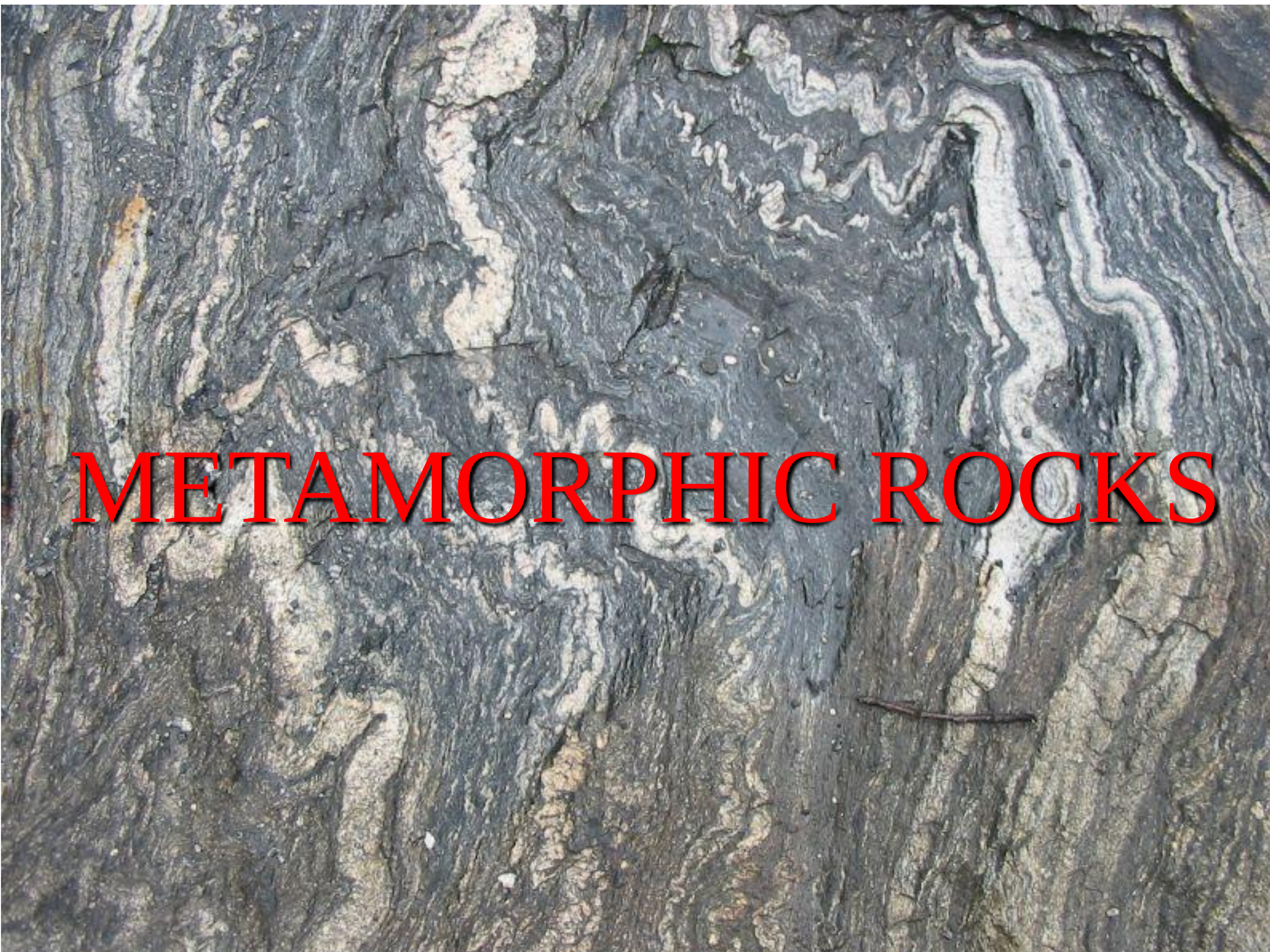
METAMORPHIC ROCKS



Definition

- Meta means **'change'**, Morph means **'form'**
- A change in form of pre-existing rocks of all types. **Sedimentary**, **igneous** and **metamorphic**
- By the action of **Heat** alone (**Contact**)
- By the action of **Pressure** alone (**Dynamic**)
- By the action of **Heat and Pressure** in combination (**Regional**)
- By Chemically active fluids

Metamorphism Excludes:

- **Weathering, Diagenesis and Lithification**
- Environments where temperatures are below 200 – 300 degrees centigrade
- Melting Of Rocks - environments where temperatures are above 650 degrees centigrade
- Environments less than 2km depth and at pressures below 1000 bars

What is metamorphism?

- "Metamorphism is the *mineralogical* and/or *textural* adjustments that take place in a rock in response to a new set of physicochemical conditions different from the ones under which the rock originally formed"

The scope and range of metamorphism is not easy to define.

- By definition, metamorphism should exclude all sedimentary and igneous processes.
- Yet the boundary between diagenesis and metamorphism is poorly defined, and is definitely a function of the composition of the rock undergoing such changes.
- This means that a metamorphic texture or mineral may form for the first time in a basaltic rock at a temperature of for example 180°C, but a shale subjected to the same temperature may not show any textural or mineralogical changes that can be clearly identified as *metamorphic*.
- Similarly, the boundary between metamorphism and igneous activity is also unclear. Most mantle rocks could be considered metamorphic, but at the same time, partial melting within the mantle results in many igneous textures and minerals.

- Although a basaltic rock will not melt at temperatures of 700°C, a shale saturated with H_2O will undergo "partial melting" at these temperatures to produce a granitic liquid that moves like a magma, leaving behind mafic minerals which can undergo further changes in the solid state.
- Nevertheless, the temperature "boundaries" between metamorphism and diagenesis on one hand and metamorphism and igneous activity on the other can be set at 150-200°C and 700-800°C, respectively.

Why study metamorphic rocks?

- Studying metamorphic petrology is essential for understanding the processes involved in the formation and evolution of the continental crust. Because almost all mountain chains (orogenic belts) contain metamorphic rocks, understanding the conditions under which these rocks form will lead to a better understanding of the processes involved in mountain building, as well as understanding the relations between deformation, metamorphism and igneous activity.

Protolith:

- The protolith of a metamorphic rock is defined as the original rock prior to metamorphism.
- Therefore, the protolith of a quartz mica schist may have been a *sandstone*, a *siltstone* or a quartz-rich *shale*, whereas the protolith of a marble must have been some sort of a *limestone* or *dolomite*.
- An amphibolite rich in Fe and Mg may have originally been a *basalt*.
- The protolith of a metamorphic rock can be "guessed" (or in some cases positively identified) based on the mineralogy and/or the texture of this metamorphic rock.
- Knowing the relative abundance of these metamorphic minerals (known as the mode), and their chemical composition, one can estimate the relative abundance of the major elements or oxides in the rock (e.g. CaO, Na_2O, ... etc.), and therefore guess its protolith.
- For example, if a rock contains abundant muscovite, it must be rich in K_2O and Al_2O_3, and the protolith was most likely a shale.

Definition of Metamorphism:

The word "Metamorphism" comes from the Greek: Meta = change, Morph = form, so metamorphism means to change form.

In geology this refers to the changes in mineral assemblage and texture that result from subjecting a rock to pressures and temperatures different from those under which the rock originally formed.

Temperature.

- Temperature increases with depth in the Earth along the Geothermal Gradient. Thus higher temperature can occur by burial of rock. Such burial usually takes place as a result of tectonic processes such as continental collisions or subduction.
- Temperature can also increase due to igneous intrusion.

Role of Temperature

- ✓ Due to increase of temperature - Minerals break down and form new minerals.
- ✓ Increasing temperature results in the growth of crystals.
- ✓ individual minerals are only stable over specific temperature ranges. Thus, as temperature changes, minerals within a rock become unstable and transform through chemical reactions to new minerals.

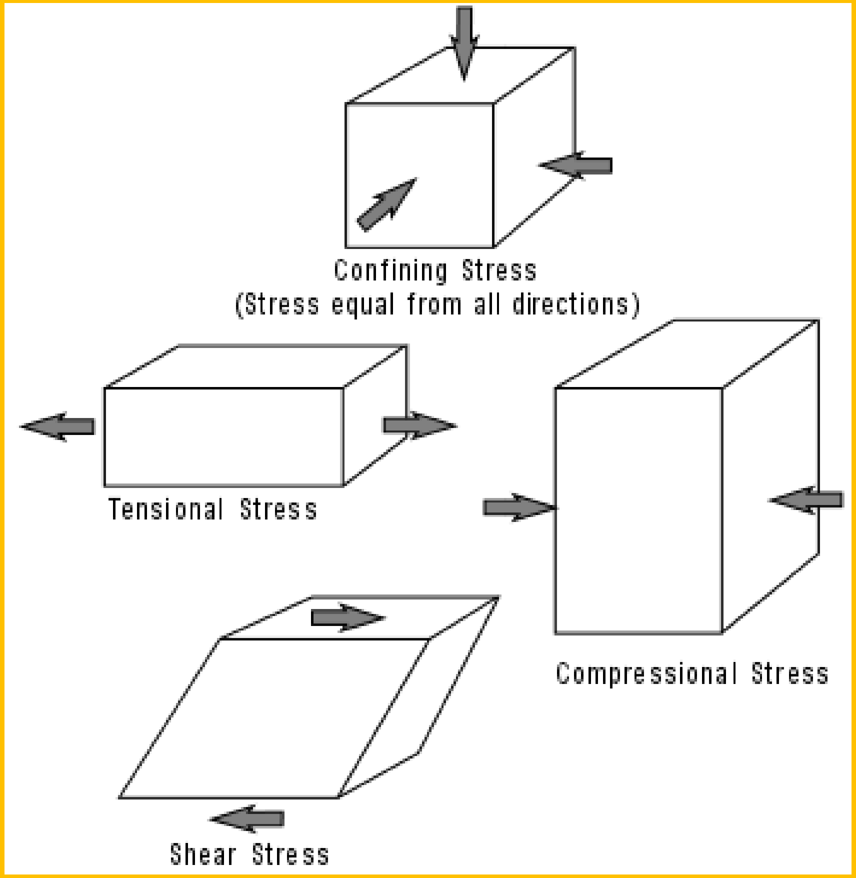
Heat:

- Most important agent of metamorphism is heat which provides the energy to drive the chemical reactions that recrystallize minerals.
- Rocks are heated by burial beneath the surface (30☜C/km) and by intrusions of molten material rising from below.
- Certain minerals, such as clay, when buried only a few kilometers recrystallize to become stable, whereas, other minerals, such as igneous minerals are stable at higher temperatures and pressures and must be buried deeper (20 km or more) before metamorphism will occur.
- Involved in both regional and contact metamorphism.

Pressure

Pressure increases with depth of burial, thus, both pressure and temperature will vary with depth in the Earth. Pressure is defined as a force acting equally from all directions. It is a type of ***stress***, called ***hydrostatic stress***, or ***uniform stress.***

If the stress is not equal from all directions, then the stress is called a ***differential stress.***

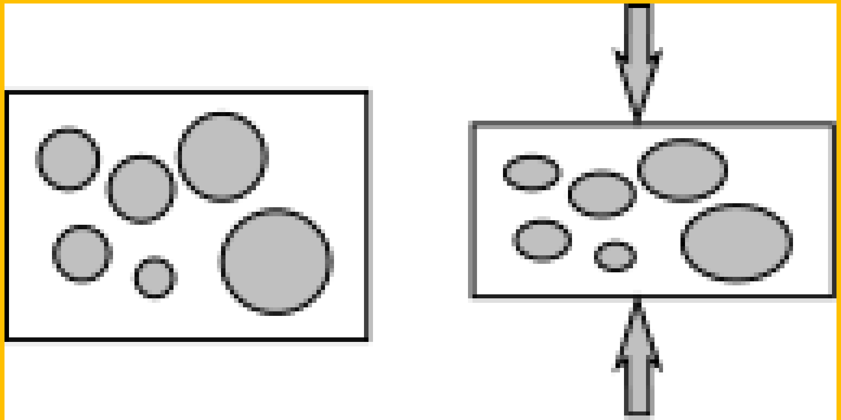


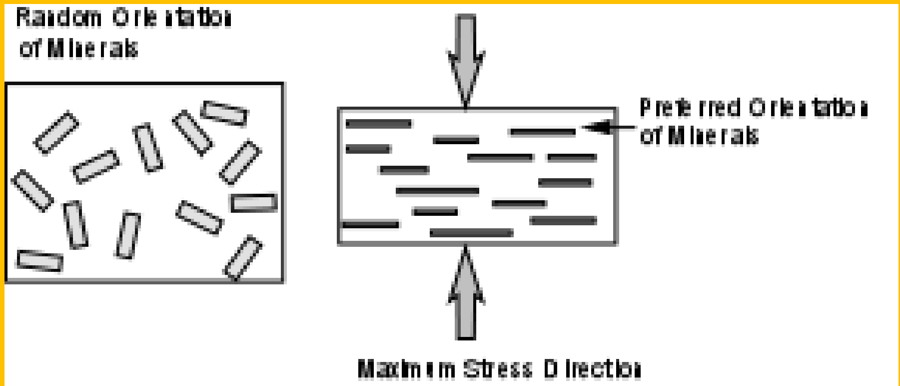
Two kinds of differential stress.

1. Normal stress causes objects to be compressed in the direction of maximum principal stress and extended in the direction of minimal stress.

2. Shear stress causes objects to be smeared out in the direction of applied stress.

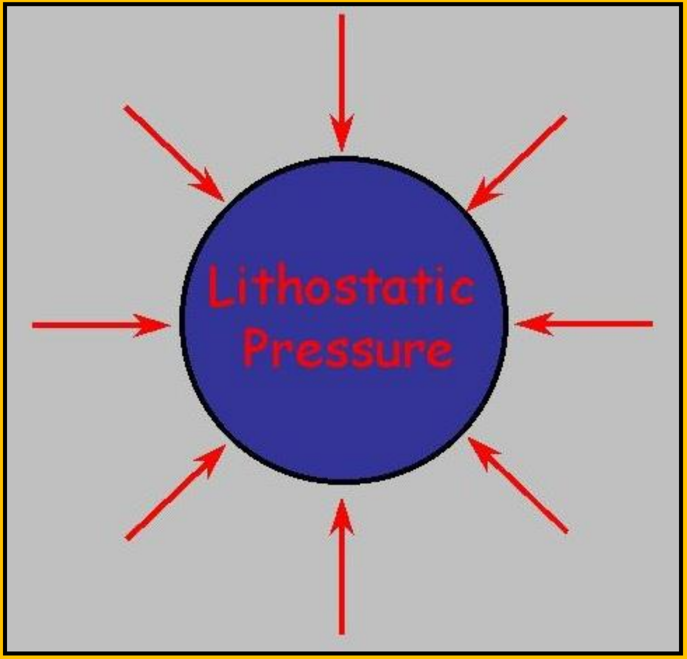
Differential stress if acting on a rocks can have a profound affect on the appearance or texture of the rock. If differential stress is present during metamorphism, it can have a profound effect on the texture of the rock.





Uniform Pressure:

The most widely experienced type of pressure is lithostatic (Uniform). This "rock-constant" pressure is derived from the weight of overlying rocks. Lithostatic pressure is experienced uniformly by a metamorphic rock Thus, there is no preferred orientation to lithostatic pressure and there is no mechanical drive to rearrange crystals.



