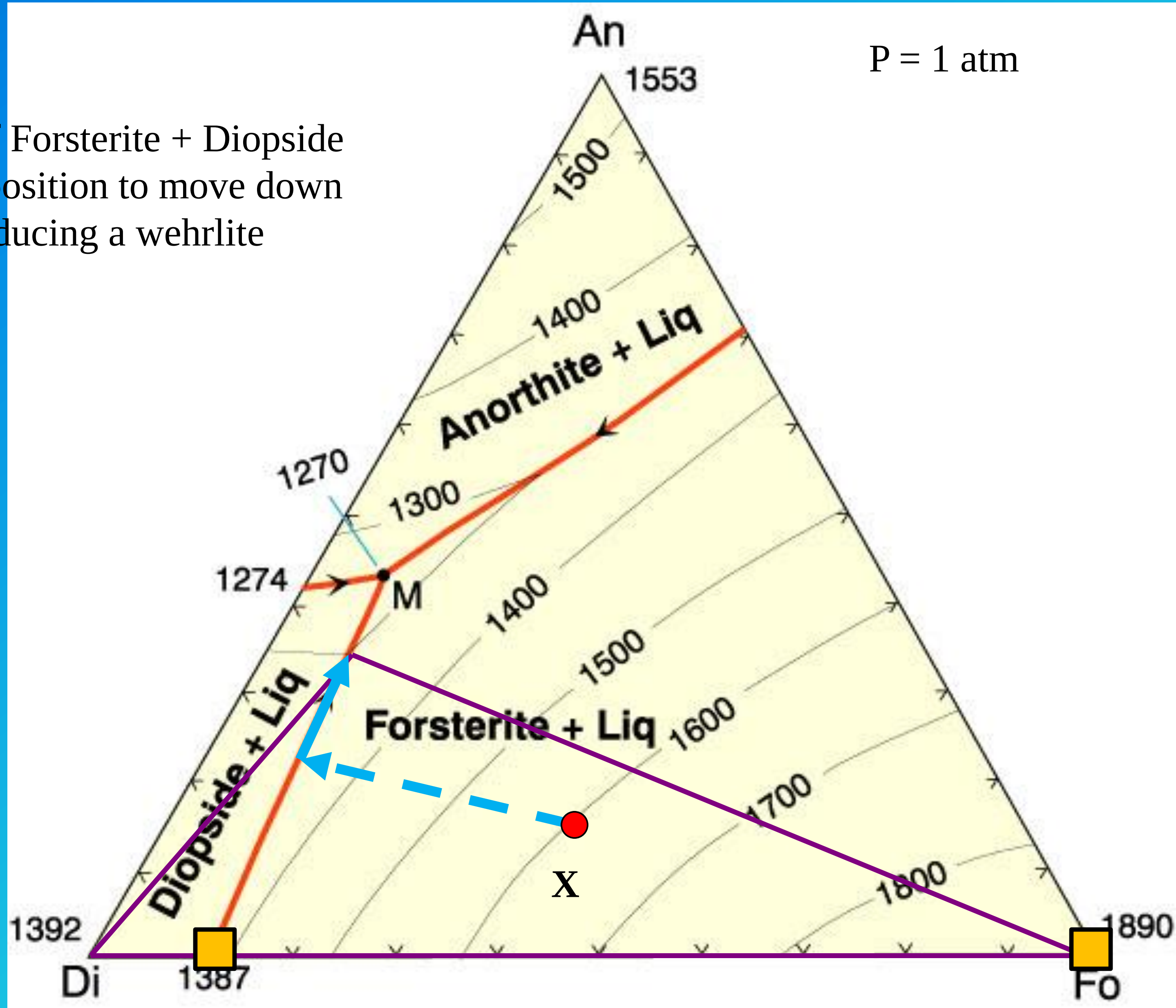
The liquid composition moves directly away from Fo, producing a dunite cumulate, until it reaches the cotectic, at which point Diopside begins to crystallize with Forsterite.





Forsterite – Diopside - Anorthite

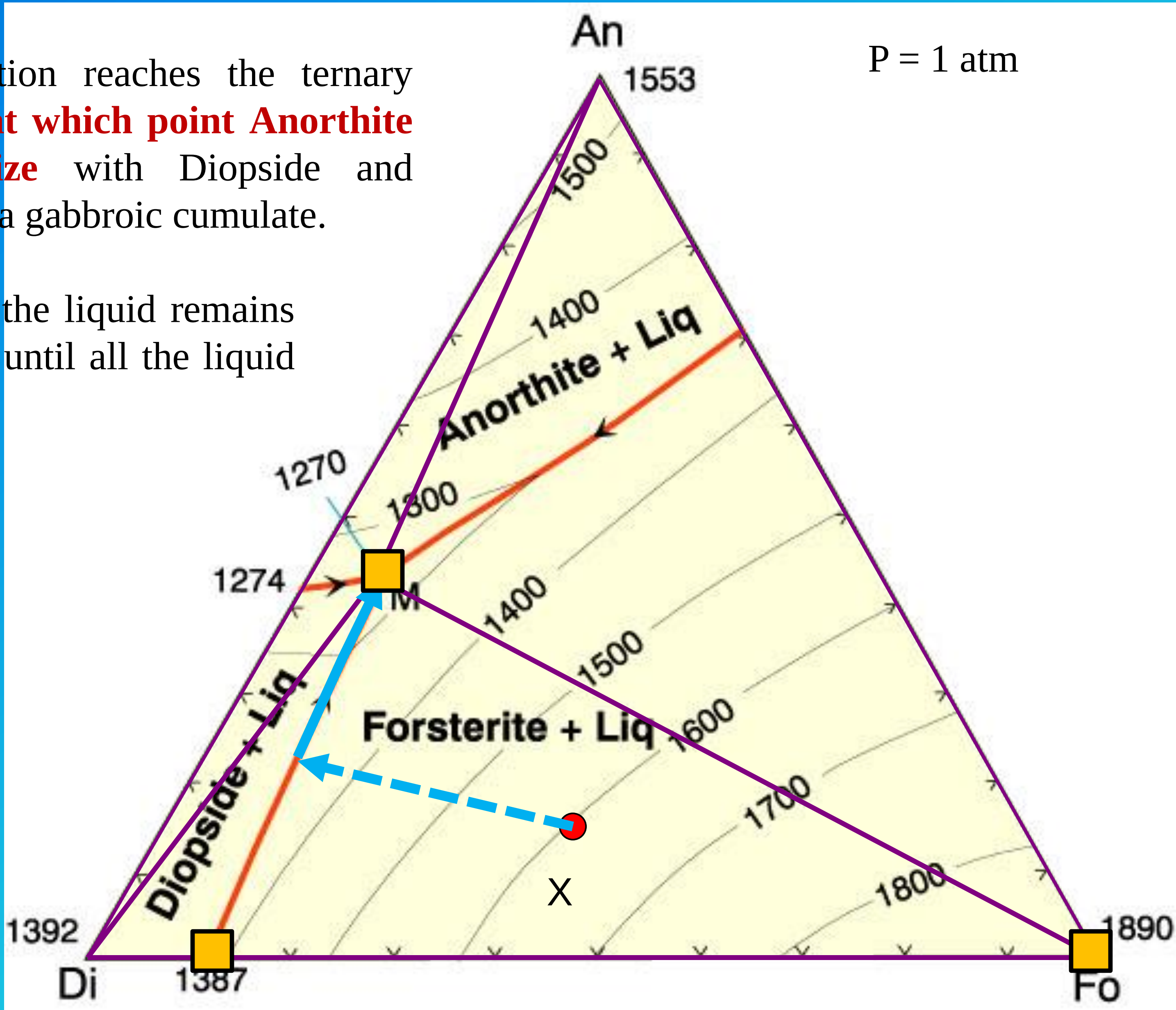
Co-precipitation of Forsterite + Diopside causes liquid composition to move down cotectic curve, producing a wehrlite cumulate.



Forsterite – Diopside - Anorthite

The liquid composition reaches the ternary eutectic at **1270°C, at which point Anorthite begins to crystallize** with Diopside and Forsterite, producing a gabbroic cumulate.

The composition of the liquid remains at the eutectic point until all the liquid is consumed.