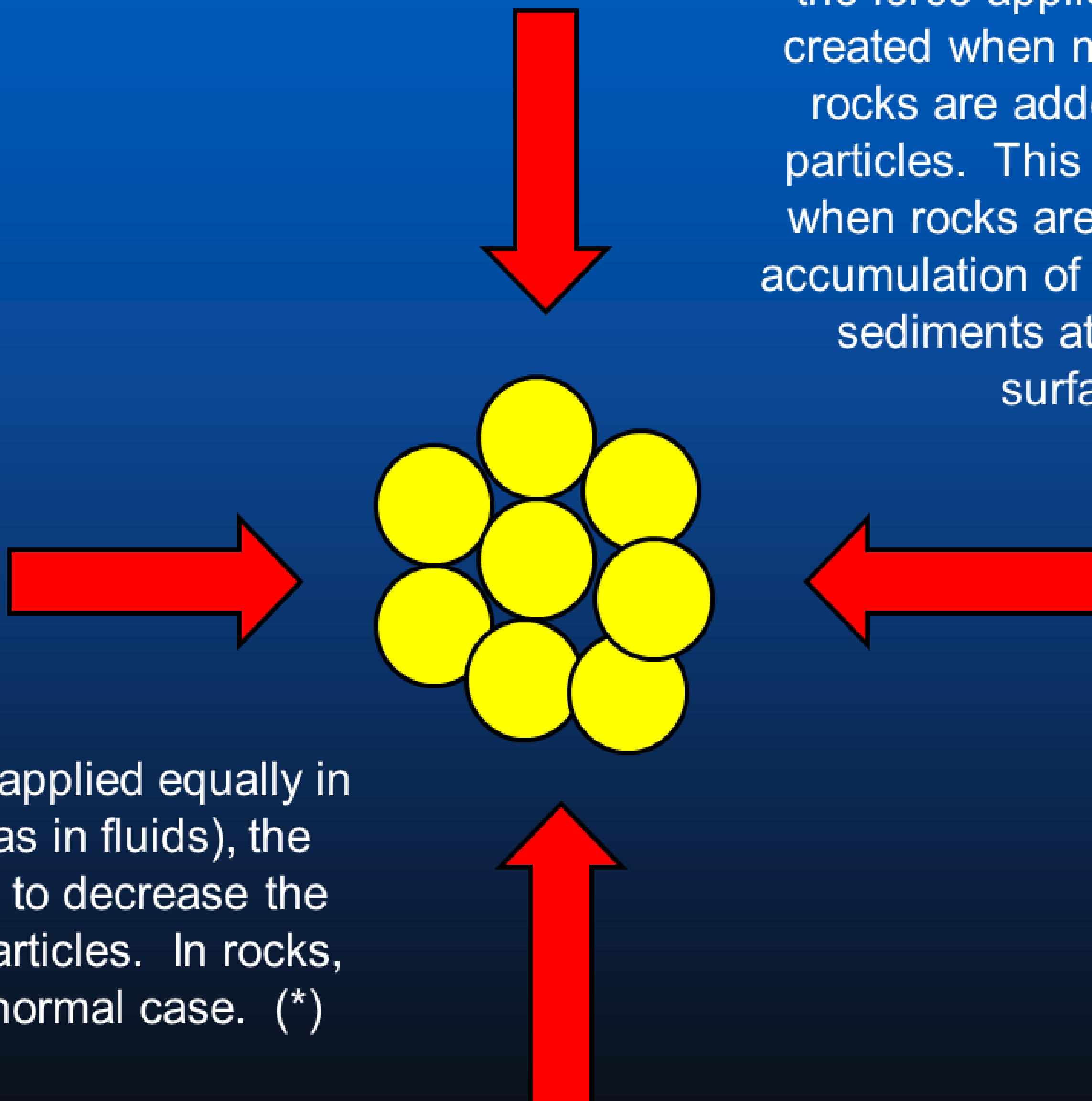
Directed Pressure:

Conversely, directed pressure, the second type of pressure associated with metamorphism, is the pressure of motion and action. Plate tectonics provide the underlying mechanical control for all forms of directed pressure. Thus, metamorphism is closely linked to the plate tectonic cycle and many metamorphic rocks are the products of tectonic interactions.

AGENT OF METAMORPHISM -- PRESSURE

Confining Pressure

In terms of metamorphic geology, confining pressure is the force applied to particles created when more and more rocks are added above the particles. This would happen when rocks are buried by the accumulation of more and more sediments at the Earth's surface.



If pressures are applied equally in all directions (as in fluids), the result would be to decrease the volume of the particles. In rocks, this is **not** the normal case. (*)

AGENT OF METAMORPHISM -- PRESSURE

Differential Pressure (Stress)

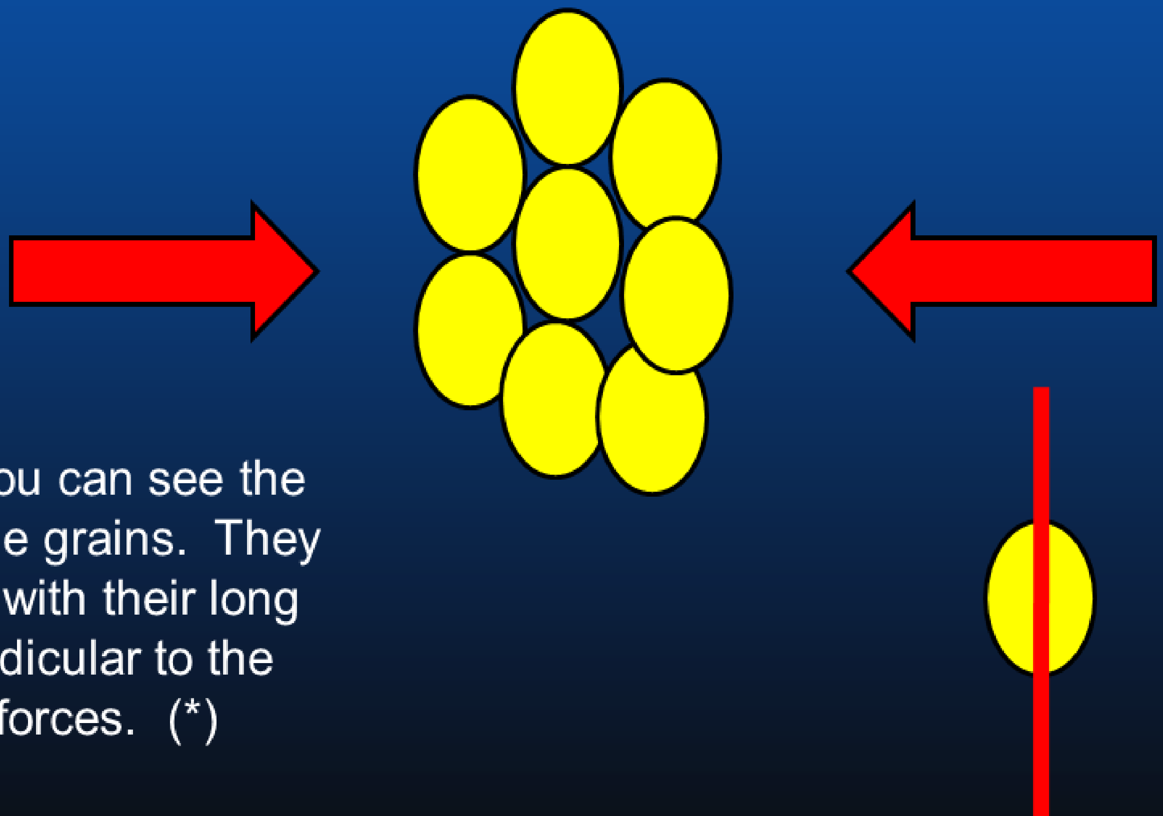
Instead, pressures are more directed. In this example, the principle stresses are from top and bottom. This would be an example of sediments being buried 1000's of feet below the surface. The force creating the pressure is simply gravity.

The particles are distorted. They have become elongate. Note that their long axis (shown by the red line on the single yellow particle) is oriented perpendicular to the maximum pressures (the red arrows). (*)

AGENT OF METAMORPHISM -- PRESSURE

Differential Pressure (Stress)

In this example the primary force is horizontal. This force could be created by the collision of continents during plate motions.



Here again you can see the distortion of the grains. They are flattened with their long axis perpendicular to the principle forces. (*)

AGENT OF METAMORPHISM --PRESSURE - Low

DEFORMATION

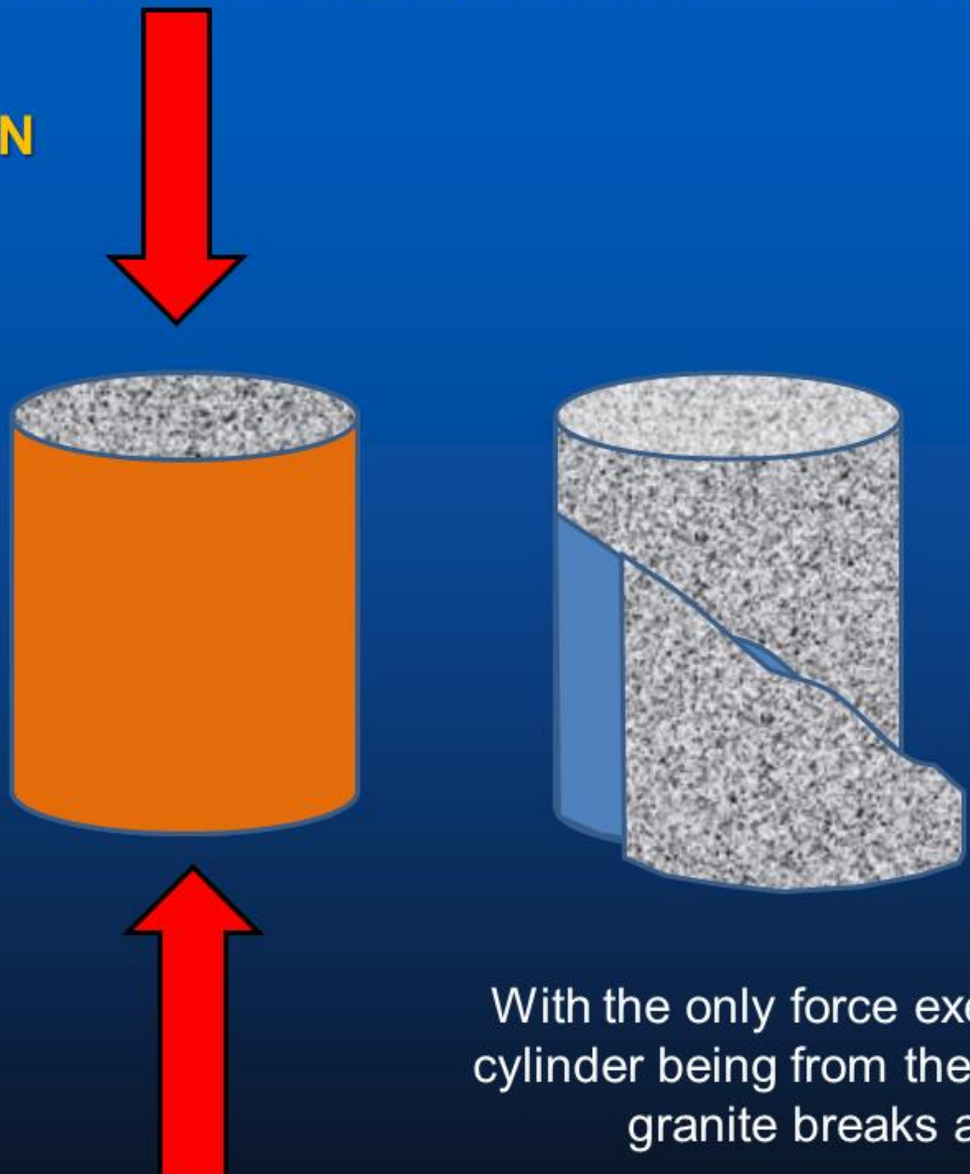
The next series of pages shows what happens when a brittle rock, like granite, is put under pressure. Low pressure at first and then greater pressures.

Each cylinder of granite is compressed in a copper jacket (shown in orange) so if there is an explosive failure, the pieces do not damage the equipment.

The principle force is applied from top and bottom. (*)

AGENT OF METAMORPHISM -- PRESSURE - Low

DEFORMATION

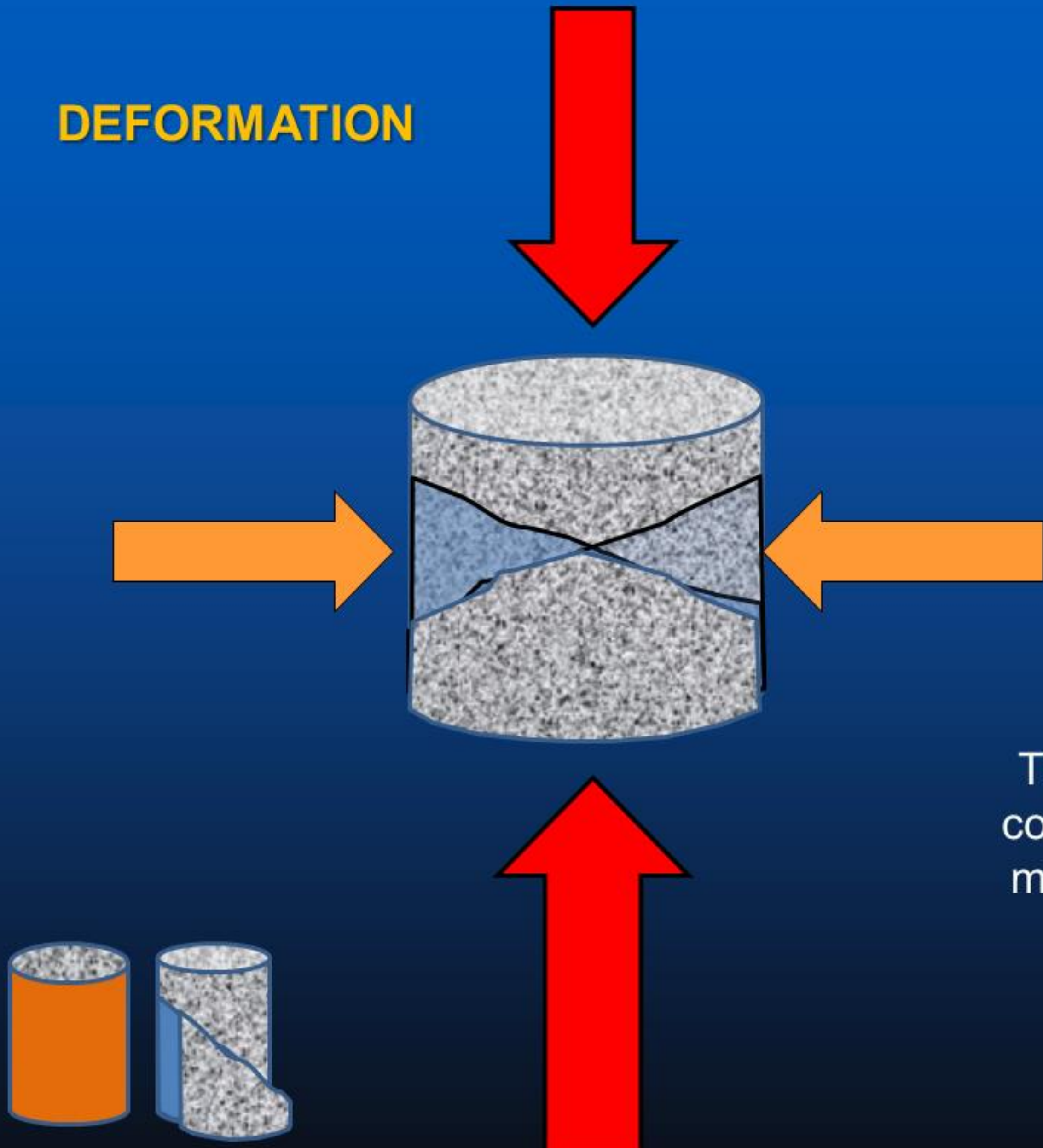


With the only force exerted on the granite cylinder being from the top and bottom, the granite breaks as shown. (*)

AGENT OF METAMORPHISM -- PRESSURE - Medium

DEFORMATION

In this example, medium confining pressure is added. This is shown by the orange arrows at the sides.

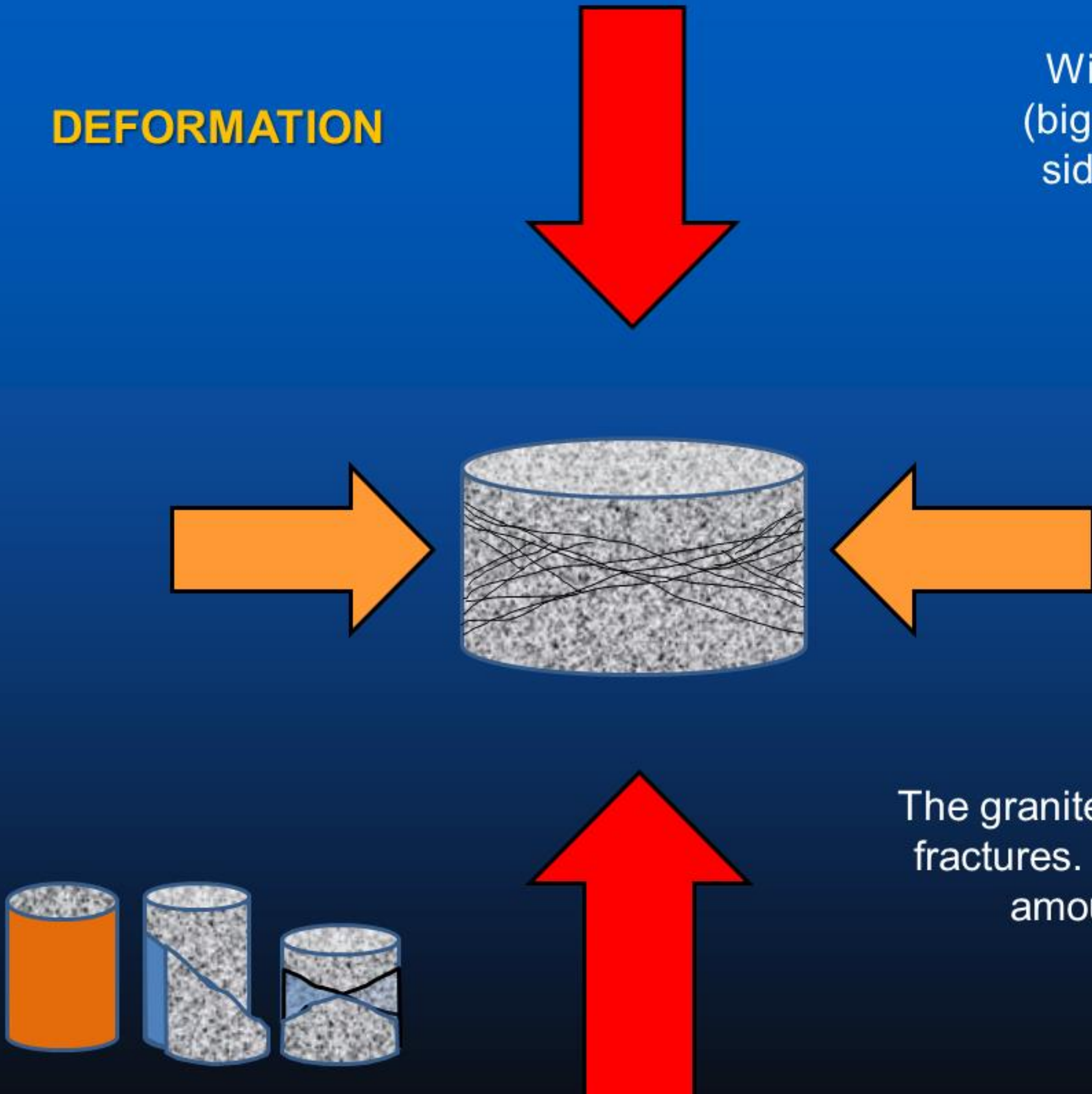


The granite breaks, but it is also compressed a little. There is also more than one main fracture. (*)

AGENT OF METAMORPHISM -- PRESSURE - HIGH

DEFORMATION

With high confining pressure (bigger orange arrows from the sides), the granite behaves a little differently.

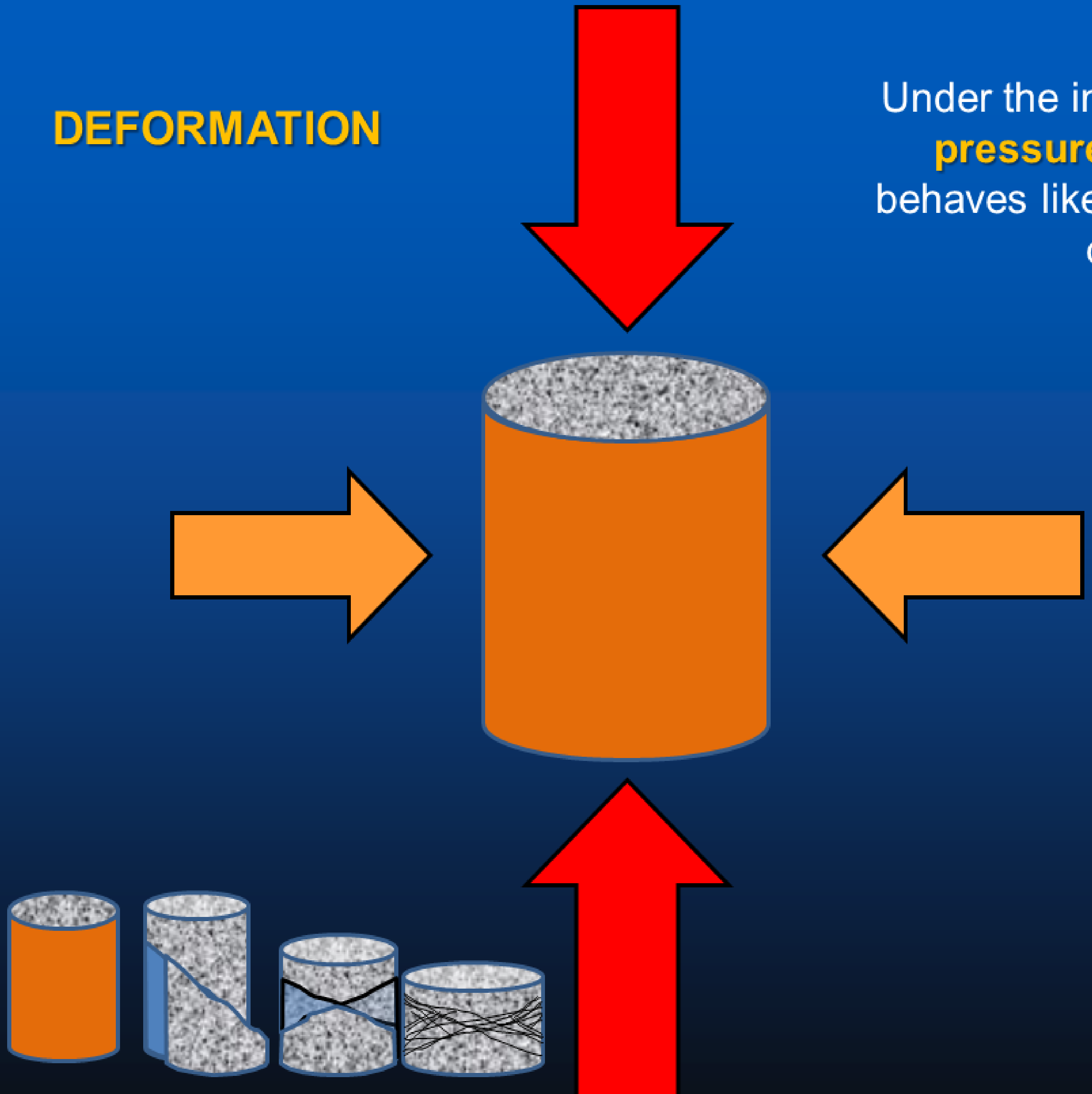


The granite is broken with many small fractures. There is also a significant amount of shortening. (*)

AGENTS OF METAMORPHISM -- PRESSURE and HEAT

DEFORMATION

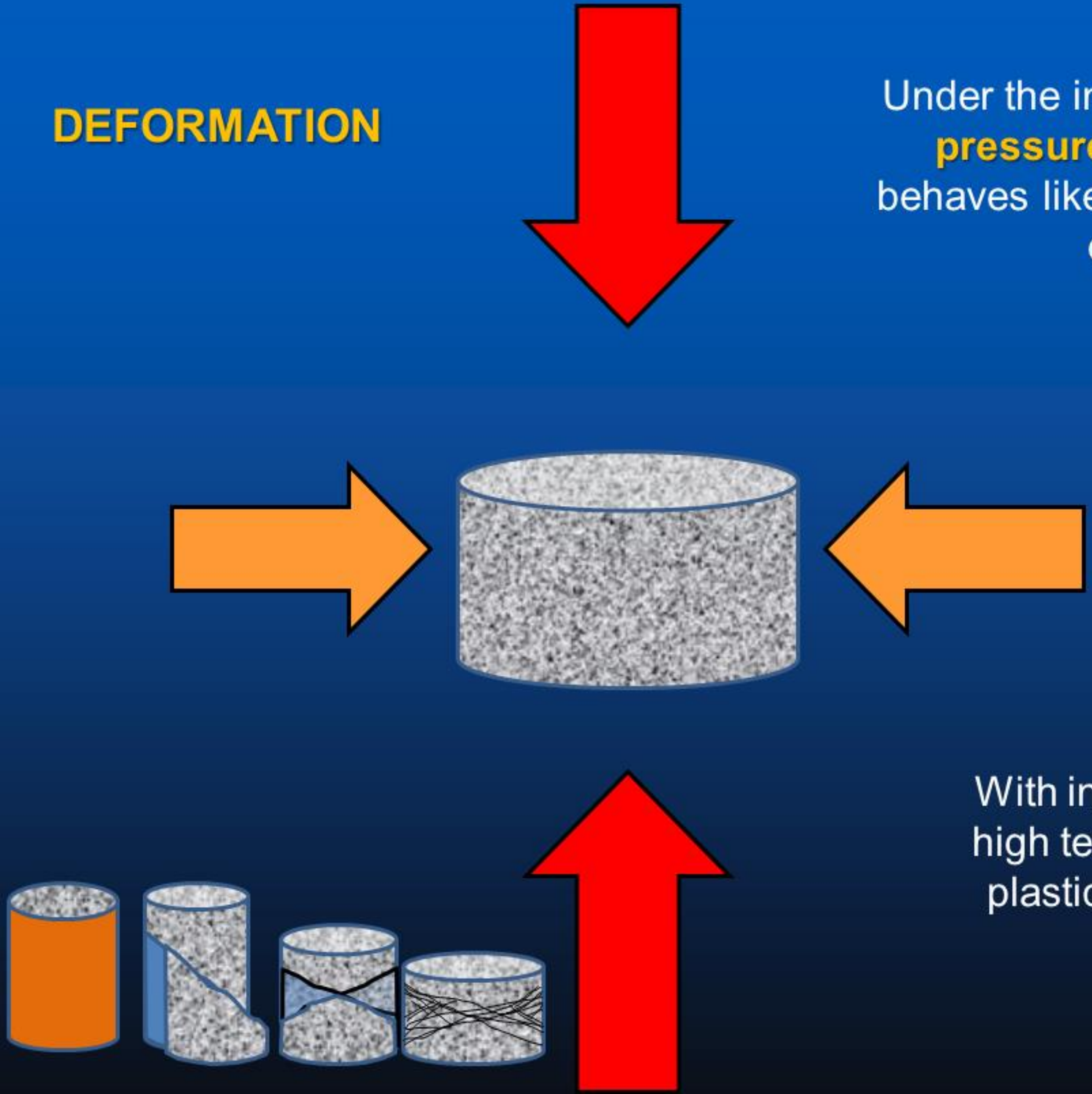
Under the influence of **high confining pressure AND heat**, the granite behaves like a plastic material, instead of a brittle rock.



AGENTS OF METAMORPHISM -- PRESSURE and HEAT

DEFORMATION

Under the influence of **high confining pressure AND heat**, the granite behaves like a plastic material, instead of a brittle rock.



With increase in burial and under high temperatures, this leads to a plastic flow of rocks, rather than brittle failure. (*)

Chemically Active Fluids:

- Has a strong influence on the metamorphism of rocks.
- Water located in pore spaces of rocks is perhaps the most common fluid involved in metamorphism.
- Water helps move the ions through the solid rock allowing the rock to recrystalize into a more stable structure. It also helps in ion exchange between minerals which is responsible for the formation of completely different minerals. For example Garnet.

Different kinds of Agents for Metamorphism:

Temperature, Pressure and Chemically active fluids are the three agents involved during the metamorphism.

Different kinds (Types) of Metamorphism

Various kinds of metamorphism is due to different combinations of four agencies which are Heat, Uniform Pressure, Directed Pressure and Chemically Active Fluids such as Contact Metamorphism, Regional Metamorphism and Cataclastic Metamorphism

Depth Zones and Metamorphism

Metamorphism is due to heat, uniform Pressure and Directed Pressure. Temperature and Uniform Pressure increases with respect to depth in the earth crust. Directed pressure, however, increases with depth only certain extent and then diminishes to zero.

- ✓ **Van Hise** distinguished katamorphic zone (near the surface), beneath this, zone of anamorphism.
- ✓ **Becke** has used the prefixes exactly opposite sense to **Van Hise**
- ✓ **Grubenmenn** DISTINGUISHED THREE ZONES…

Uppermost or epizone, intermediate or mesozone and a lowermost katazone of metamorphism.

Epizone is, in general, nearest to the surface of the earth crust, Mesozone of intermediate depth and Katazone is most remote in depth.

These zones, however, cannot be marked sharply off from each zones or no strict relation to depth.

Further, **FERMOR** has made valuable suggestions that the term hypozone should replace Grubbenmenn's incorrect katazone.

Metamorphic Zones by Grubenmann

Zone	Tempe rature	Uniform Pressure	Directed Pressure	Rocks
Epizone	L to M	Small	Often Strong	Phyllite, Sericite, talc, epidote, cholorite, glaucophane schist, quarz schist; schistose grit etc
Mesozone	M	Conside rable	Mostly Strong	Mica schist, garnet mica schist, staurolite schist, hornblende schist and hornblende gneiss.
Katazone	H	Very High	Feeble or Absent	Coarse biotite, pyroxenes, sillimanite and cordierite gneiss, Granulites, eclogites, etc

Facies and Grade of Metamorphism:

The Mineral composition of the metamorphic rocks depends Pressure, Temperature and chemical compositions of the original rock.

Grubenmenn's Zones represent a rough attempt to delimit Pressure, Temperature conditions but there are not enough divitions to express the great diversity of metamorphic rocks.

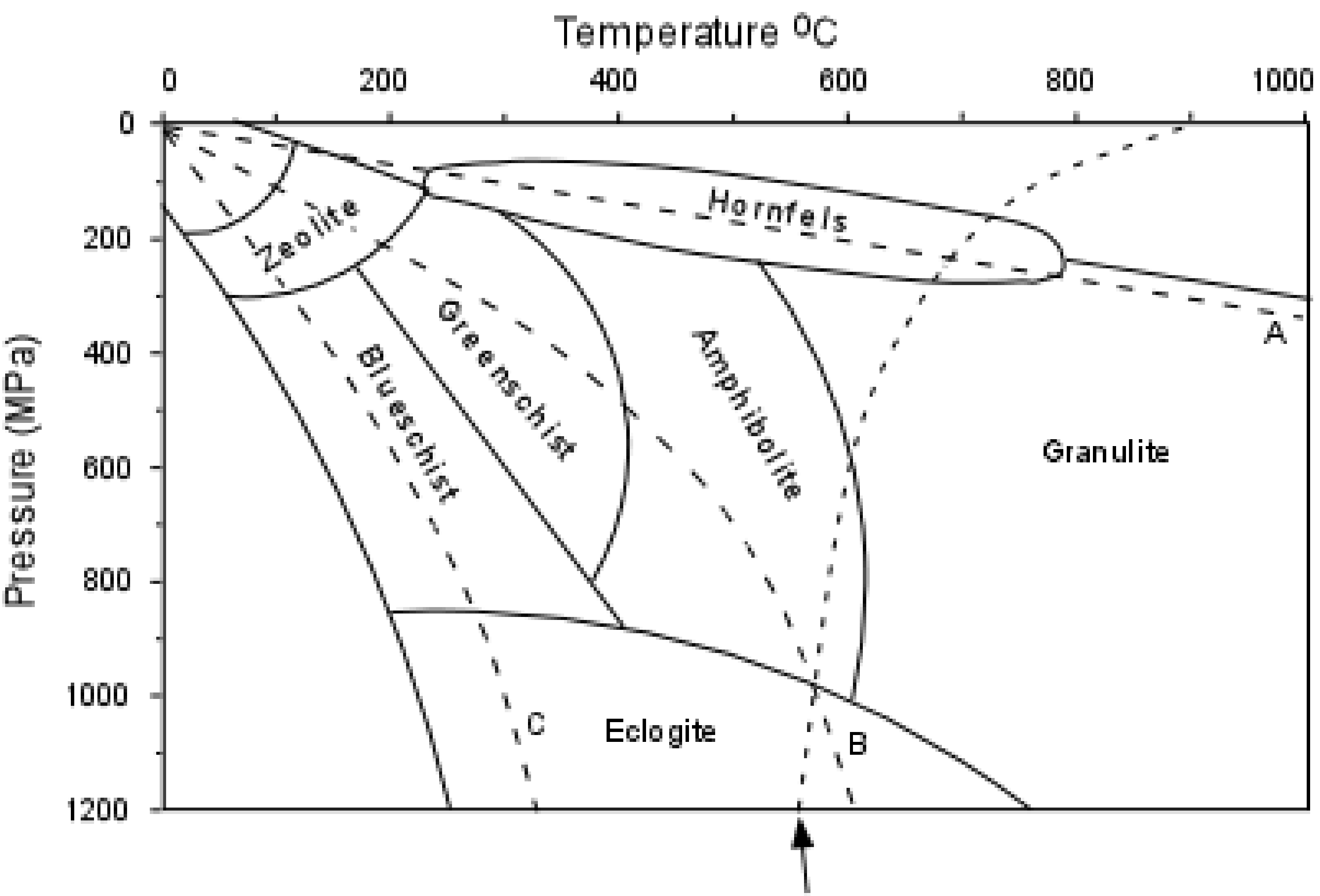
To overcome this problem, **ESKOLA** has supplemented the zone concept by that of **metamorphic facies**.