Origin of magma
USGS

Origin of magma

- **Highly debated topic**
- **Generating magma from solid rock**
  - **Role of heat**

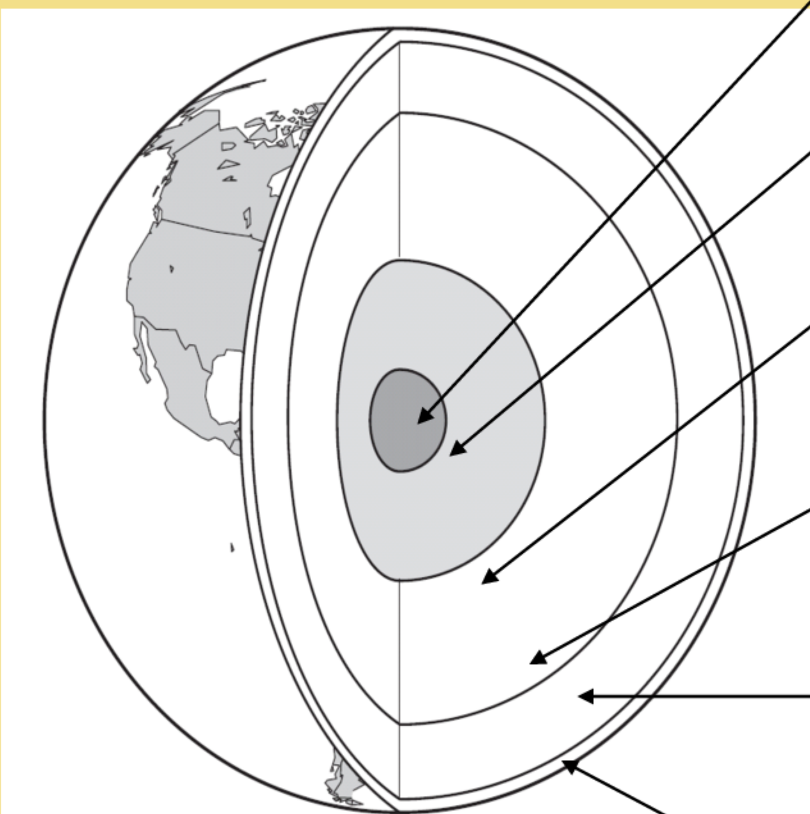
➢ **Temperature increases in the upper crust (geothermal gradient) average between 20°C to 30°C per kilometer of depth**

➢ **Rocks in the lower crust and upper mantle are near their melting points**

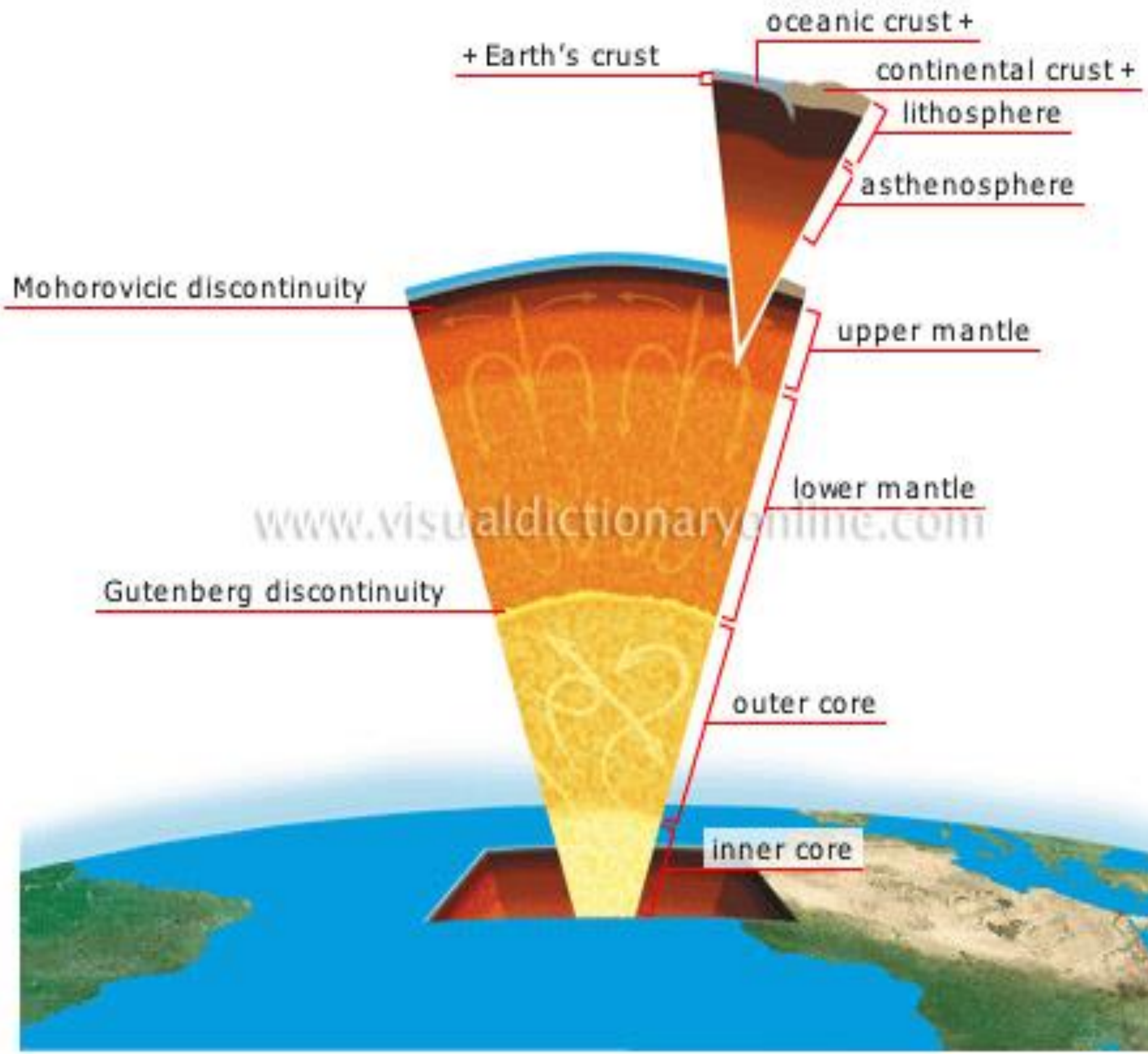
➢ **Any additional heat may induce melting**

UMR

Earth's Layers:



a. inner core
b. outer core
c. mantle
d. asthenosphere
e. lithosphere
f. crust

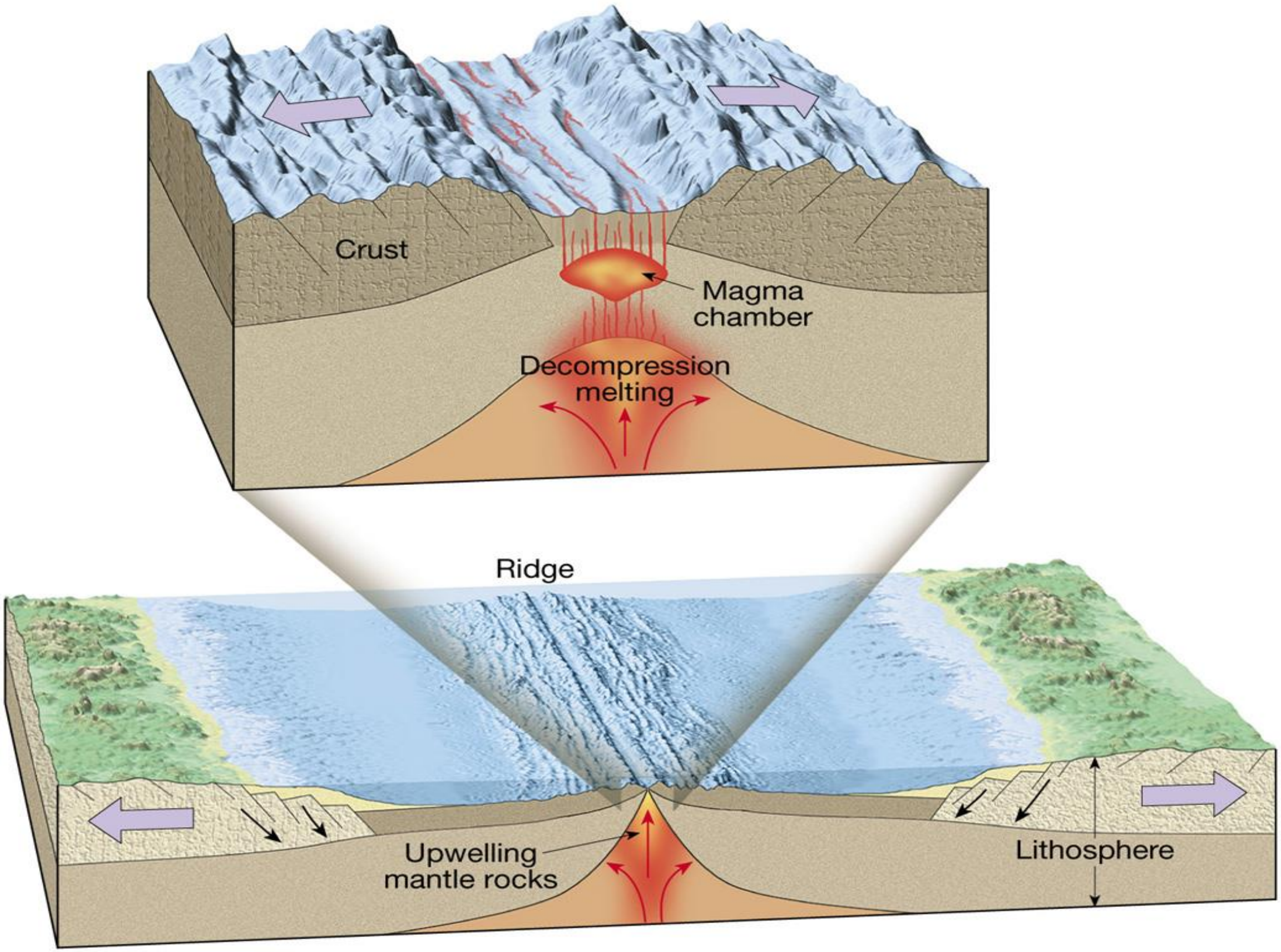

oceanic crust +
+ Earth's crust
continental crust +
lithosphere
asthenosphere
Mohorovicic discontinuity
upper mantle
lower mantle
Gutenberg discontinuity
outer core
inner core