ESKOLA has described hornfel facies, sanidinite facies, green schist facies, amphibolite facies and eclogite facies.

- Facies is **grouping of metamorphic rocks** of various compositions that have formed under the ***same grade of metamorphism***.
- By evaluating the changes in texture and composition within metamorphic rocks it is possible to delineate regions of high and low metamorphic grade.
- Different kinds of metamorphic rocks are formed from different parent rocks at the same Metamorphic grade. Thus, **compositional variation in the precursor rocks** is inherited by the metamorphic rocks.
- Different kinds of metamorphic rocks are formed from the **same precursor** at different metamorphic grades.

- In general, metamorphic rocks do not undergo significant changes in *chemical composition* during metamorphism.
- The changes in mineral assemblages are due to changes in the temperature and pressure conditions of metamorphism.
- Thus, the mineral assemblages that are observed must be an indication of the temperature and pressure environment that the rock was subjected to. This pressure and temperature environment is referred to as ***Metamorphic Facies.***

Metamorphic Facies



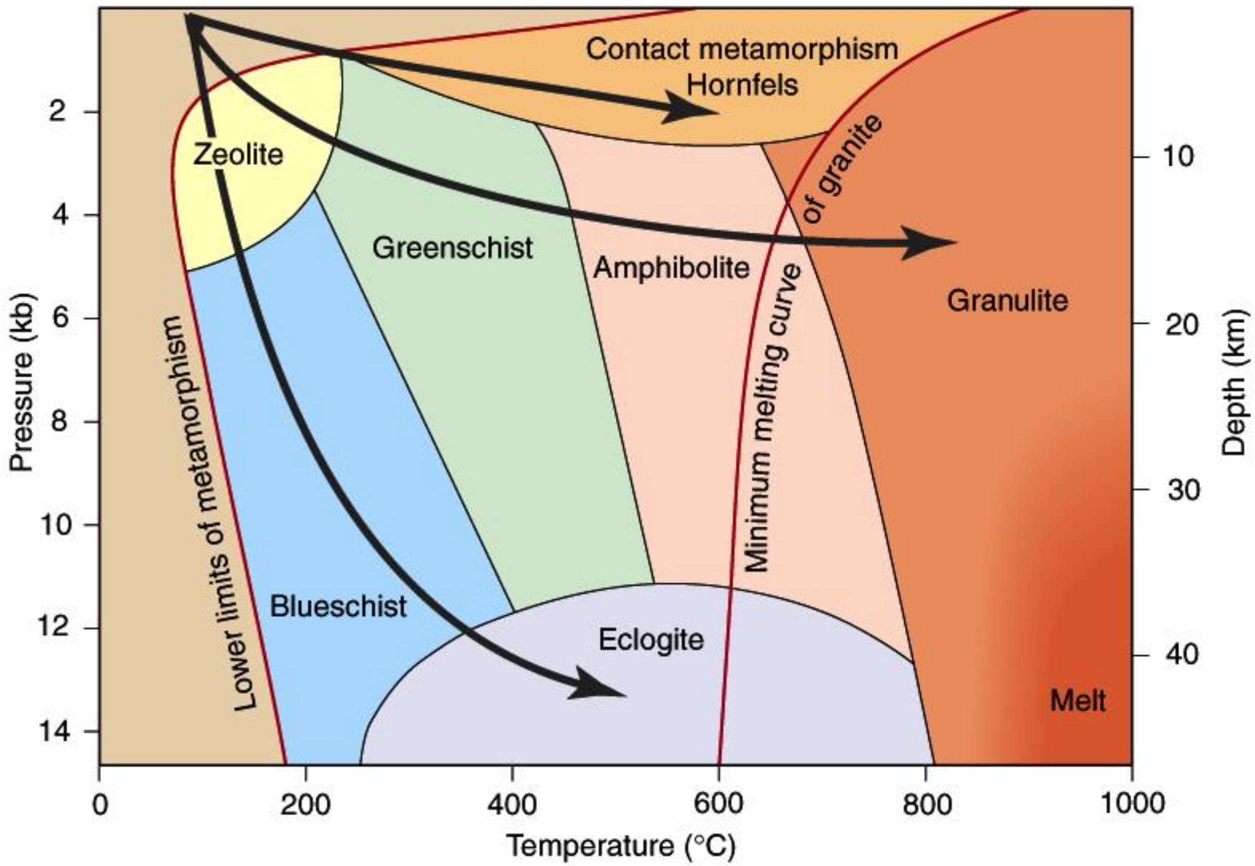
A = High Geothermal Gradient (contact metamorphism), Low P, High T

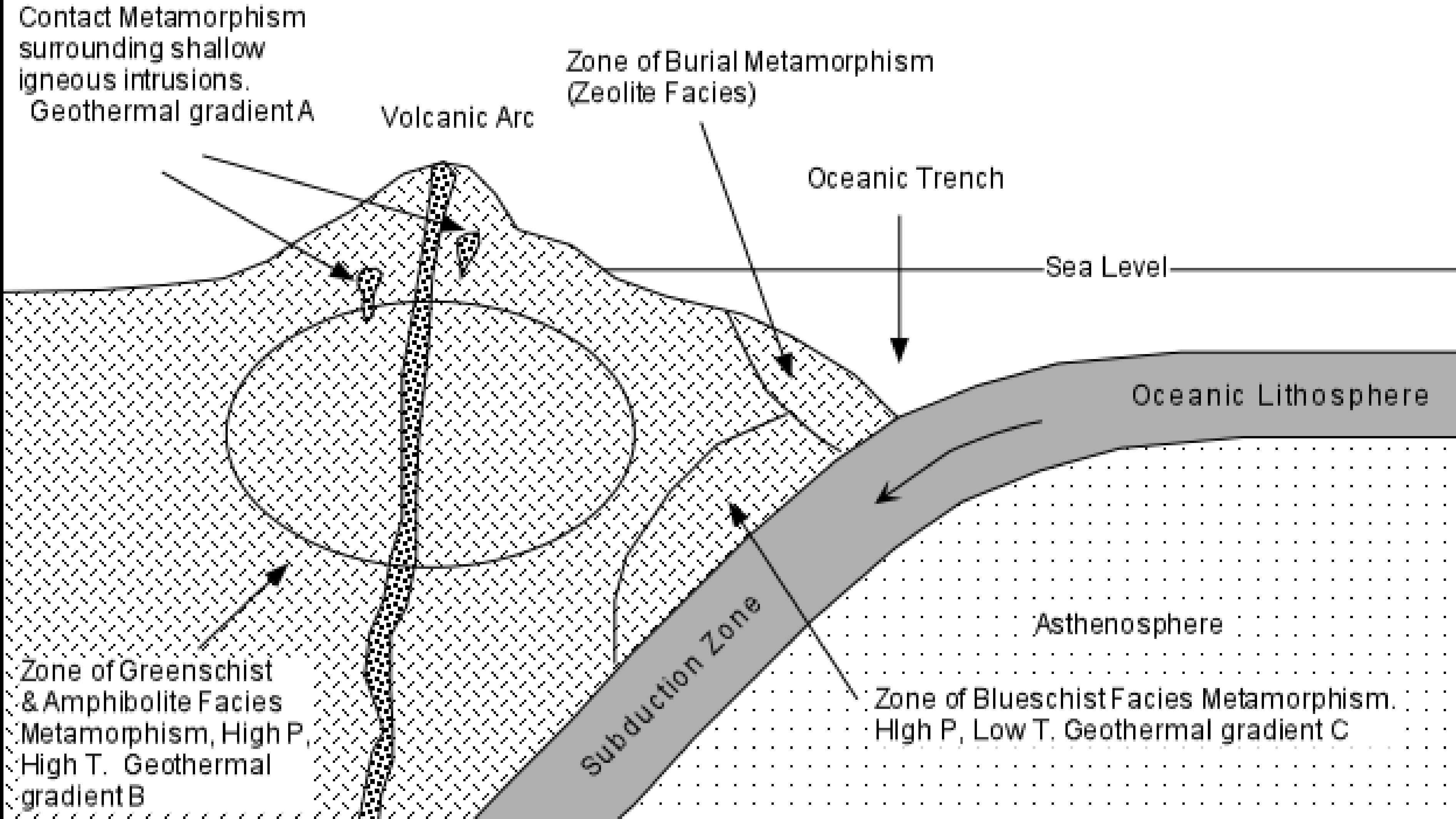
B = Normal Geothermal Gradient (regional metamorphism), High P, High T

C = Low Geothermal Gradient (subduction), High P, Low T

Metamorphic Facies

- Different minerals form at different temperatures and pressures
- Group of stable minerals define a facies




Contact Metamorphism
surrounding shallow
igneous intrusions.
Geothermal gradient A
Volcanic Arc
Zone of Burial Metamorphism
(Zeolite Facies)
Oceanic Trench
Sea Level
Oceanic Lithosphere
Asthenosphere
Subduction Zone
Zone of Greenschist
& Amphibolite Facies
Metamorphism, High P,
High T. Geothermal
gradient B
Zone of Blueschist Facies Metamorphism.
High P, Low T. Geothermal gradient C

Grade of Metamorphism

- Based on the idea of facies, **TILLEYS** has united that of grade, which refers to the stage or degree of metamorphism at which the rocks have been arrived.
- **Green schist facies**, for example, is a type of **low-grade metamorphism** and Eclogite facies is a type of high-grade metamorphism.
- Thus, rocks belonging to the same facies may be said to be the same grade of metamorphism.
- In Green schist facies, a chlorite-quartz-muscovite-schist is isogradic with a green schist of chlorite, epidote and albite. However this chlorite-quartz-muscovite-schist remains stable over a considerable range of temperature and pressure conditions and may belong to more then one facies.

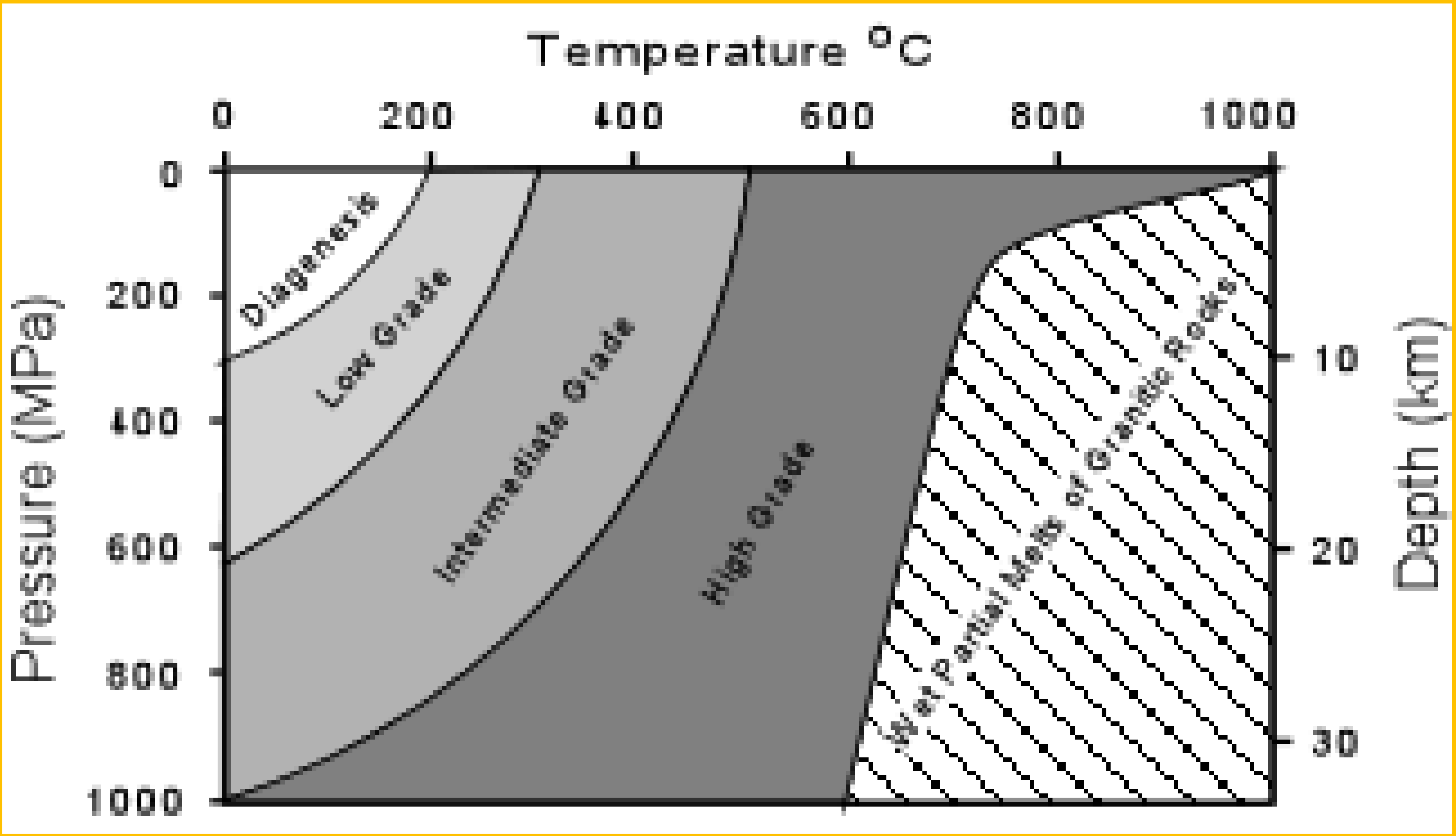
Grade of Metamorphism

- ***Metamorphic grade*** is a general term for describing the relative temperature and pressure conditions under which metamorphic rocks form.
- As the temperature and/or pressure increases on a body of rock we say that the rock undergoes ***prograde metamorphism*** or that the grade of metamorphism increases.
- As temperature and pressure fall due to erosion of overlying rock or due to tectonic uplift, one might expect metamorphism to a follow a reverse path and eventually return the rocks to their original unmetamorphosed state. Such a process is referred to as **retrograde metamorphism**.

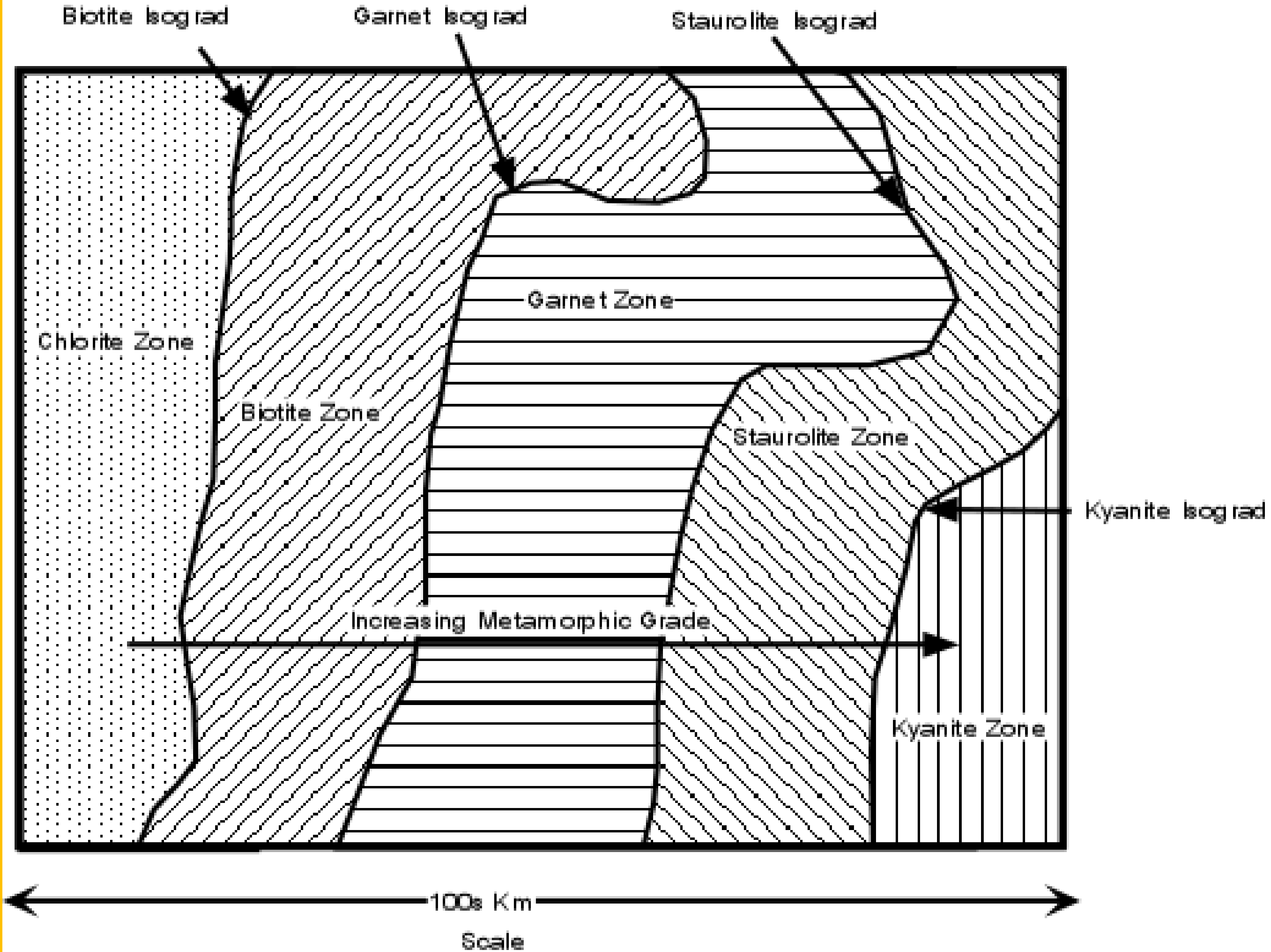
Retrograde metamorphism does not appear to be common. The reasons for this include:

- Chemical reactions take place more slowly as temperature is decreased.
- During prograde metamorphism, fluids such as H_2O and CO_2 are driven off, and these fluids are necessary to form the hydrous minerals.
- Chemical reactions take place more rapidly in the presence of fluids, but if the fluids are driven off during prograde metamorphism, they will not be available to speed up reactions during retrograde metamorphism.

- The intensity of a metamorphic event described through the use of the concept of metamorphic grade.
- Ambient temperature and pressure conditions rise steadily with increasing depth. Thus, within the continental crust, temperatures vary from approximately 200 °C at 5 km to 800 °C at 35 km.
- Similarlly, pressure also increases 2kb or about 2000 times atmospheric pressurefor each 5km. Deeper within the crust, at about 35 kilometers, the pressure increases to some 10 kb.
- Geologists describe **low temperature** and pressure setting as **low-grade metamorphism**, while high temperature and intense pressure is known as high-grade metamorphism..


Temperature °C
0
200
400
600
800
1000
Pressure (MPa)
0
200
400
600
800
1000
Depth (km)
10
20
30
Diagenesis
Low Grade
Intermediate Grade
High Grade
Wet Partial Melts of Granitic Rocks

BARROW has delimit the zones using by the entry of certain INDEX minerals like Chlorite, biotite, granet, staurolite, kyenite and sillimenite


Biotite Isograd
Garnet Isograd
Staurolite Isograd
Garnet Zone
Chlorite Zone
Biotite Zone
Staurolite Zone
Kyanite Isograd
Increasing Metamorphic Grade
Kyanite Zone
100s Km
Scale

Metamorphic grades:

Metamorphic grade is a degree of Metamorphisn in which the rocks have arrived.
In the Barrovian sequence (described by George Barrow in zones of progressive metamorphism in Scotland), metamorphic grades are also classified by mineral assemblage based on the appearance of key minerals in rocks of pelitic (shaly, aluminous) origin:

Low grade ---------------- Intermediate -----------------High grade

Greenschist ------------- Amphibolite ------------------Granulite

Slate --- Phyllite ---------- Schist -----------Gneiss --- Migmatite

Chlorite zone
Biotite zone
Garnet zone
Staurolite zone
Kyanite zone
Sillimanite zone

Low Grade Metamorphism

Example: SLATE

- Rocks become more dense and compact
- Forms at low temperature and pressure
- Microscopic crystals
- Dull luster
- Clay and mica minerals
- Foliated

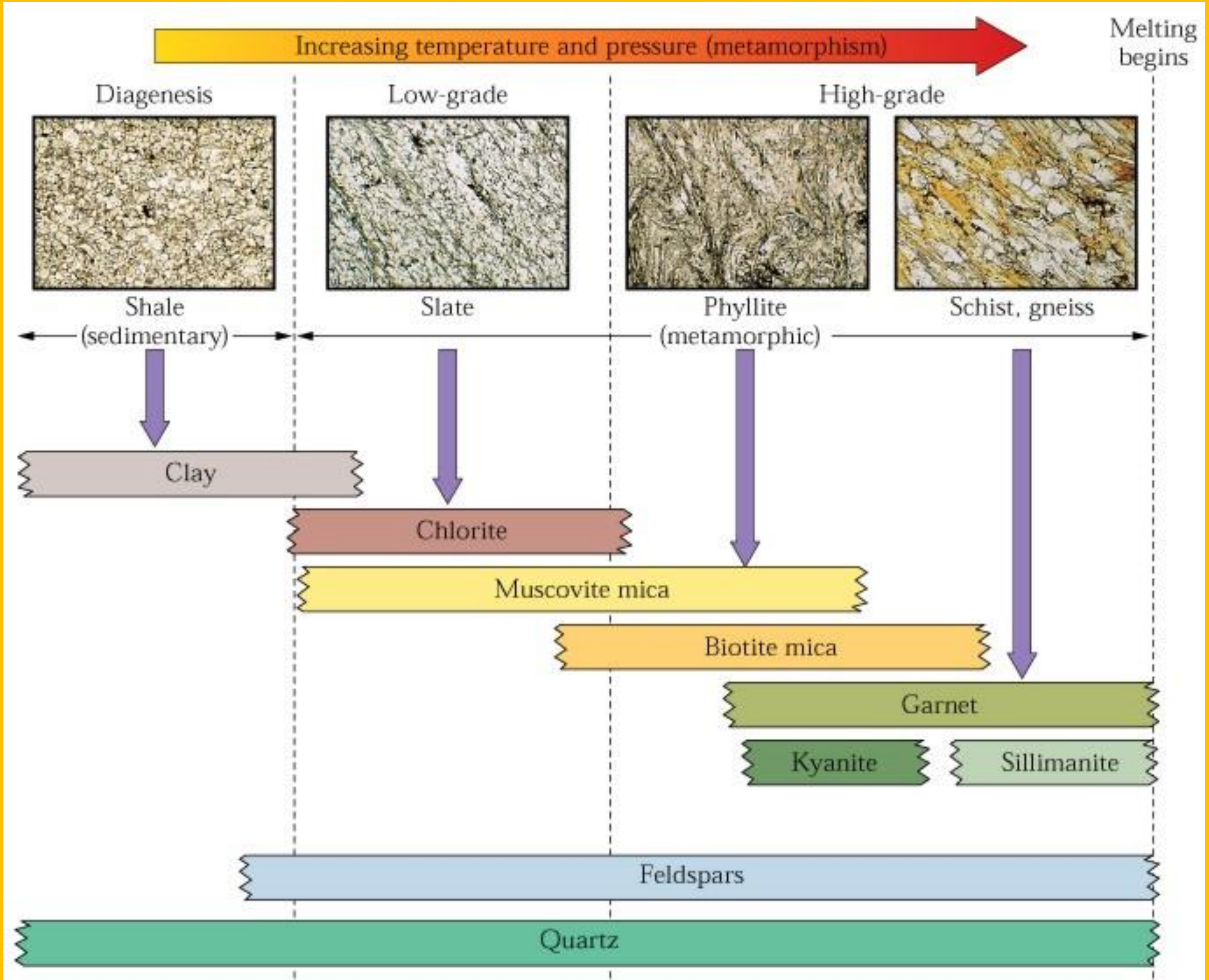
Low Grade - Slate

- Shale forms slate. In slate, foliation layers are microscopically thin.

Shale → slate

(sedimentary rock)

Metamorphic Grade



Intermediate Grade Metamorphism

Example: PHYLLITE

- Intermediate temperature and pressure
- Small crystals
- Shiny luster
- Mostly mica minerals
- Foliated

Intermediate Grade – Phyllite

High Grade Metamorphism

Example: SCHIST

- High temperature and pressure
- Large crystals
- Mica-rich
- Foliated

High Grade - Schist

High Grade Metamorphism

Example: GNEISS

- High temperature and pressure
- Large crystals
- Mica-poor
- foliated

Granite → Gneiss

METAMORPHISM OF SHALE


gneiss


schist


phyllite


slate


shale

METAMORPHISM OF COAL

Anthracite Coal

Bituminous Coal

Lignite

Peat

Kinds or Types of Metamorphism

Three Major kinds of Metamorphism differentiated on the basis of factors most dominant in causing it area:

1. **Thermal Metamorphism**
   - Contact Metamorphism
   - Pyro-metamorphism
   - Plutonic Metamorphism
2. **Dynamic or Cata-clastic Metamorphism**
3. **Dynamo-thermal Metamorphism**
   - Regional Metamorphism
   - Orogenic Metamorphism
   - Burial Metamorphism
   - Ocean Floor Metamorphism

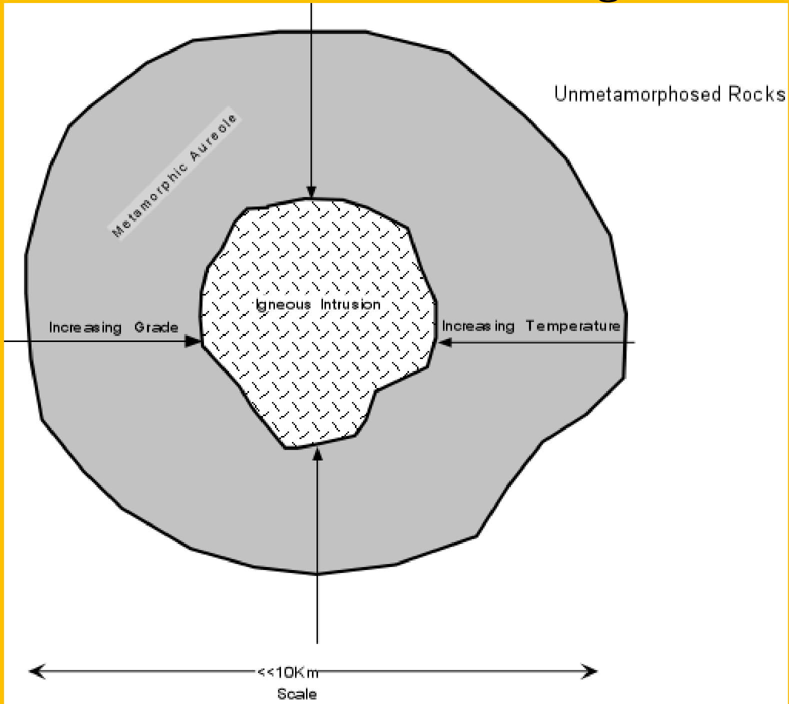
Hydrotheraml Metamorphism

Fault zone and Impact Metamorphism

Types of Metamorphism

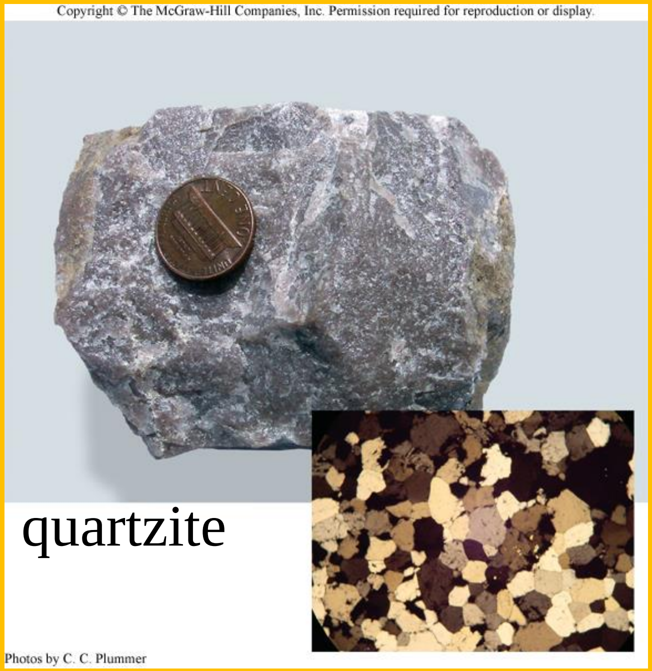
Contact Metamorphism

- This type of metamorphism occurs locally adjacent to the igneous intrusion; with high temp. and low stress
- There is little change in bulk composition of the rock
- Area surrounding the intrusion (Batholith) is heated by the magma; metamorphism is restricted to a zone surrounding the intrusion, this zone is know as METAMORPHIC AUREOLE.
- The rocks formed are non-foliated fine-grained rocks called as **HORNFELS**.



- ***Contact metamorphism***
  - High temperature
  - Produces *non-foliated* rocks
  - Rocks come in contact with magma bodies intruding cooler country rock

marble



quartzite

Hornfels

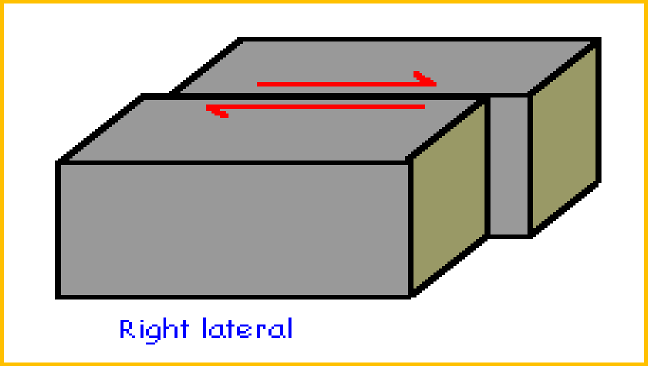
This is a metamorphic rock created by contact metamorphism when molten rock (like the peridotite) comes into contact with something like a mudstone. The mudstone is completely re-crystalised into a rock which has crystals all roughly the same size, but their colours vary depending on the type of mineral, so the rock looks more like a mosaic.

Pyrometamorphism

- A minor type of contact metamorphism
- Very high temperatures at very low pressures, generated by a volcanic or sub-volcanic body
- Also developed in xenoliths (pieces of solid rocks carried up by magma)
- Pyro-metamorphism may be accompanied by various degrees of partial melting

Type of Metamorphism

- **Cataclastic Metamorphism**
- This type of metamorphism occurs mainly due to direct pressure
- eg. when two bodies of rock slide past one another along a fault zone. Heat is generated by the friction of sliding along the zone, and the rocks tend to crushed and pulverized due to the sliding.
- Cataclastic metamorphism is mere mechanical breakdown of rocks without any new mineral formation, however, sometime due to intense shearing few new minerals are formed.