Origin of magma

- **Role of pressure**
  - **Increases in confining pressure cause an increase in a rock's melting temperature**
  - **When confining pressures drop, decompression melting occurs**
- **Role of volatiles**
  - **Volatiles (primarily water) cause rocks to melt at lower temperatures**
  - **Important factor where oceanic lithosphere descends into the mantle**

UMR

Decompression melting



Evolution of magmas

- **Processes responsible for changing a magma's composition**

1. Magmatic differentiation

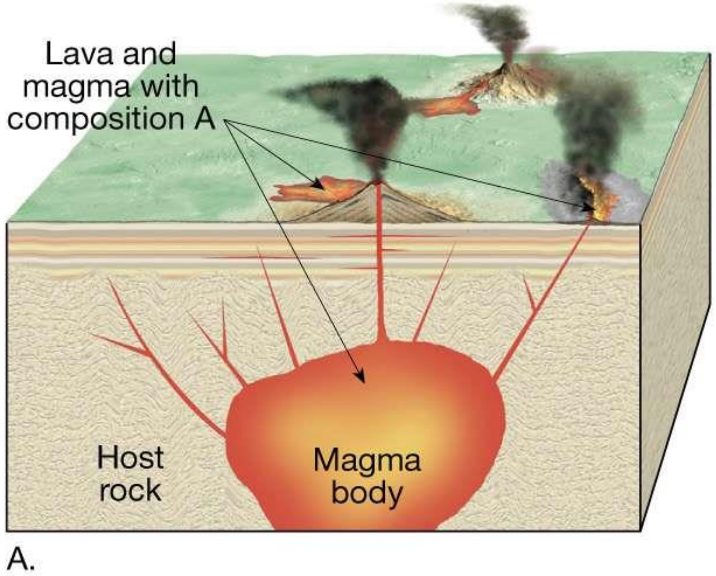
- **Separation of a melt from earlier formed crystals**

2. Assimilation

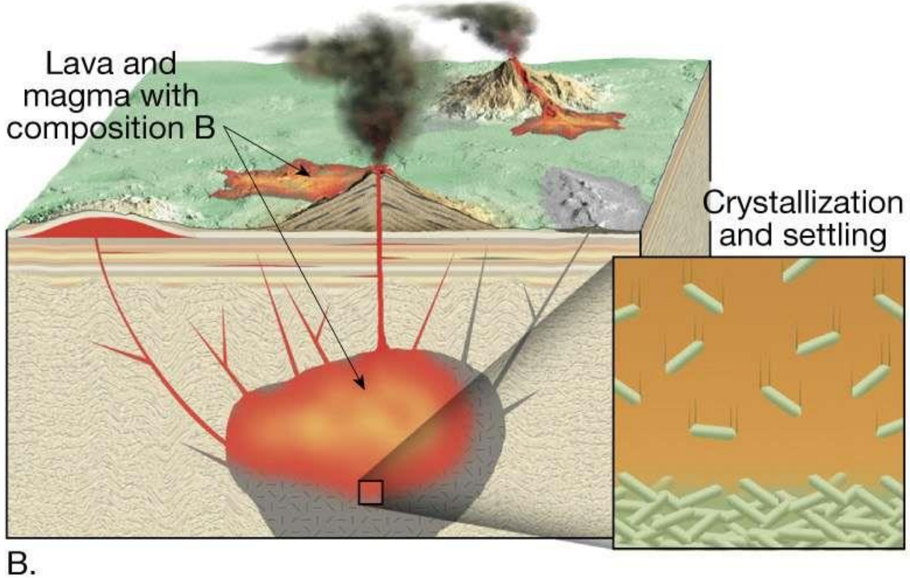
- **Changing a magma's composition by the incorporation of surrounding rock bodies into a magma**

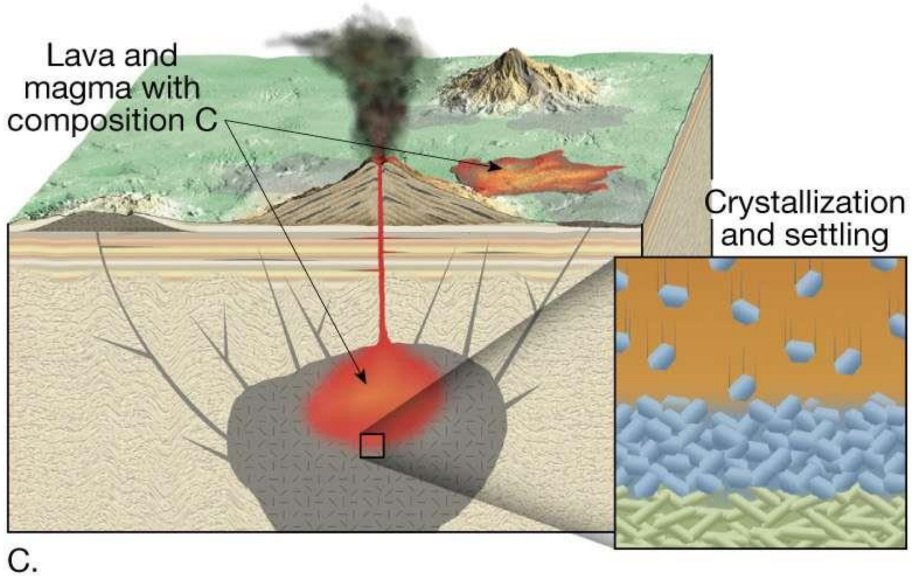
UMR

Differentiation



Magma evolves as the hotter minerals crystallize and settle to the bottom of the magma chamber





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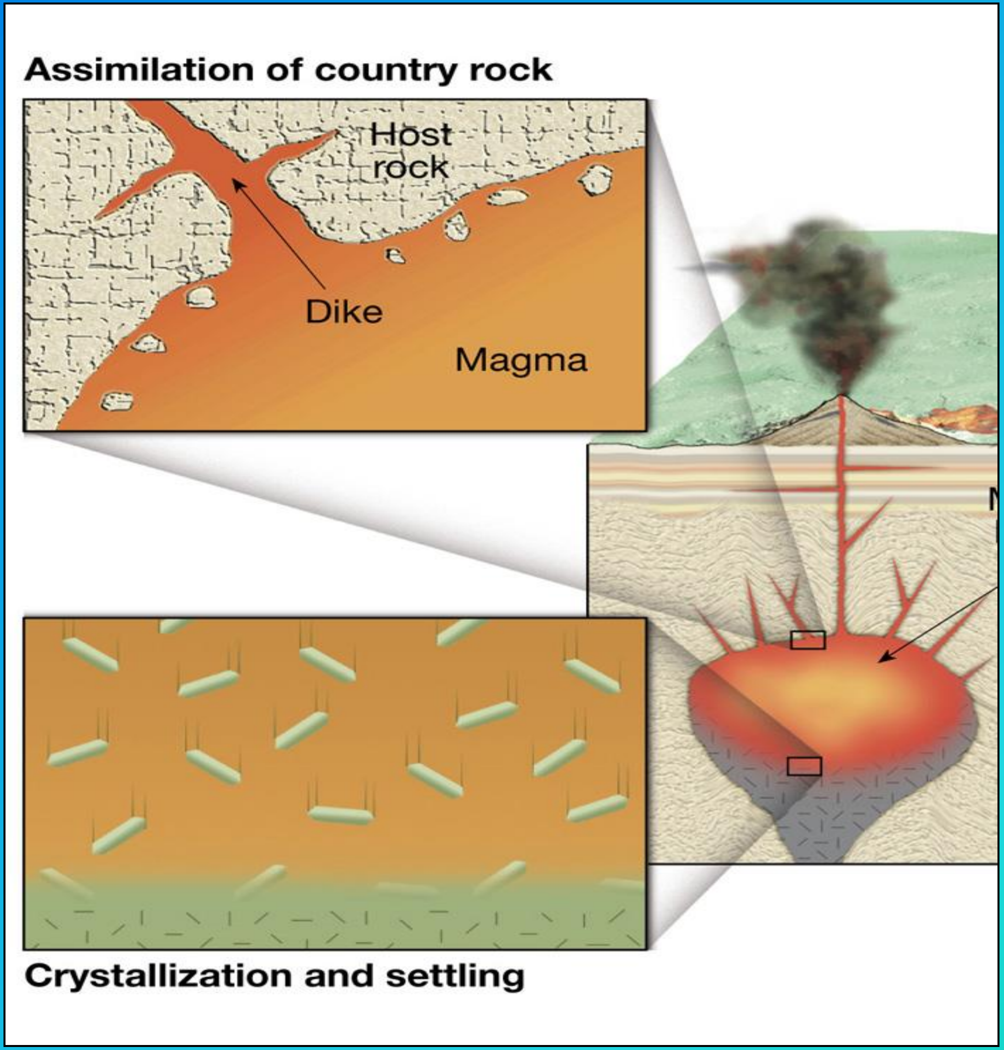
Assimilation