Types of Metamorphism

- ***Regional metamorphism***
  - High pressure
  - Results in rocks with *foliated* textures
  - Can deform in mountain ranges
  - May occur over wide temperature range

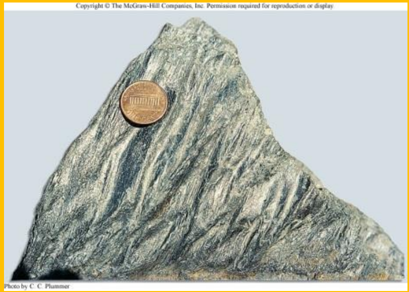
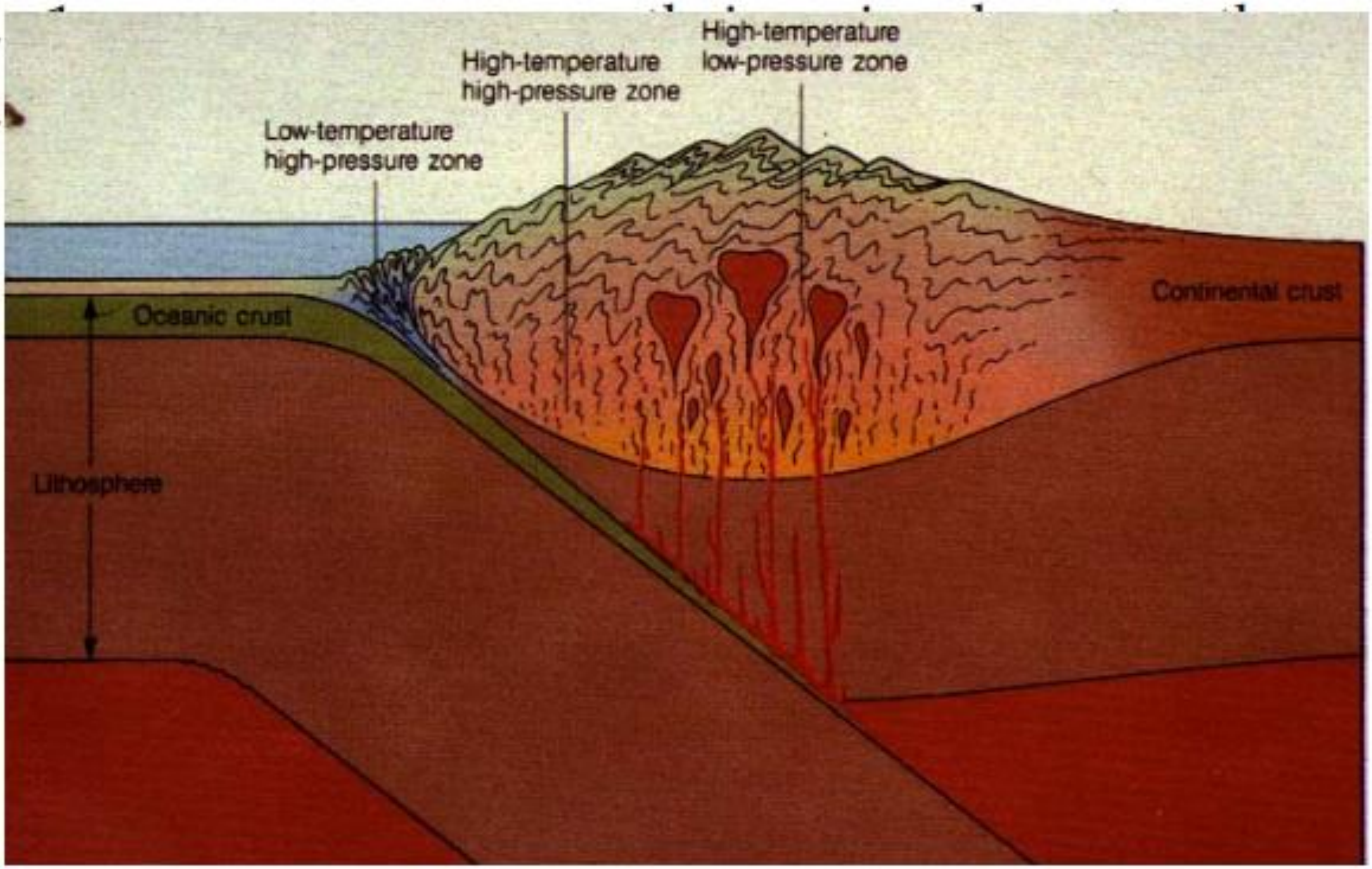


Photo by P. D. Rowley, U.S. Geological Survey

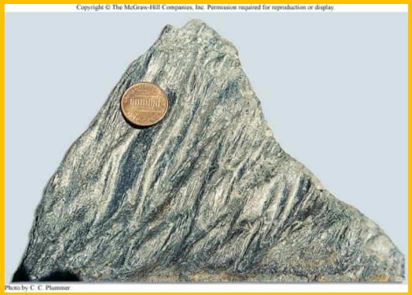
Photo by C. C. Plummer

A. Regional Metamorphism- Regional metamorphism occurs when large areas of rock are under intense heat and pressure, it causes rocks to change form

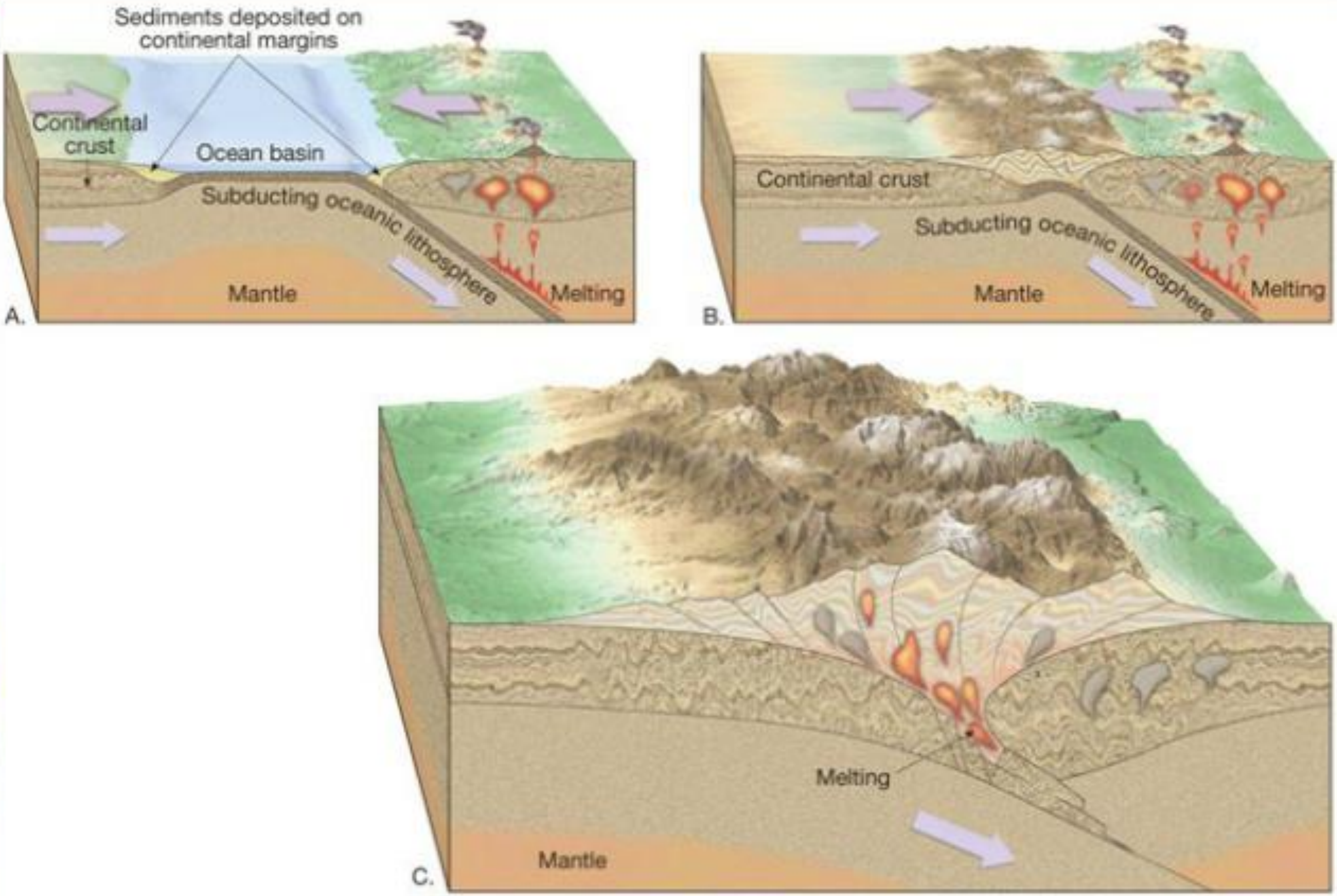


Types of Metamorphism

- ***Regional metamorphism***
  - Higher pressure *and* temperature will produce increased *metamorphic grade*
  - Prograde metamorphism of shale produces:
    - *slate*
    - *phyllite*
    - *schist*
    - *gneiss*

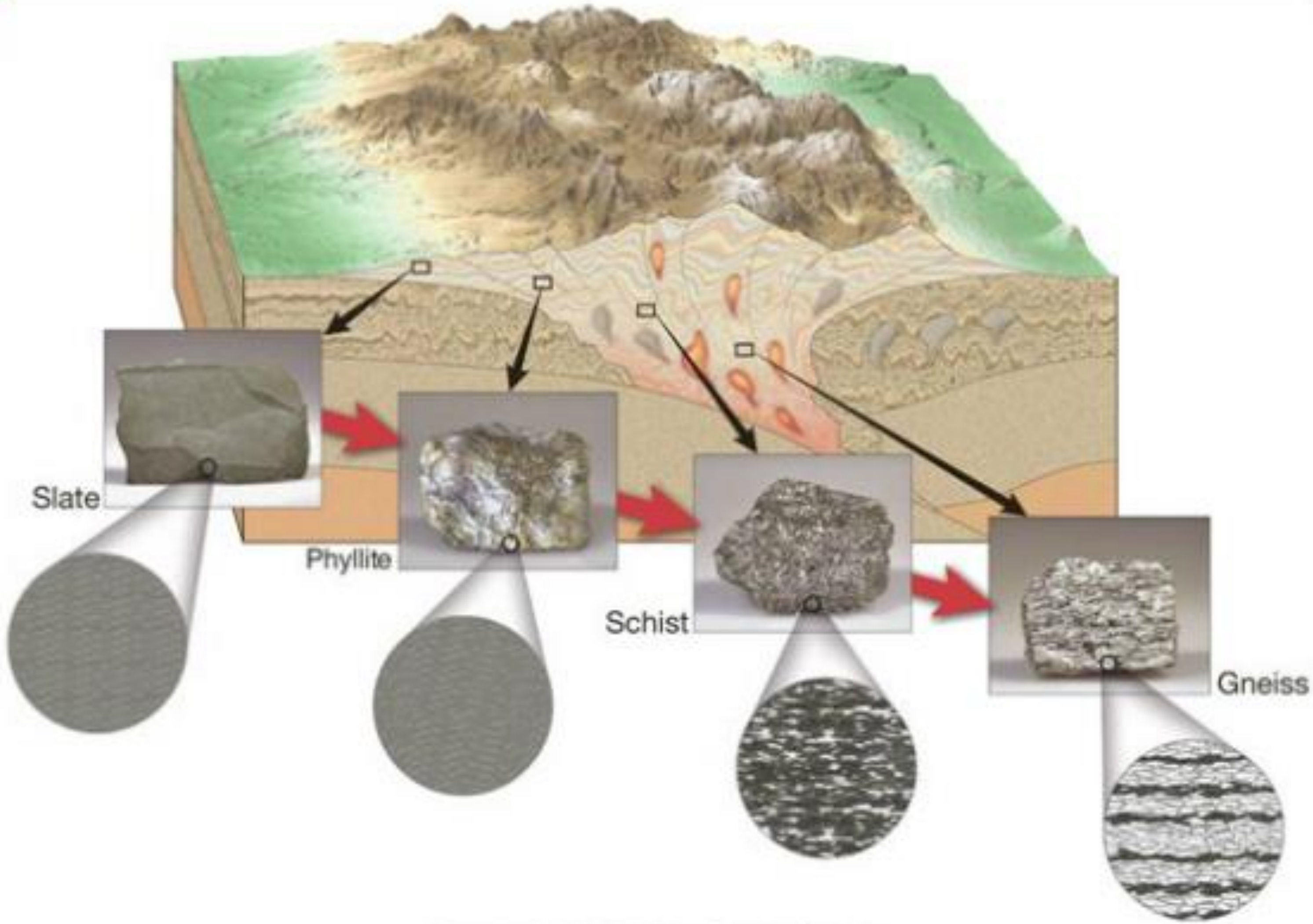


slate → phyllite → schist → gneiss



- **Regional metamorphism occurs when rocks are squeezed between converging plates during mountain building**

UMR



- **Progressive regional metamorphism: from low grade (slate); to high grade (gneiss)**

UMR

Regional Metamorphism

Three principal types:

- **Orogenic metamorphism**
- **Burial metamorphism**
- **Ocean-floor metamorphism**

The term, "Regional Metamorphism" is often used synonymously with "orogenic metamorphism" (OROGENY=mountain building)

Orogenic Metamorphism is the type of metamorphism associated with **convergent plate margins**

- **<u>Dynamo-thermal</u>: one or more episodes of orogeny with combined elevated geothermal gradients and deformation (differential stress)**

- **Foliated rocks are a characteristic product**

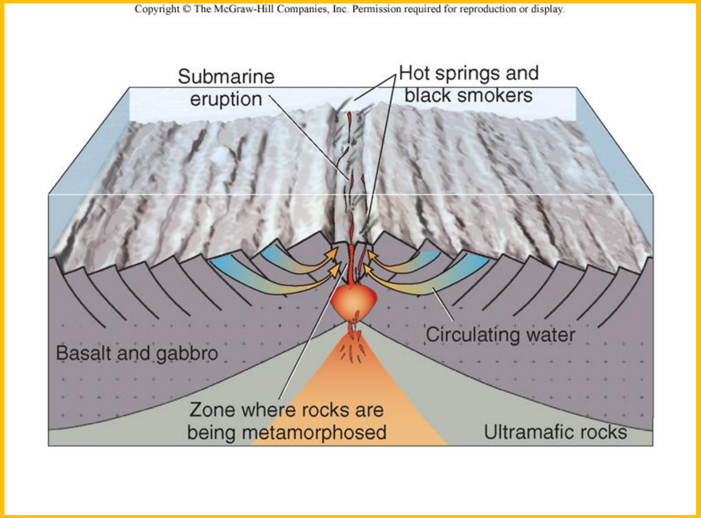
Burial metamorphism = low-grade metamorphism in sedimentary basins

- Metamorphic effects attributed to increased temperature and pressure due to burial
- Occurs in areas that have not experienced significant deformation or orogeny
- Mild deformation, no igneous intrusions discovered

Ocean-Floor Metamorphism affects the oceanic crust at ocean ridge spreading centers

- A wide range of temperatures at relatively low pressure
- Seawater penetrates down fracture systems, where it becomes heated, and leaches metals and silica from the hot basalts
- Considerable metasomatic alteration, notably **loss of Ca and Si** and **gain of Mg and Na**

Hydrothermal Processes



- Rocks precipitated from or altered by hot water are referred to as *hydrothermal*
  - Common at spreading centers (under water)
- Hydrothermal processes add water for metamorphic reactions

- Formation of *hydrothermal rocks*
  - Water passes through rocks and *precipitates new minerals* on walls of cracks and in pore spaces
  - *Metallic ore deposits* often form this way (*veins*)

Classification of Metamorphic Rocks

- Metamorphic processes cause many changes in existing rocks, including increased density, formation of larger crystals, foliation, and formation of new minerals.