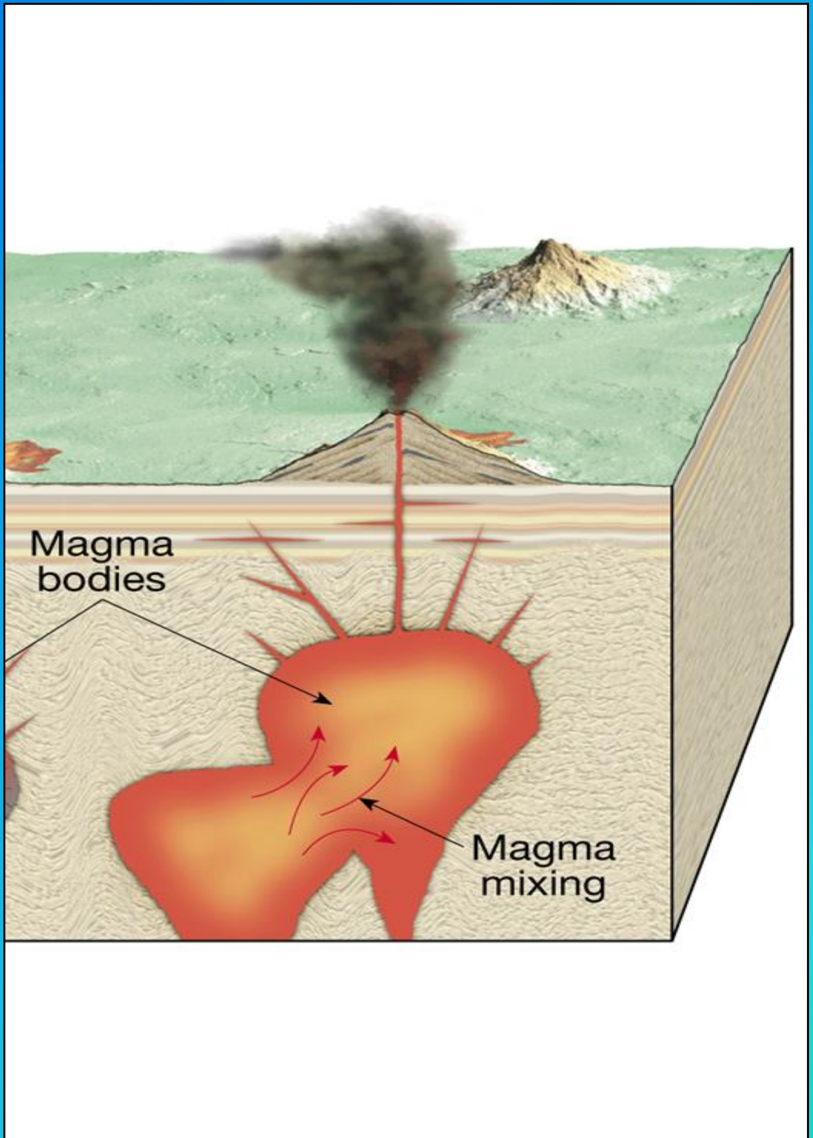


Evolution of magmas

3. Magma mixing

- Two chemically distinct magmas may produce a composition quite different from either original magma

Magma mixing,



Evolution of magmas

- **Partial melting and magma formation**
  - **Incomplete melting of rocks is known as partial melting**
  - **Formation of Basaltic magmas**
    - ➢ **Mostly originate from partial melting of ultramafic rock in the mantle at oceanic ridges**
    - ➢ **Large outpourings of basaltic magma are common at Earth's surface**

UMR

Evolution of magmas

- **Partial melting and magma formation**
  - **Formation of Andesitic magmas**
    - **Produced by interaction of basaltic magmas and more silica-rich rocks in the crust**
    - **May also evolve by magmatic differentiation**

UMR

Evolution of magmas

- **Partial melting and magma formation**
  - **Formation of Granitic magmas**
    - **Most likely form as the end product of crystallization of andesitic magma**
    - **Granitic magmas are more viscous than other magmas so they tend to lose their mobility before reaching the surface**
    - **Tend to produce large plutonic structures**

UMR

Common Igneous Rocks

1. Granite
2. Gabbro
3. Diorite
4. Peridotite
5. Rhyolite
6. Basalt
7. Andesite
8. Obsidian
9. Scoria
10. Pumice
11. Tuff
12. Volcanic Breccia

Granite

Granite is a phaneritic, felsic igneous rock composed primarily of quartz and feldspar.

Granite occurs in a variety of colors, but is usually white, light gray, or pink.

Gabbro

Gabbro is a phaneritic, mafic igneous rock composed primarily of calcium-rich feldspar, pyroxene, and olivine.

Diorite

Diorite is a medium-colored (or intermediate), phaneritic igneous rock.
This sample is composed of light-colored orthoclase feldspar and quartz crystals and dark-colored hornblende.

Peridotite

Peridotite is a phaneritic, mafic igneous rock. This sample is composed entirely of olivine and pyroxenes.

Rhyolite

Rhyolite is an aphanitic, felsic igneous rock composed primarily of orthoclase feldspar and quartz.

A few larger crystals of orthoclase feldspar are visible in this sample.

Basalt

Basalt is an aphanitic, **mafic igneous rock.**

Its dark color is due to its dark-colored mineral composition.

Andesite

Andesite is an aphanitic, **intermediate igneous rock.**

Larger, dark-colored crystals in this example of andesite are hornblende.

Obsidian

Obsidian is a **glassy igneous rock.**

Extremely rapid cooling of volcanic material prevents crystal development and creates this volcanic glass.

Scoria

- Scoria is an igneous rock with vesicular texture.
- The vesicles, or holes, in the rock form from bubbles of volcanic gas.
- Scoria forms the crust of lava flows.

Pumice

- Pumice is another volcanic igneous rock with vesicular texture.
- Pumice is less dense and lighter colored than scoria.
- t is commonly identified by its scratchy surface and low density.

Tuff

- Tuff is an igneous rock with pyroclastic texture.
- Tuffs consist of fine-grained fragments created during volcanic eruptions.
- Some larger fragments are visible in this specimen.

Volcanic Breccia

Volcanic breccia is an igneous rock with large, angular fragments of volcanic material.

This breccia probably formed during a violent volcanic eruption.

TYPES OF BASALTS

- Tholeiitic basalt: relatively rich in silica and poor in sodium. Basalts of the ocean floor and continental flood basalts comes under this.
- MORB (Mid Ocean Ridge Basalt): characteristically low in incompatible elements. Commonly erupted only at ocean ridges.
- High alumina basalt :may be silica-undersaturated or oversaturated. Alumina (Al_2O_3) content is more than 17% and intermediate in composition i.e.between tholeiite and alkali basalt

CONT….

- Alkali basalt:relatively poor in silica and rich in sodium. It is silica-undersaturated and may contain feldspathoids, alkali feldspar and phlogopite
- Boninite: is a high-magnesium form of basalt that is erupted generally in back-arc basins, distinguished by its low titanium content and trace element composition.

ORIGIN

- The origin of basaltic magma is universally accepted as involving melting within the earth's mantle
- Evolve by fractional crystallization as separate series along different paths. Each is chemically distinct
- Tholeiites are generated at mid-ocean ridges, oceanic islands, subduction zones
- Alkaline basalts generated at oceanic islands and at subduction zones

Cont..

- The melting behavior of basalts indicates that it is the partial melting products of a more primitive rock (e.g. garnet peridotite).
- In the region of magma generation (below 60 km) the parental material, presumed to be garnet peridotite, yields an eclogitic magma and its fractionation depends on the garnet and omphacite of the eclogite, not on plagioclase and clinopyroxene of a basaltic magma.

Cont…

- Increase of the garnet constituents in the magma at high pressure by effective removal of omphacite or shift of the garnet-omphacite boundary surface will give rise to a tholeiite-type magma at low pressure.
- Increase of the omphacite constituents in the magma at high pressure by physical or physicochemical means will give rise to an alkali basalt-type magma at low pressure.
- In general, alkali basalt-type magmas are to be expected to be generated at greater depths than tholeiite-type magmas from the same primary source rock.

Theories

Origin 1: Mechanism involving partial melting under under different condition

-higher pressure or lower temperature partial melting of mantle material produce alkaline basalt whereas lower pressure or higher temperature partial melting produce tholeiitic magma

2: Mechanism involving stage of melting or degree of melting

-early stage of partial melting of garnet peridotite produce tholeiitic basalt, whereas an intermediate stage give rise to alkaline olivine basalt

Cont….

3. Mechanisms involving partial melting of a mantle source of different composition

- MOR basalts contain less radiogenic Pb and Sr, and more radiogenic Nd, and depleted light REEs compared with continental tholeiites and are probably derived from mantle of different compositions
- Tholeiitic basalts form by partial melting of peridotite containing H_2O, K_2O, and Na_2O whereas alkaline basalts form by partial melting of peridotite richer in CO_2, TiO_2, and P_2O_5

Cont…

4. Mechanisms involving differentiation or fractional crystallisation

- Higher pressure fractionation of basalt formed by partial melting in the mantle could give alkaline basalt, whereas lower-pressure fractionation of the same basalt could give tholeiitic magma
- Partial melting at a depth of about 60km could give alkali basalt. Partial crystallisation at a depth of about 40km could produce transitional basalt
- Partial melting of peridotite and leaching of

Cont…

Wall rocks during ascent of the magma could form alkali basalt

- limited partial melting of garnet peridotite could produce alkali basalt and more extensive melting give tholeiitic basalt
- Incipient melting of heated mantle wall rocks produced early alkalic melts; later melting could produce tholeiitic melts; stagnation as the volcano moved off the hot spot and a decrease in melting of the wall rocks would form the latest alkalic basalts

Cont…

-Separation of high Mg olivine and pyroxene at a depth of 15 to 35 km could form high Al basalt

5. Mechanisms involving a particular tectonic environment

-Basaltic melt from a deep mantle plume accumulates at the base of the lithosphere.

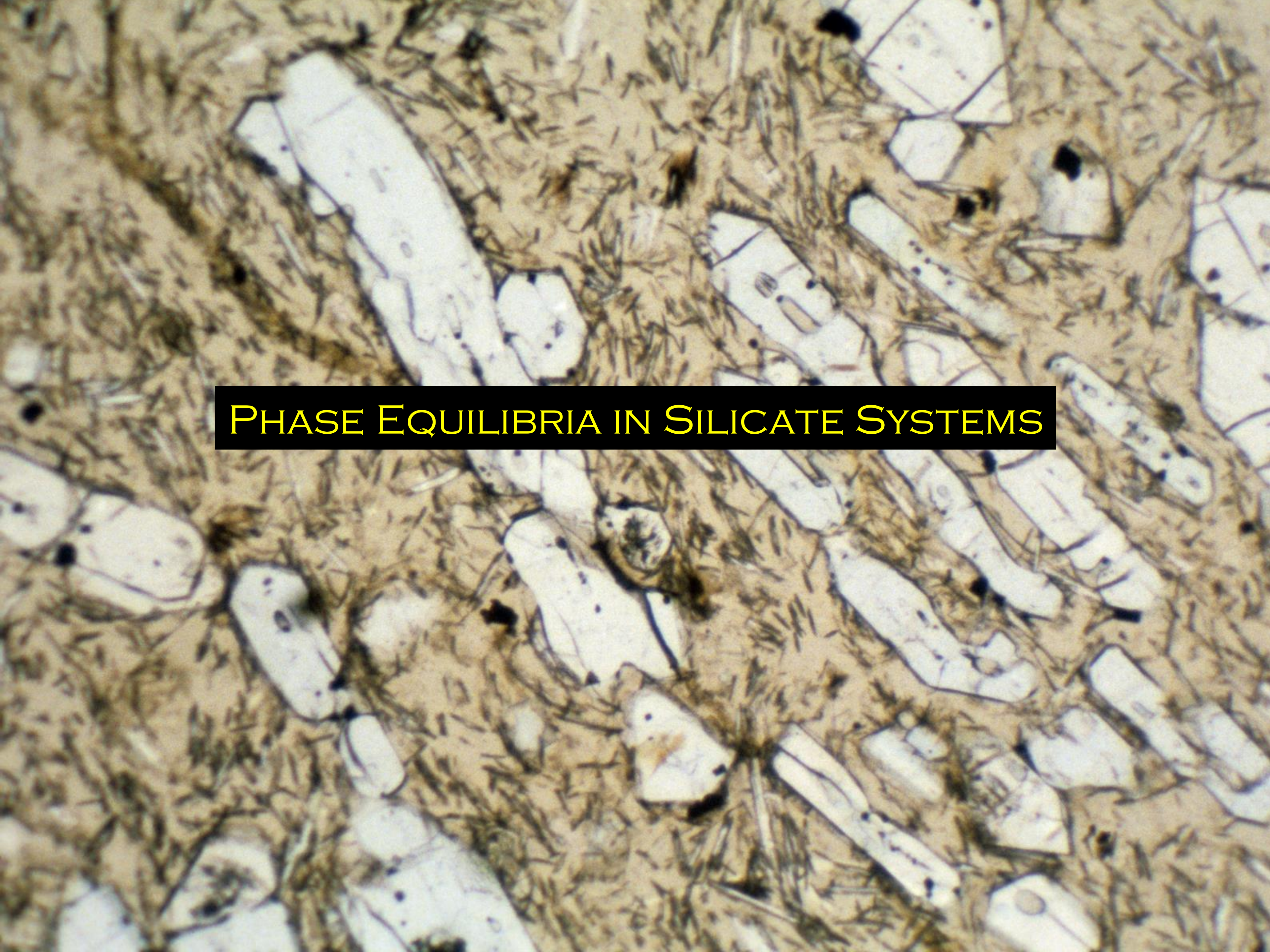
Magma at the base of the lithospheric plate finds access to the surface along zones of crustal weakness

Cont….

- Alkali basalts volcanism may be associated with the lateral edge of a subducting lithosphere plate.
- Tholeiitic and transitional basalts such as those formed at a mid-oceanic ridge could originate by partial melting at modest pressures below about 8 to 10 kbars or depths of 30 to 35 km.

Deccan Traps

- The **Deccan Traps** are a large igneous province located on the Deccan Plateau of west-central India and one of the largest volcanic features on Earth
- They consist of multiple layers of solidified flood basalt that together are more than 2,000m thick and cover an area of 500,000 km^2 and a volume of 512,000 km^3
- The basalt flows are generally massive, compact and coarse grained in central part but become fine grained near top and bottom parts


Phase Equilibria in Silicate Systems

THE PHASE RULE

For a system at equilibrium the phase rule relates:

- **P** = **number of phases** that can coexist,
- **C** = **number of components** making up the phases, and
- **F** = **degrees of freedom.**

- Where these three variables are related in the equation

$$\mathbf{P + F = C + 2}$$

The degrees of freedom represent the environmental conditions which can be independently varied without changing the number of phases in the system. Conditions include:

- **Temperature,**
- **Pressure,**
- **Chemical Composition,**
- **pH,**
- **Eh,**
- **Oxygen Fugacity.**

Minerals are the monitors of the physical and chemical conditions under which they formed.

The occurrences of minerals, their parageneses (stable associations), types of reactions, and compositional variation (e.g. zoned minerals) all provide important information about geologic history and processes.

Gibbs' Phase Rule provides the theoretical foundation, based in thermodynamics, for characterizing the chemical state of a (geologic) system, and predicting the equilibrium relations of the phases (minerals, melts, liquids, vapors) present as a function of physical conditions such as pressure and temperature.

Gibbs' Phase Rule also allows us to construct phase diagrams to represent and interpret phase equilibria in heterogeneous geologic systems.

The Phase Rule

It was first presented by ***Gibbs*** in 1875.

It is very useful to understand the effect of intensive variables, such as temperature, pressure, or concentration, on the equilibrium between phases as well as between chemical constituents.

It is used to deduce the number of degrees of freedom (f) for a system. Sometimes called: "*the variance of the system*".

It states that :

When the equillibrium between any number of phases is influenced only by temperature, pressure and concentration but not influenced by gravity, or elctrical or magnetic forces or by surface action then the number of Degrees of Freedom (F) of the system is related to the number of Components (C) and of Phases (P) by the phase rule equation:

$$F + P = C + 2$$

A phase is any physically separable material in the system. Every unique mineral is a phase (including polymorphs); igneous melts, liquids (aqueous solutions), and vapor are also considered unique phases.

It is possible to have two or more phases in the same state of matter (e.g. solid mineral assemblages, immiscible silicate and sulfide melts, immiscible liquids such as water and hydrocarbons, etc.)

Phases may either be pure compounds or mixtures such as solid or aqueous solutions–but they must "behave" as a coherent substance with fixed chemical and physical properties.

Terminology used…..

Phase:

A phase is defined as any homogeneous and physically distinct part of a system having all physical and chemical properties the same throughout the system. ***A system may consist of one phase or more than one phase.***

E.g.

- A system containing only liquid water is one-phase system
- A system containing liquid water and water vapour (gas) is a two phase system
- A system containing liquid water, water vapour and solid ice is a three phase system.
- Pure substances (solid, liquid, or gas) made of one chemical species only, is considered as one phase, thus, oxygen, benzene, and ice are all one phase.

Contd….

Component:

*The term component is defined as the **least number of independent chemical constituents** in terms of which the **composition of every phase can be expressed by means of a chemical equation.***

E.g.

- **Water system has three phases,** ice, water and water vapour and the composition of all these phases is expressed in terms of one chemical individual water.
- **Thus water system has one component only.**
- **Similarly Sulphur system has four phases:** rhombic sulphur, monoclinic sulphur liquid sulphur and sulphur vapour and the composition of all these phases is expressed by one chemical individual sulphur. **Therefore Sulphur system is one component system.**

Thus, all the phases in one component system is expressed by only one chemical individual.

DEGREES OF FREEDOM(F)

It is defined as the least number of variable factors of a system which must be specified so that the remaining variables are fixed automatically and the system is completely defined.

E.g.

MONOVARIANT or **UNIVARIANT SYSTEM**

For Water = Water Vapour system, F=1, The system has two variables, P and T. At definite T, the vapour pressure of water can have only one fixed value. Thus if one variable is specified , the other is fixed automatically. Hence this system has one degree of freedom, it is **MONOVARIANT** or **UNIVARIANT.**

BIVARIANT SYSTEM

For a pure gas, PV=RT, if P and T values are specified there can have be only one definite value of V or that the volume is fixed automatically. Thus it has two degrees of freedom, the system is **BIVARIANT.**

F is the number of degrees of freedom in the system (also referred to as the variance of the system).

For geologic applications, this generally refers to the number of variables (e.g. pressure and temperature) that can be independently changed without altering the state of the system (i.e. the number of phases and their compositions are constant).