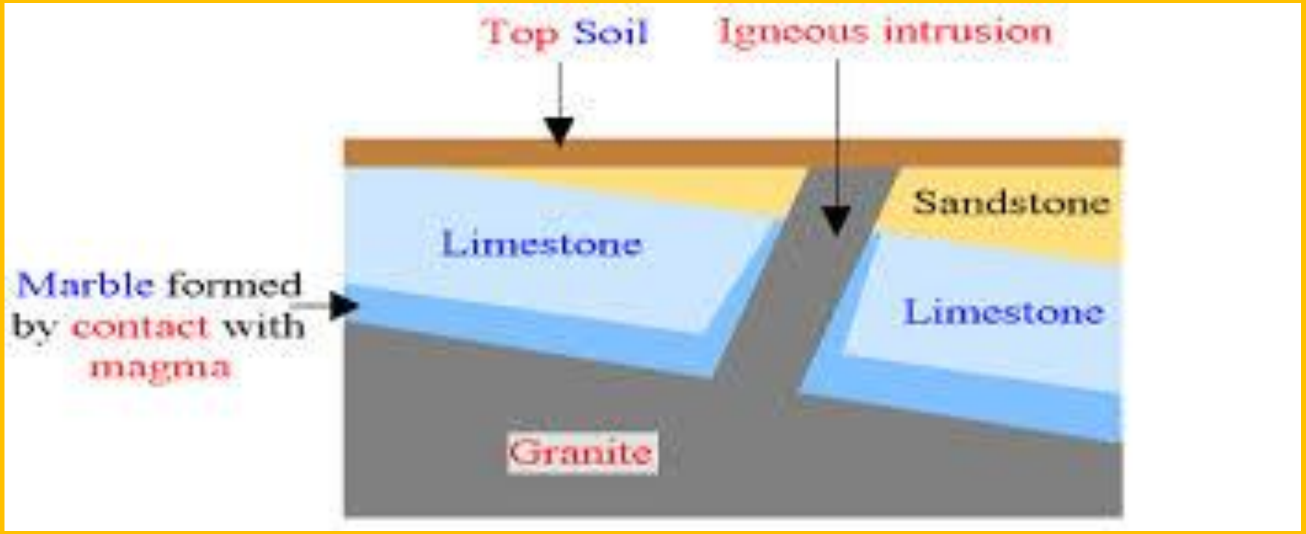
- Metamorphic rocks are generally classified as;

1) Foliated Rocks

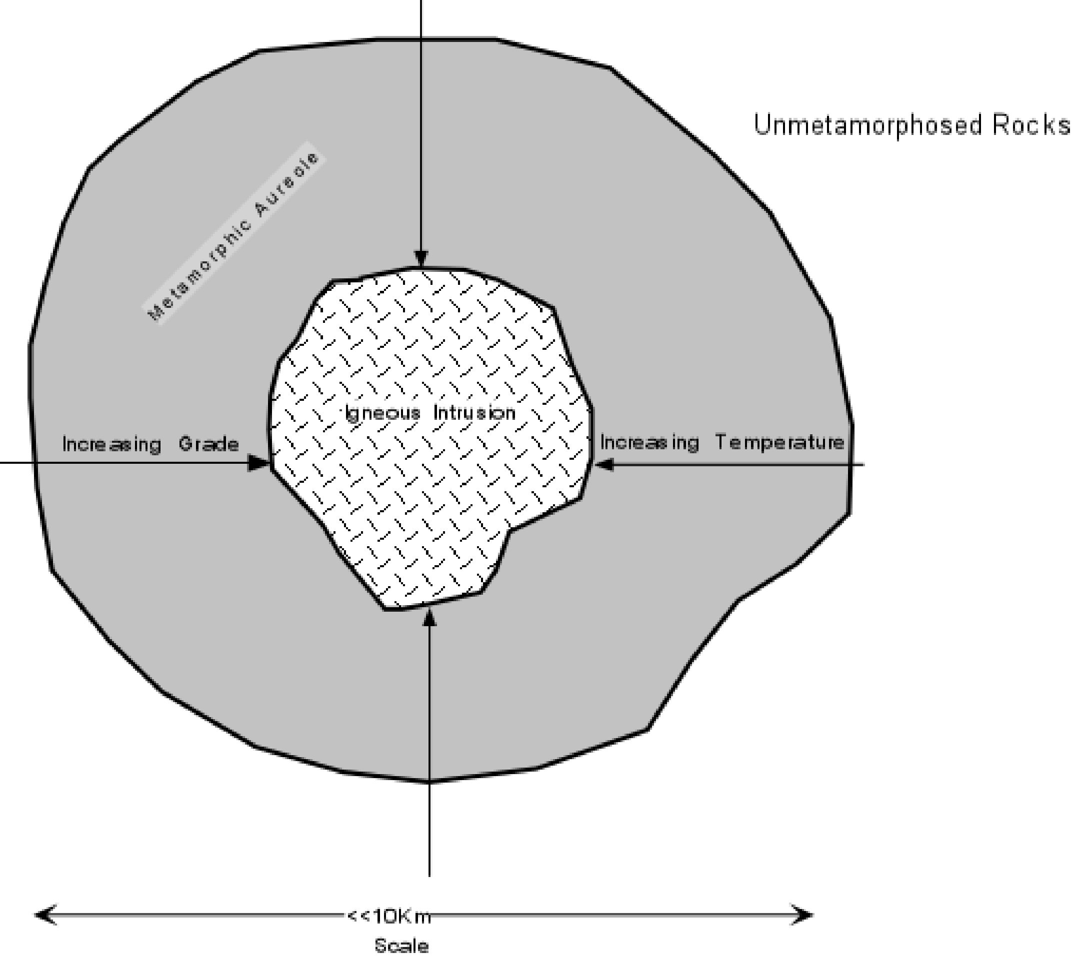
2) Non-Foliated Rocks or Lineation Rocks

Metamorphism in relation to magma

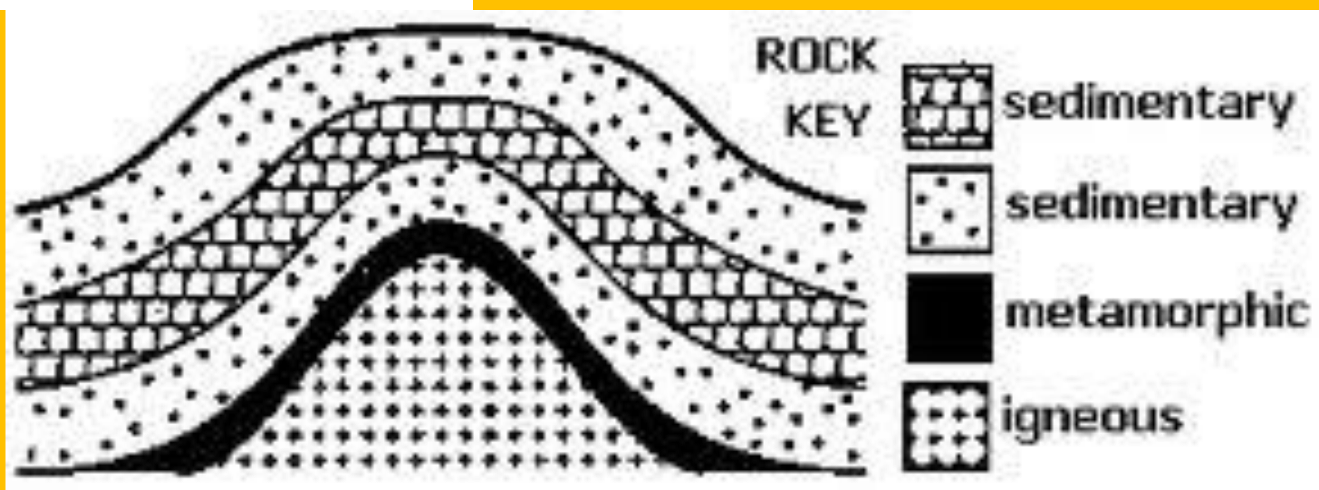
- The heat of the magma bakes the surrounding rocks causing them to change. The changes due to contact metamorphism are relatively small and are said to be low-grade metamorphism.
- *An example of contact metamorphism is the metamorphic rock marble.*
- *Marble is created from limestone that has been subjected to heat.*
- *Quartzite is also formed from the contact metamorphic processes.*



- Contact Metamorphism Occurs adjacent to igneous intrusions and results from high temperatures associated with the igneous intrusion.
- Since only a small area surrounding the intrusion is heated by the magma, metamorphism is restricted to zone surrounding the intrusion, called a **metamorphic aureole/ contact aureole**.
- Outside of the contact aureole, the rocks are unmetamorphosed.
- The grade of metamorphism increases in all directions toward the intrusion. Because temperature differences between the surrounding rock and the intruded magma are larger at shallow levels in the crus.
- Contact metamorphism is usually referred to as high temperature, low pressure metamorphism. The rock produced is often a fine-grained rock that shows **no foliation**, called a **hornfels**



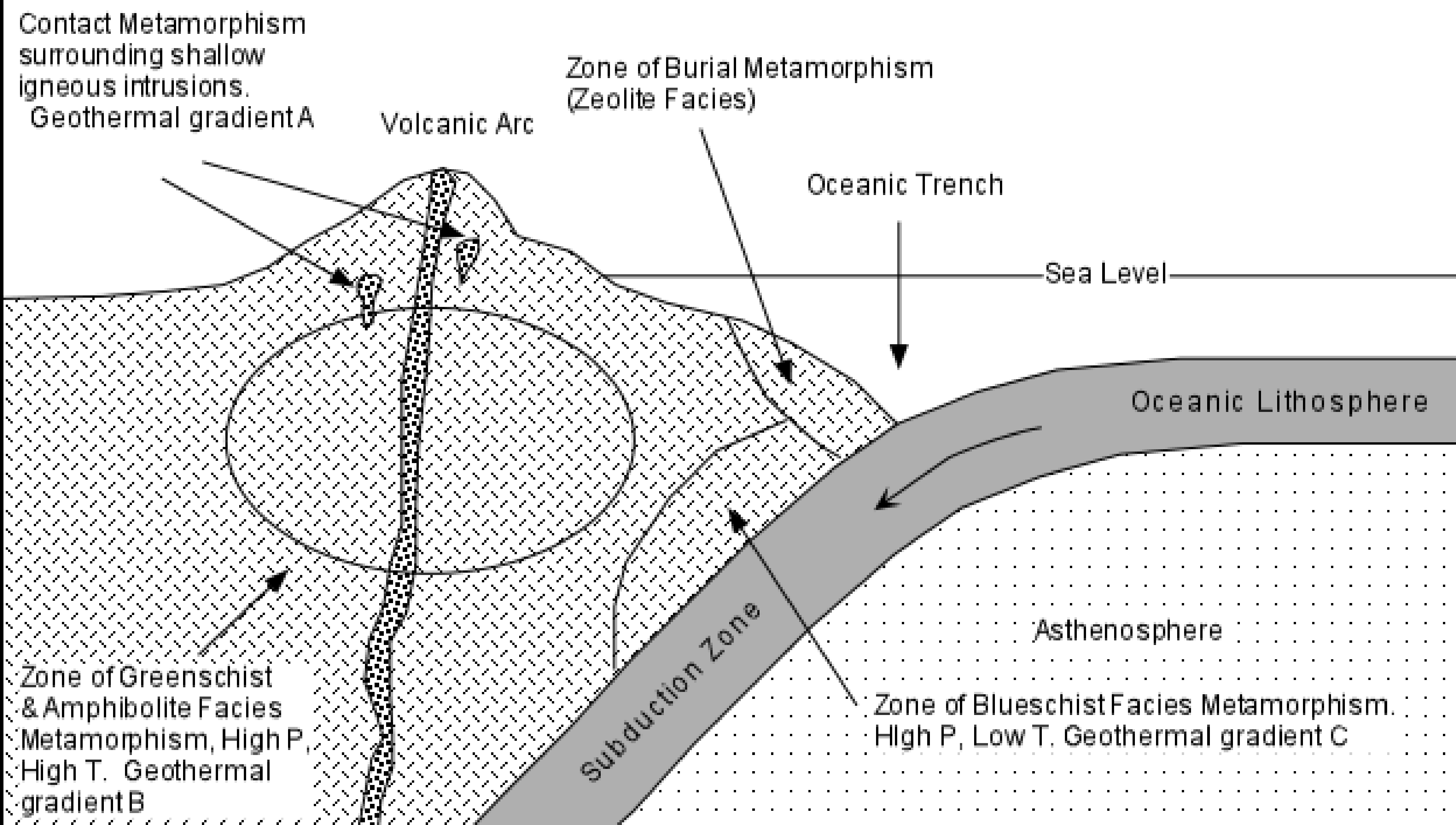
Unmetamorphosed Rocks
Metamorphic Aureole
Igneous Intrusion
Increasing Grade
Increasing Temperature
<<10Km
Scale



ROCK
KEY
sedimentary
sedimentary
metamorphic
igneous

Metamorphism in relation to Plate Tectonic/Orogeny

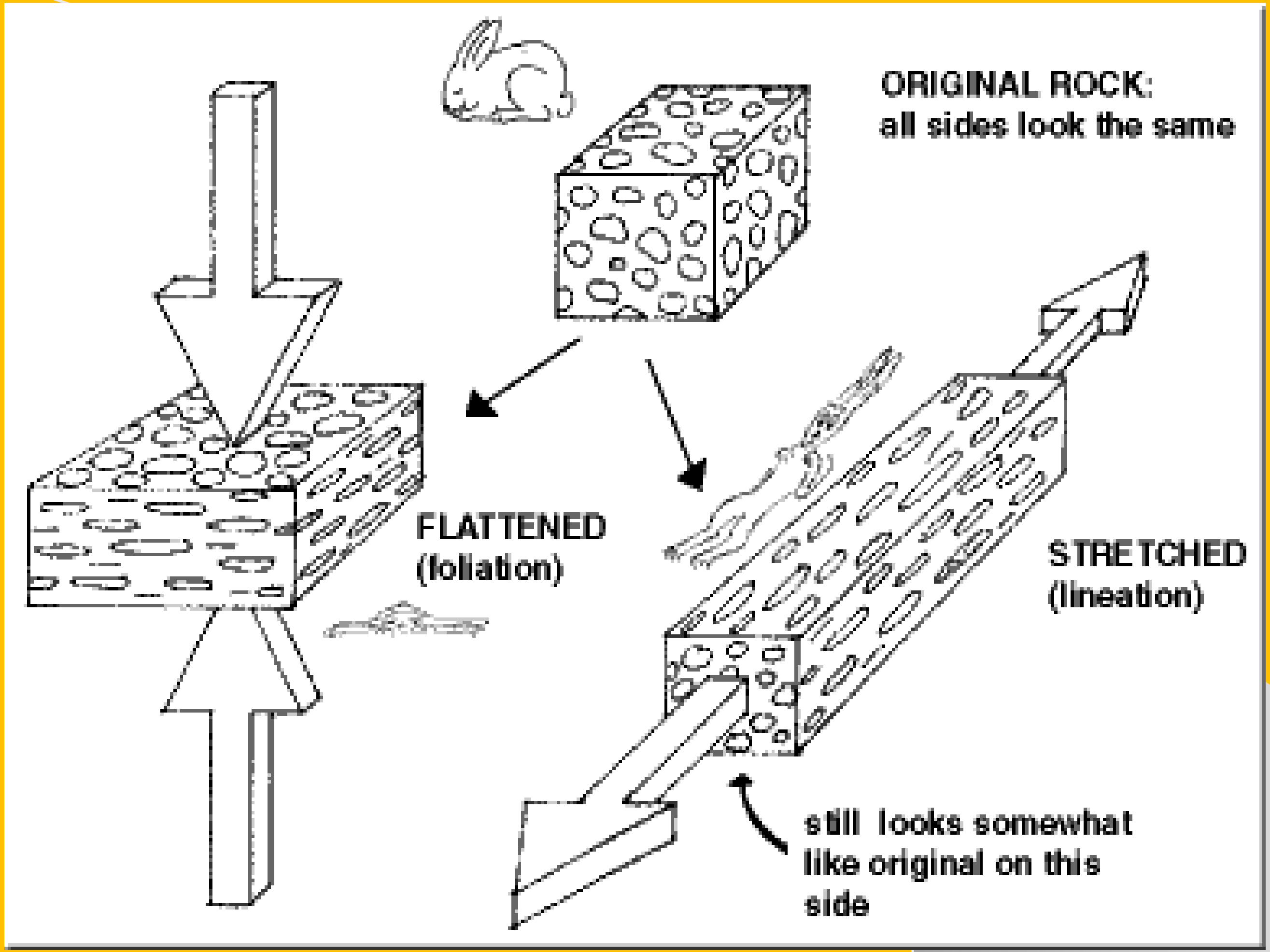
- Regional metamorphism is associated with mountain building activity. It is contrast to contact metamorphism, takes place over large areas and is high-grade metamorphism.
- When the plates of the earth collide, they squeeze the rocks at the borders with unbelievable force. This force increases the pressure in this and surrounding areas.
- Friction is also created by the plates grinding together. This friction generates enough heat to melt the rocks at the point of contact.