Three common types of equilibria are possible:

Invariant equilibria, in which neither P or T can be changed; on a phase diagram, this is represented as a singular invariant point

Univariant equilibria, in which either P or T can be changed independently, but to maintain the state of the system, there must be a corresponding change in the other variable; on a phase diagram this is referred to as a univariant curve

and

Divariant equilibria, in which both P and T are free to change independently without changing the state of the system (but bounded by the conditions defined by the univariant equilibria).

Advantages of Phase Rule

• Phase rule is applicable to both Chemical and Physical equilibria.

• Phase rule is applicable to macroscopic systems and hence no information is required regarding molecular or micro structure.

• We can conveniently classify equilibrium states in terms of phases, components and degrees of freedom.

• The behaviour of system can be predicted under diff. conditions.

• According to phase rule, diff. systems behave similarly if they have same degrees of freedom.

• Phase rule helps in deciding under a giving set of conditions:

1) Existence of equilibrium among various substances.
2) Interconvergence of substance or
3) Disappearance of some of the substances.

Limitations of Phase Rule

•Phase rule is applicable only for those systems which are in equilibrium. It is not much use for those systems which attain the equilibrium state very slowly.

•Only three degrees of freedom *viz*, temperature, pressure and components are allowed to influence the equilibrium systems.

•Under the same conditions of temperature and pressure, all the phases of the system must be present.

•It considers only the number of phases, rather than their amounts.

Applying the phase rule to:

- One-component systems.
- Binary systems.
- Liquid-vapor equilibrium.
- Temperature-composition diagrams.

Phase Rule in One-Component Systems

- Notice that in one-component systems, the number of degrees of freedom seems to be related to the number of phases.

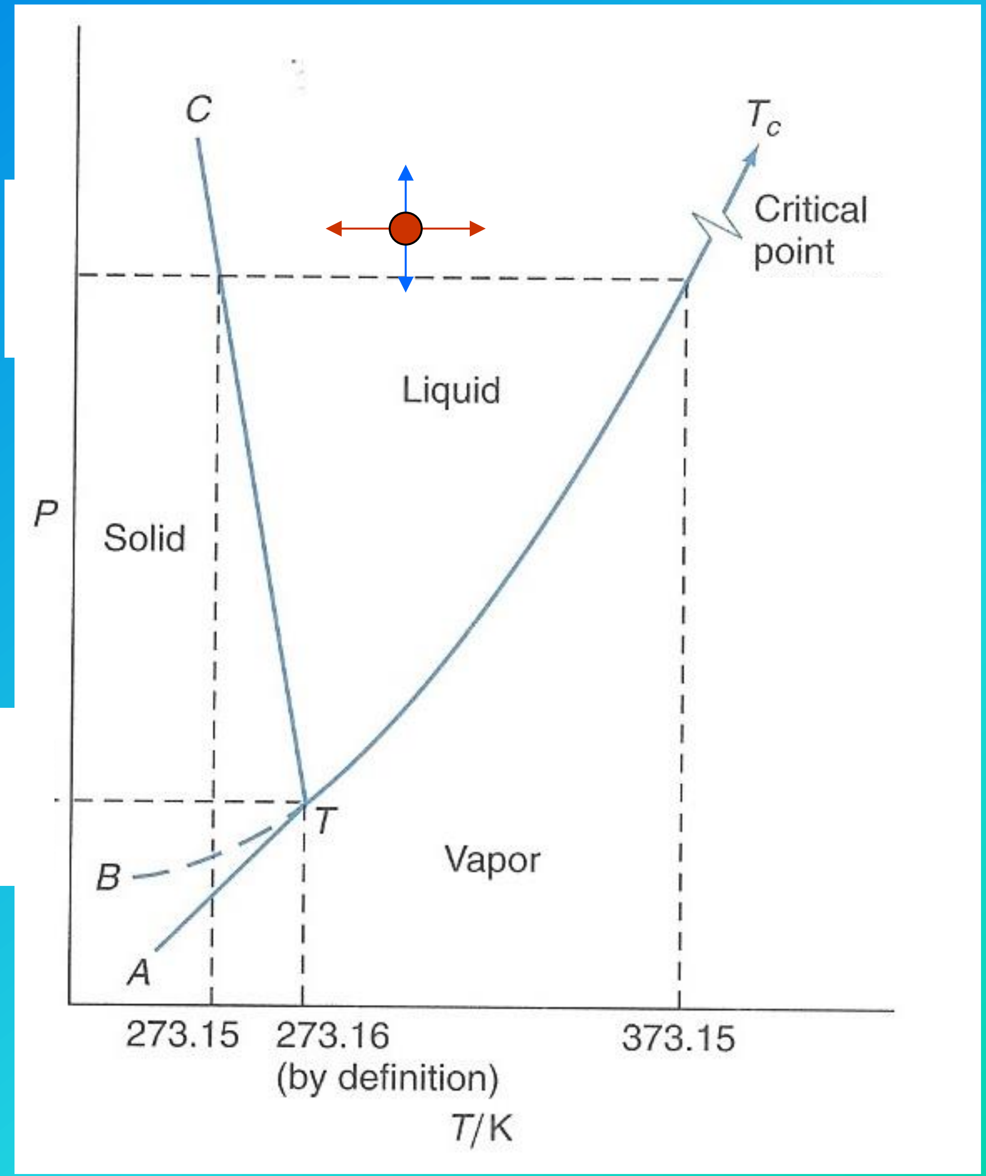
Phase Rule with Single Component Systems			
System	# of phases	Degrees of Freedom	Comments
Gas, liquid or solid	1	2	System is bivariant
Gas-liquid, liquid-solid, or gas-solid	2	1	System is univariant
Gas-liquid-solid	3	0	System is invariant

The Water System

How many components do you have?

We have only one component which is H_2O.

In the one-phase regions, one can vary either the temperature, or the pressure, or both (within limits) without crossing a phase line.
We say that in these regions:
$f = c - p + 2$
$= 1 - 1 + 2$
$= 2$ degrees of freedom.

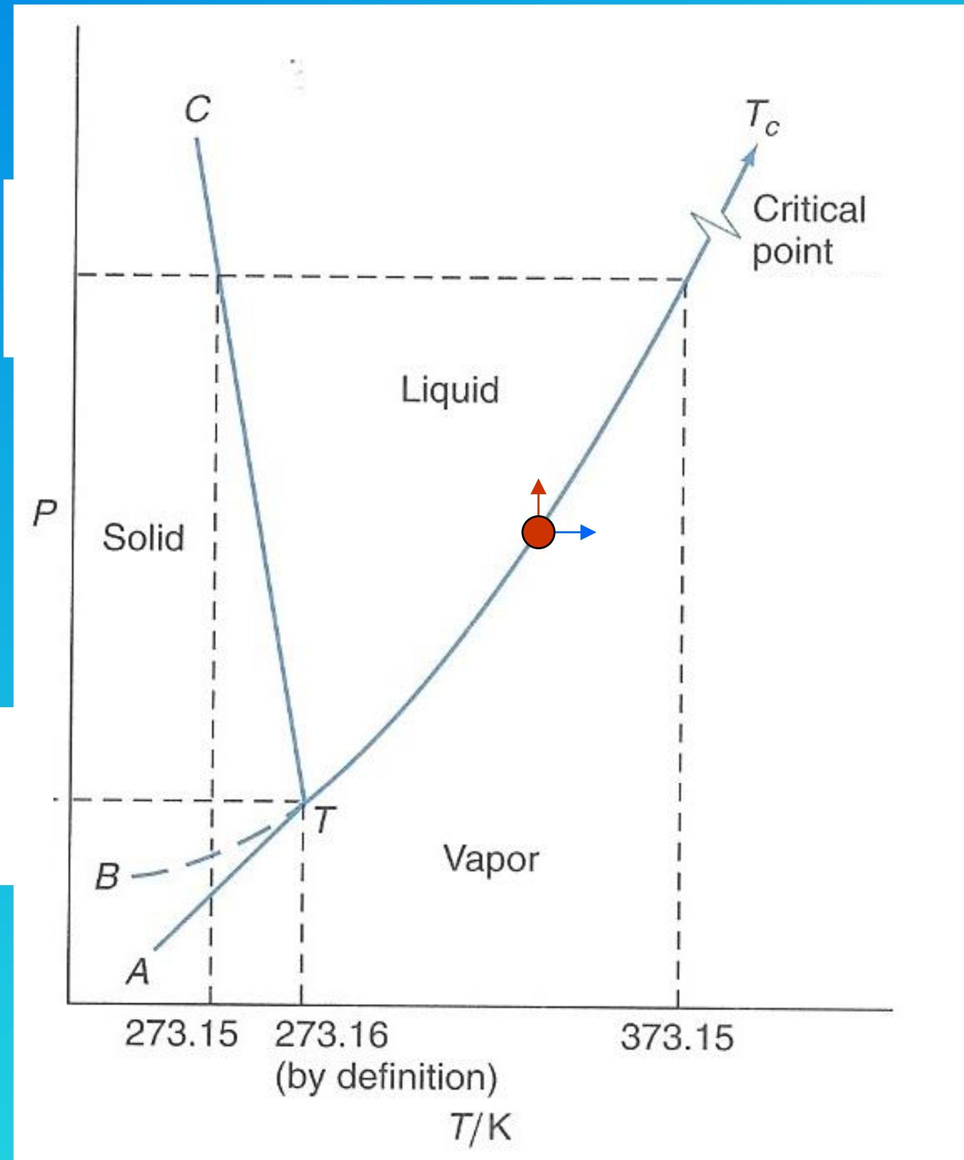


Phase Diagram of Water

Along a phase line we have two phases in equilibrium with each other, so on a phase line the number of phases is 2.
If we want to stay on a phase line, we can't change the temperature and pressure independently.

We say that along a phase line:

$f = c - p + 2$
$= 1 - 2 + 2$
$= 1$ degree of freedom.



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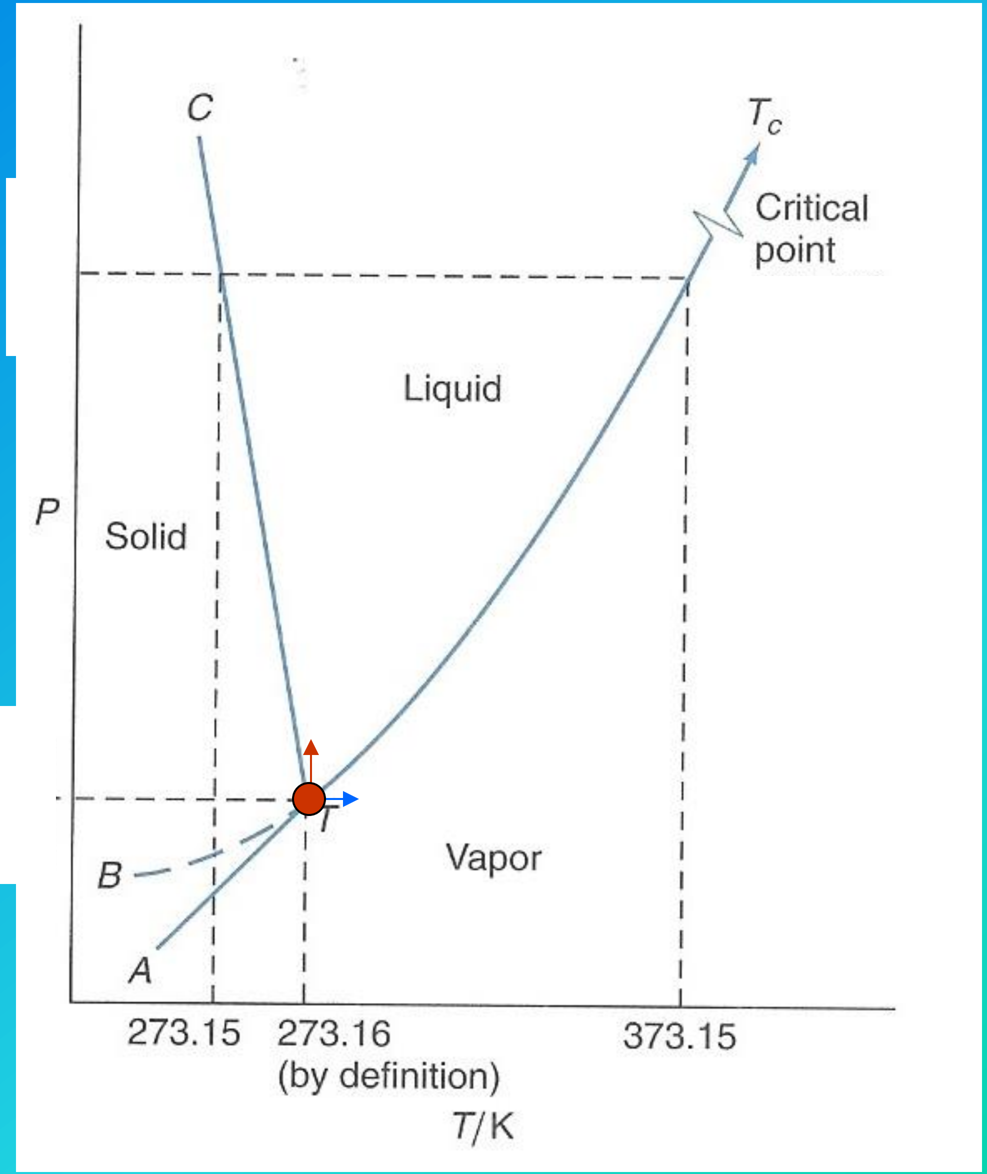
At the triple point there are three phases in equilibrium, but there is only one point on the diagram where we can have three phases in equilibrium with each other.

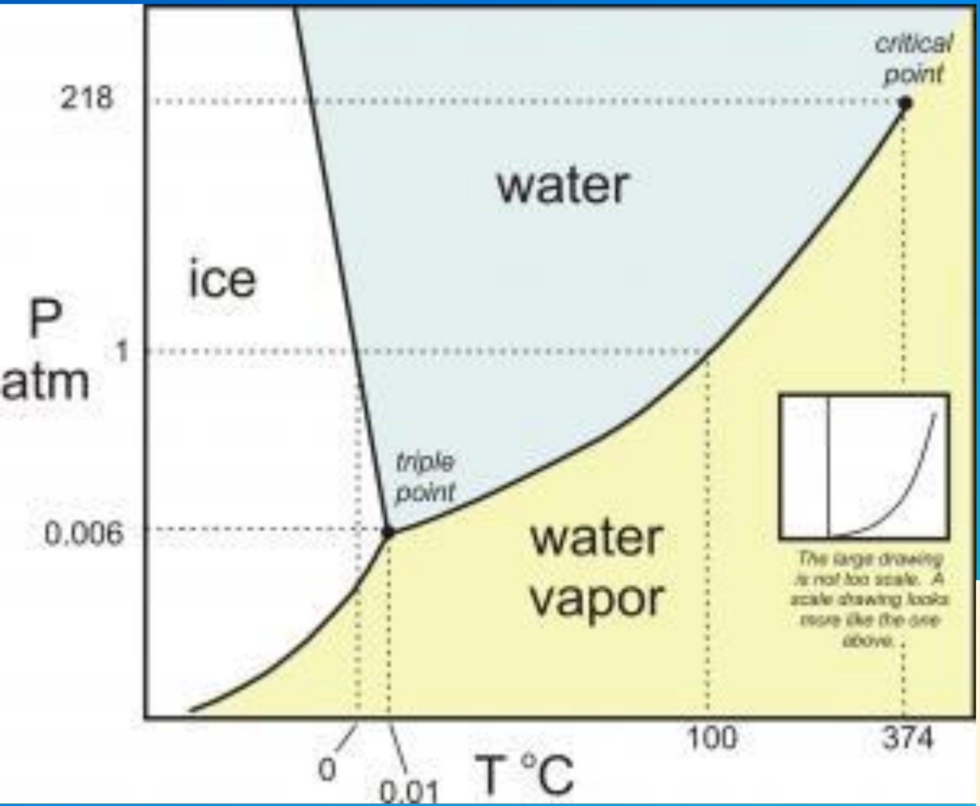
We say that at the triple point:

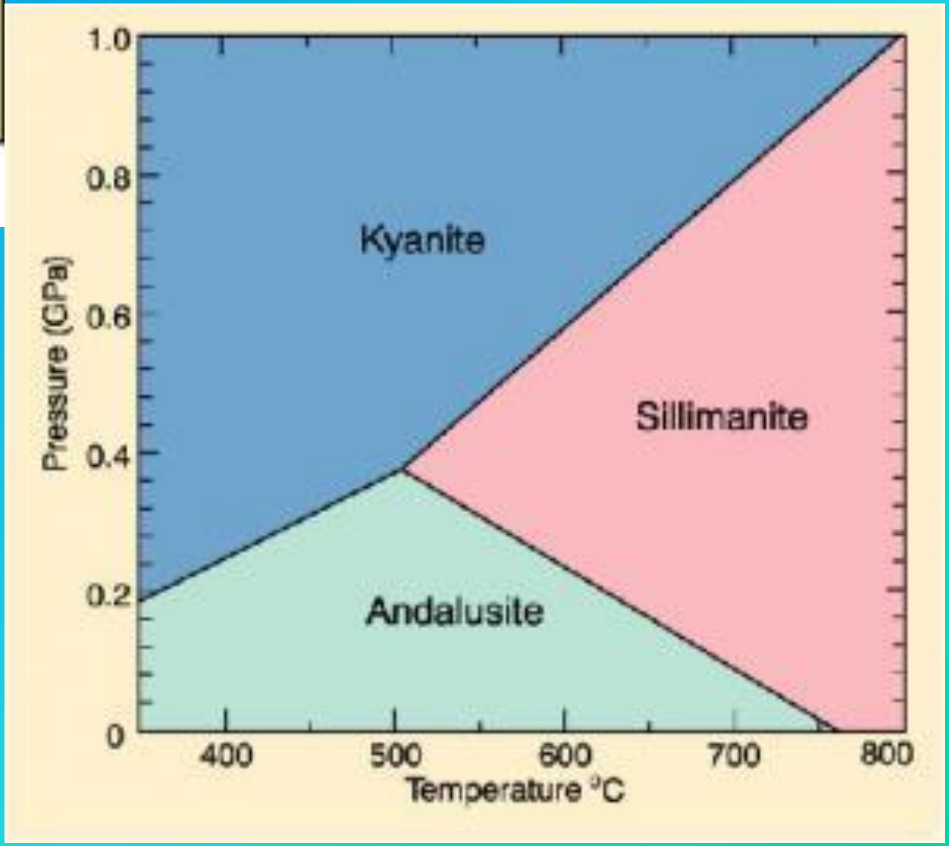
$f = c - p + 2$

$= 1 - 3 + 2$

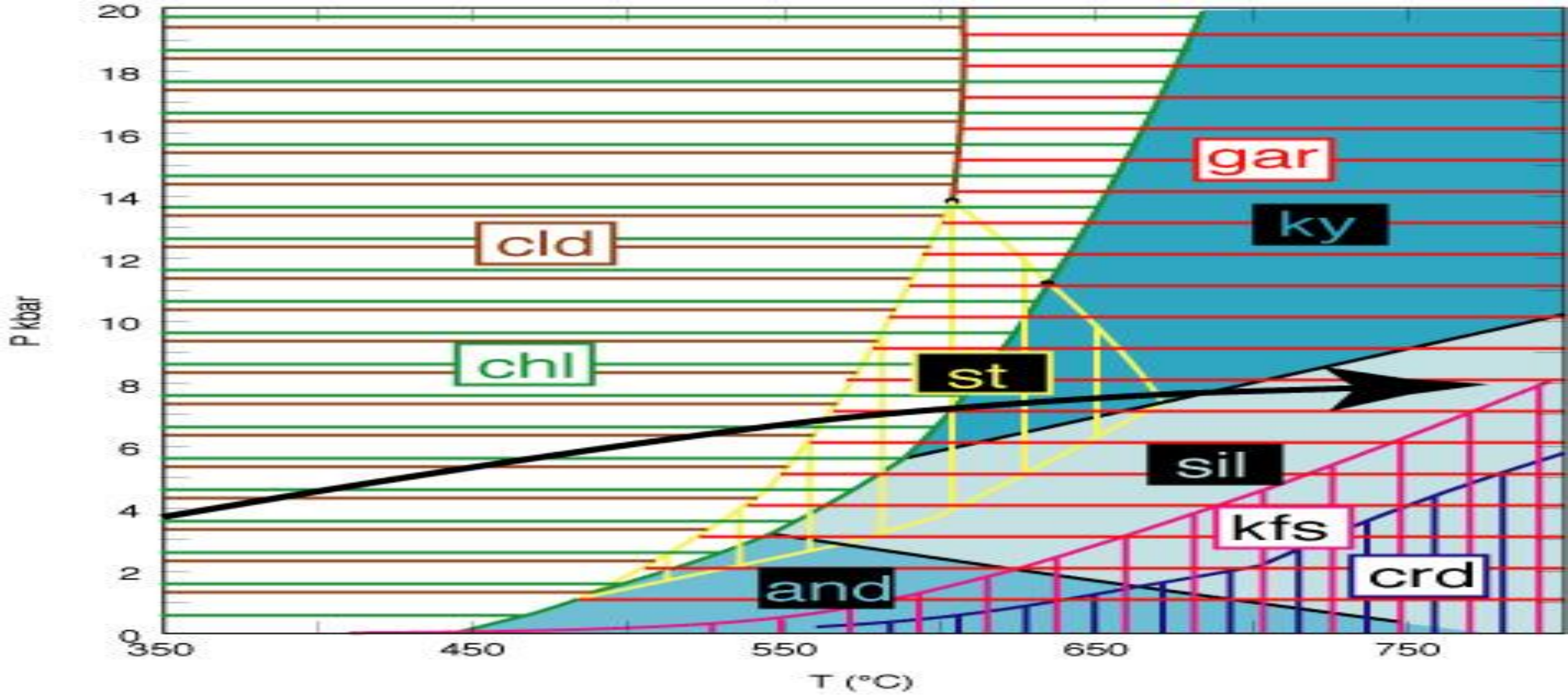
$= 0$ degrees of freedom.




critical point
218
water
ice
P atm
1
triple point
0.006
water vapor
The large drawing is not too scale. A scale drawing looks more like the one above.
0
0.01
T °C
100
374


1.0
0.8
0.6
0.4
0.2
0
Pressure (GPa)
Kyanite
Sillimanite
Andalusite
400
500
600
700
800
Temperature °C

- Equilibrium Mineral Assemblages
- At equilibrium, the mineralogy (and the composition of each mineral) is determined by T, P, and X . “Mineral paragenesis”



F = C - P + 2

- Application:
  - A gas, e.g. water vapour confined to a particular volume.
  - Apply phase rule: F=1-1+2=2.
  - This means that two intensive variables (temperature and pressure, temperature and concentration) must be known to duplicate this system exactly.
  - Such a system is usually described as bivariant.

$F = C - P + 2$

- Application:
  - A liquid such as water in equilibrium with its vapor (we have 2 phase system)
  - F=1-2+2=1.
  - By stating temperature, the system is completely defined because the pressure under which liquid and vapor can coexist is also fixed.
  - If we decide to work under a particular pressure, then the temperature of the system is automatically defined:
  - The system is described as univariant.
- Application:
  - When we have a liquid water, vapor and ice
  - Phase rule states that the degrees of freedom = 1-3+2=0
  - There are no degrees of freedom, if we attempt to vary the conditions of temperature or pressure necessary to maintain the system, we will lose a phase.
  - The combination is fixed and unique.
  - The system is invariant.

$F = C - P + 2$

- As the number of components increases, so do the required degrees of freedom needed to define the system. Consequently, as the system becomes more complex, it becomes necessary to fix more variables to define the system.
- As the number of phases in equilibrium increases, the number of the required degrees of freedom becomes less.
- Liquid water+vapor F=1-2+2=1

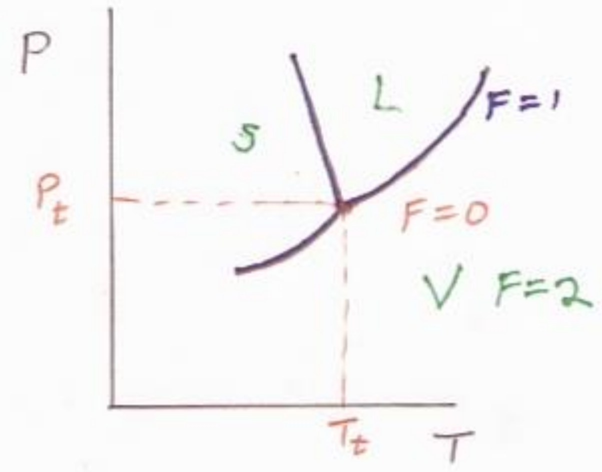
  ethyl alcohol+vapor F=1-2+2=1

  liquid water+liquid ethanol+vapor F=2-2+2=2

  liquid water+liquid benzyl alcohol+vapor mixture →

  F=2-3+2=1 → benzyl alcohol and water form two separate liquid phases and one vapor phase.

In single phase regions, F = 2. Both T and P may vary.



At the equilibrium between two phases, F = 1. Changing T requires a change in P, and vice versa.

At the triple point, F = 0. T_t and P_t are unique.

Four phases cannot be in equilibrium (for a single component.)

Binary solid-liquid Equilibrium
Melting Point Variation with Composition

c = 2

p = 3

liquid, pure solid A, pure solid B

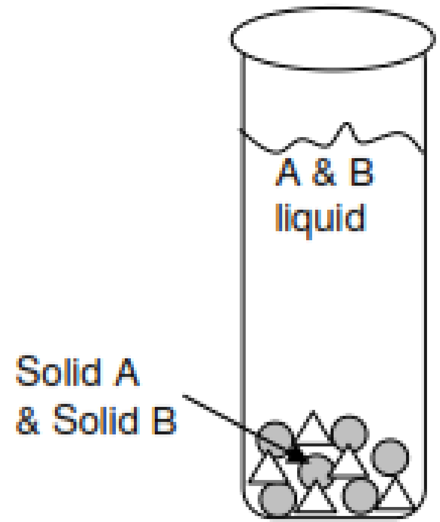
Solid-liquid 2-phase region:

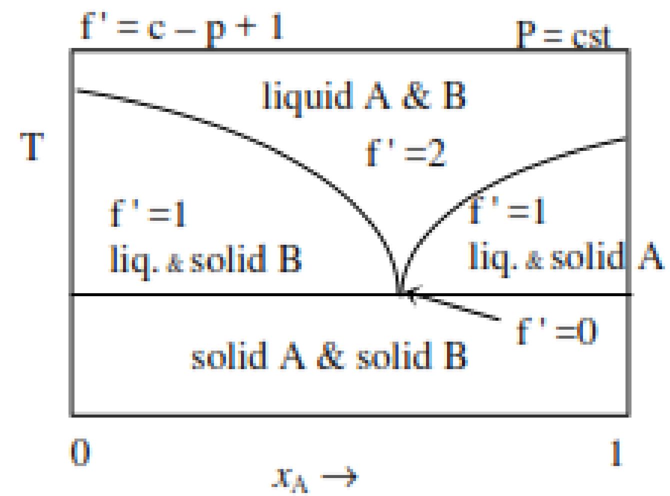
f ' = 2 – 2 + 1 **= 1**

Eutectic:

f ' = 2 – 3 + 1 **= 0**

invariant at cst P





ICE-WATER-STEAM SYSTEM