Contact Metamorphism surrounding shallow igneous intrusions. Geothermal gradient A
Volcanic Arc
Zone of Burial Metamorphism (Zeolite Facies)
Oceanic Trench
Sea Level
Oceanic Lithosphere
Subduction Zone
Asthenosphere
Zone of Greenschist & Amphibolite Facies Metamorphism, High P, High T. Geothermal gradient B
Zone of Blueschist Facies Metamorphism. HIgh P, Low T. Geothermal gradient C

- **MIGMATITE**
- **Migmatite** is a rock that is a mixture of metamorphic and igneous rock.
- It is created when a metamorphic rock such as gneiss partially melts, then that part refreezes into an igneous rock, creating a mixture of the unmelted metamorphic part with the recrystalized igneous part.
- They can also be known as *diatexite*.
- Migmatites form under extreme temperature conditions during prograde metamorphism, where partial melting occurs in pre-existing rocks.
- Migmatites are not crystallized from a totally molten material, and are not generally the result of solid-state reactions.

A leucosome is the lightest colored part of migmatite. The melanosome is the darker part, and occurs between two leucosomes

- Foliation: any planar fabric element
- Lineation: any linear fabric elements



Foliated Textures

- **Slatey**
  - looks like blackboard
    - >dull surface
  - smooth, thin layering
  - breaks into flat slabs
    - >referred to as slatey cleavage
  - no mineral grains visible
- **Phyllitic**
  - looks like waxed surface
    - >has a "sheen" to it
  - may have little "waves" on surface
    - >referred to as *crenulations*
  - some small grains visible
- **Schistose**
  - distinct bands of minerals
  - visible mineral grains
    - >garnets, staurolites
  - may have shiny appearance
    - >due to mica minerals
- **Gneissic**
  - larger grains
  - may look like igneous rock
  - may have crude banding
    - >intensely distorted
  - different minerals than schistose

Classification of Metamorphic Rocks

Foliated Rocks Include:

1) Slate

- Forms from low-grade metamorphism of shale.
- Fine-grained foliated rock. but foliation is not visible.
- Has excellent rock cleavage and splits easily. This property makes slate useful for tiles and billiard tables.

(i) Slaty structure:

The slaty structure is also called slaty cleavage.

The rock possessing slaty cleavage has a unique property of splitting into thin sheets. The slaty cleavage may form at any angle to the bedding planes of the shale from which the slaty rock has been derived as shown in 3.19.

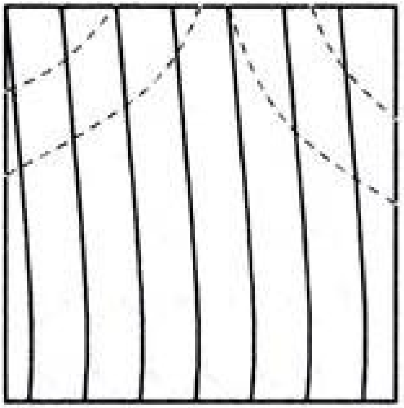


Fig. 3.19 *Slaty structure*

Classification of Metamorphic Rocks

Foliated Rocks Include:

2) Phyllite

- Forms from intermediate-grade metamorphism of slate.
- Fine-grained foliated rock,with visible foliation.
- New minerals are often formed. For example, Garnet.

Classification of Metamorphic Rocks

Foliated Rocks Include:

3) Schist

- Forms from high-grade metamorphism of phyllite.
- Coarse-grained foliated rock, with distinct foliation.
- These rocks are "platy" and can be split into flakes or slabs.
- New minerals are often formed. For example, Garnet.

(ii) Schistose structure:

It is formed by the parallel arrangement of flat, tabular, elongated or flaky minerals, such as Muscovite, Biotite, Chlorite, talc and Hornblende as shown in Fig. 3.20.

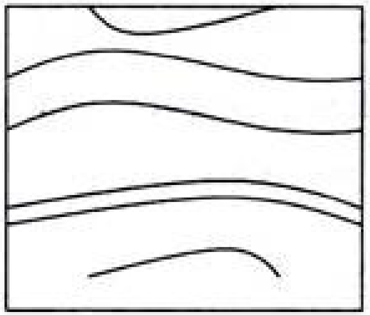


Fig. 3.20 *Schistose texture*

The rock having Schistose structure has a tendency to split readily into flakes, leaves or thin slabs.

Classification of Metamorphic Rocks

Foliated Rocks Include:

4) Gneiss

- Forms from high-grade metamorphism of schist.
- Coarse-grained foliated rock, with distinct foliation.
- These rocks display elongated and granular minerals which give the rock a dark and light banded appearance.
- Most common minerals are quartz and feldspar.

(iii) Gneissose structure:

A rock possessing gneissose structure exhibits a pronounced appearance in which light and dark coloured band alternate as in Fig. 3.21.

The light coloured bands are due to quartz and Feldspar, while the dark coloured bands are due to the presence of Ferro-magnesium minerals.

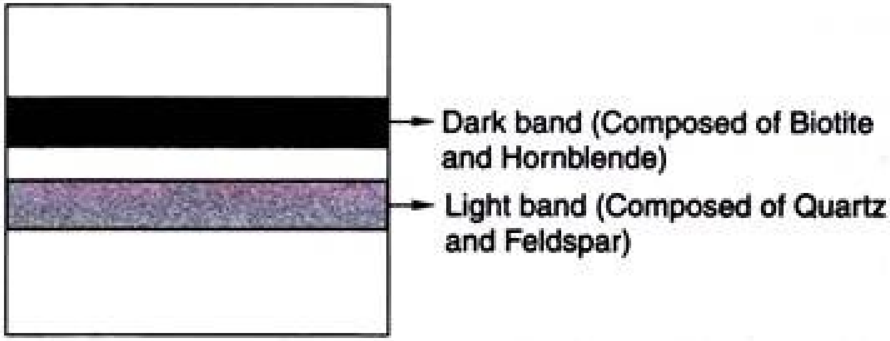


Fig. 3.21 *Gneissose texture*

(iv) Granulose structure:

Granulose (even grained) structure is produced due to the predominance of equigranular minerals such as quartz, feldspar, pyroxenes and calcite as shown in Fig. 3.22.

The flaky minerals are absent or present only in small amount on breaking a granulose rock producing a rough fracture surface.

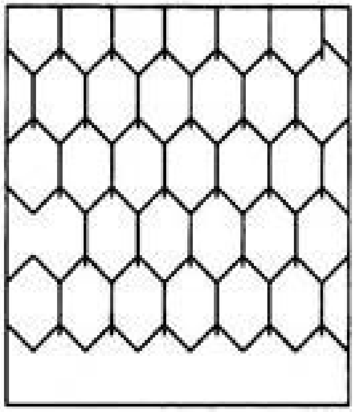


Fig. 3.22 *Granulose structure*

Classification of Metamorphic Rocks

Non - Foliated Rocks Include:

5) Marble

- Coarse crystalline network of calcite grains that form as a result of recrystallization. The parent rock of marble is Limestone.
- During recrystallization of limestone, bedding, fossils, and other sedimentary features are destroyed.
- Marble is used for statues and gravestones.

Classification of Metamorphic Rocks

Non - Foliated Rocks Include:

6) Quartzite

- Forms when silica sand grains and silica cement recrystallize forming a coarse grained network of silica. The parent rock of quartzite is quartz sandstone.
- Moderate to high-grade metamorphism fuses the sand grains. Sometimes outlines of the original grains may be seen, a feature called ghosting.
- Quartzite is a very hard rock.

Non-Foliated Metamorphic Rocks

Granofels: a comprehensive term for any rock with no preferred orientation

An outdated alternative to granofels is ***granulite***, but this term is now used to denote very high grade rocks (whether foliated or not), and is not endorsed here as a synonym for granofels.

Non-Foliated Metamorphic Rocks

Marble: a metamorphic rock composed predominantly of calcite or dolomite. The protolith is typically limestone or dolostone.

Non-Foliated Metamorphic Rocks

Quartzite: a metamorphic rock composed predominantly of quartz.

The protolith is typically sandstone. Some confusion may result from the use of this term in sedimentary petrology for a pure quartz sandstone.

Metamorphic Rock Facies

Greenschist/Greenstone: a low-grade metamorphic rock that typically contains chlorite, actinolite, epidote, and albite.

Note that the first three minerals are green, which imparts the color to the rock. Such a rock is called greenschist if foliated, and greenstone if not. The protolith is either a mafic igneous rock or graywacke.

Metamorphic Rock Facies

Amphibolite: a metamorphic rock dominated by hornblende + plagioclase. Amphibolites may be foliated or non-foliated. The protolith is either a mafic igneous rock or graywacke.

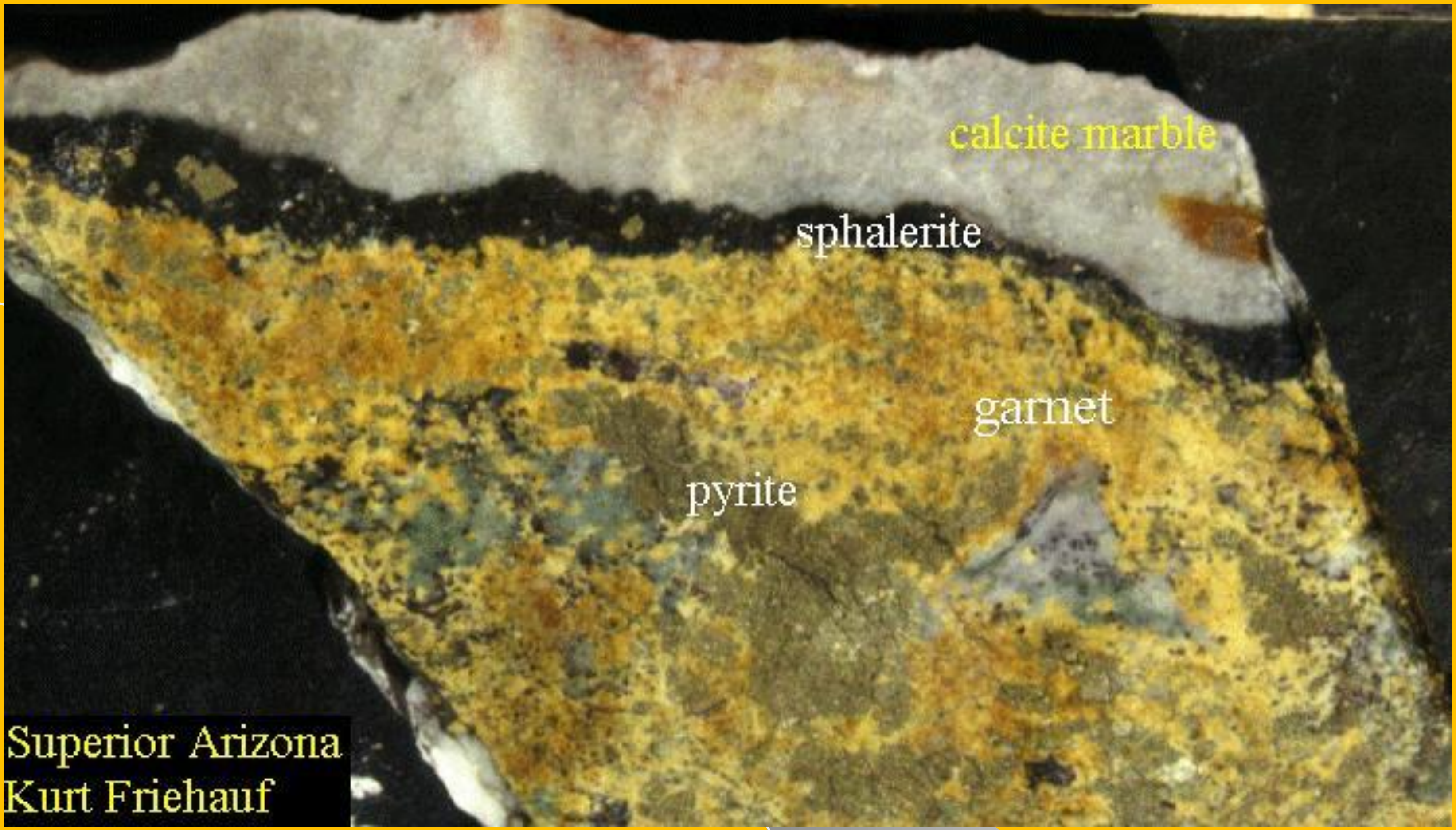
Serpentinite: an ultramafic rock metamorphosed at low grade, so that it contains mostly serpentine.

Blueschist:

A blue glaucophane bearing metamorphosed mafic igneous rock or mafic graywacke. This term is even applied to non-schistose rocks.

Eclogite: a green and red metamorphic rock that contains the green clinopyroxene omphacite and pink garnet pyrope. The protolith is typically basaltic.

Granulite: a high grade rock of pelitic, mafic, or quartzo-feldspathic parentage that is predominantly composed of OH-free minerals. Muscovite is absent and plagioclase and orthopyroxene are common.

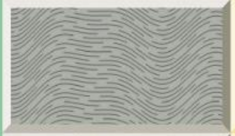
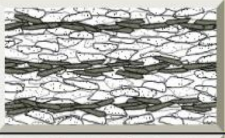
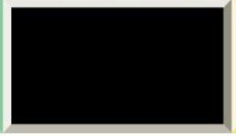


Skarn: a contact metamorphosed and silica metasomatized carbonate rock containing calc-silicate minerals, such as grossular, epidote, tremolite, vesuvianite, etc. **Tactite** is a synonym.

Migmatite: a composite silicate rock that is heterogeneous on the 1-10 cm scale, commonly having a dark gneissic matrix (*melanosome*) and lighter felsic portions (*leucosome*).

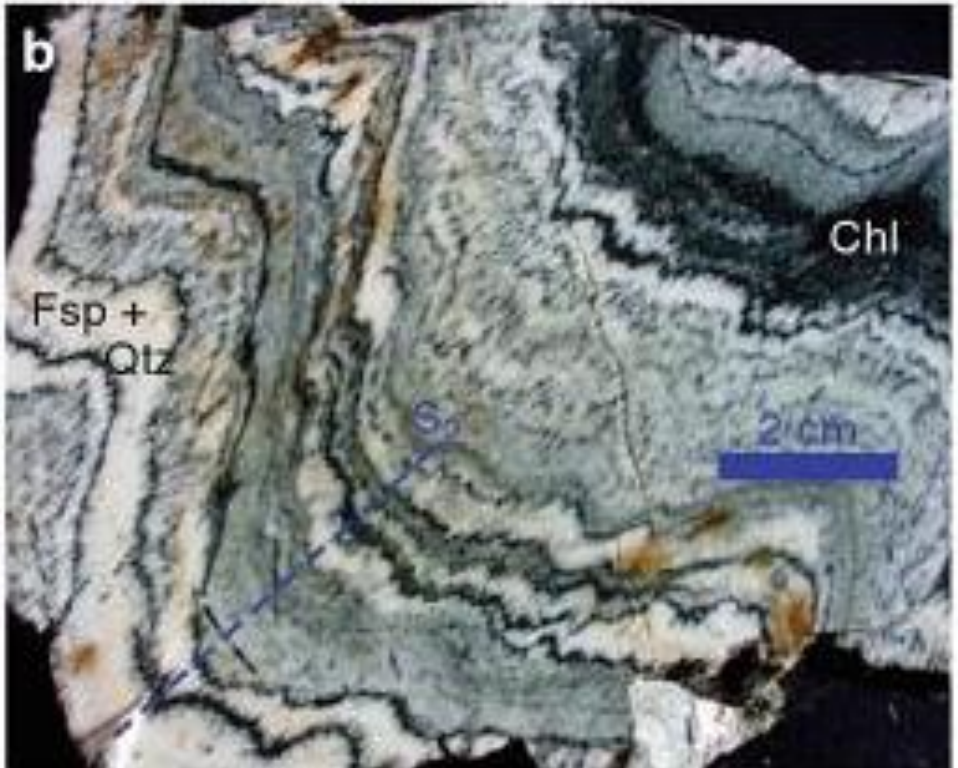
Migmatites may appear layered, or the leucosomes may occur as pods or form a network of cross-cutting veins.

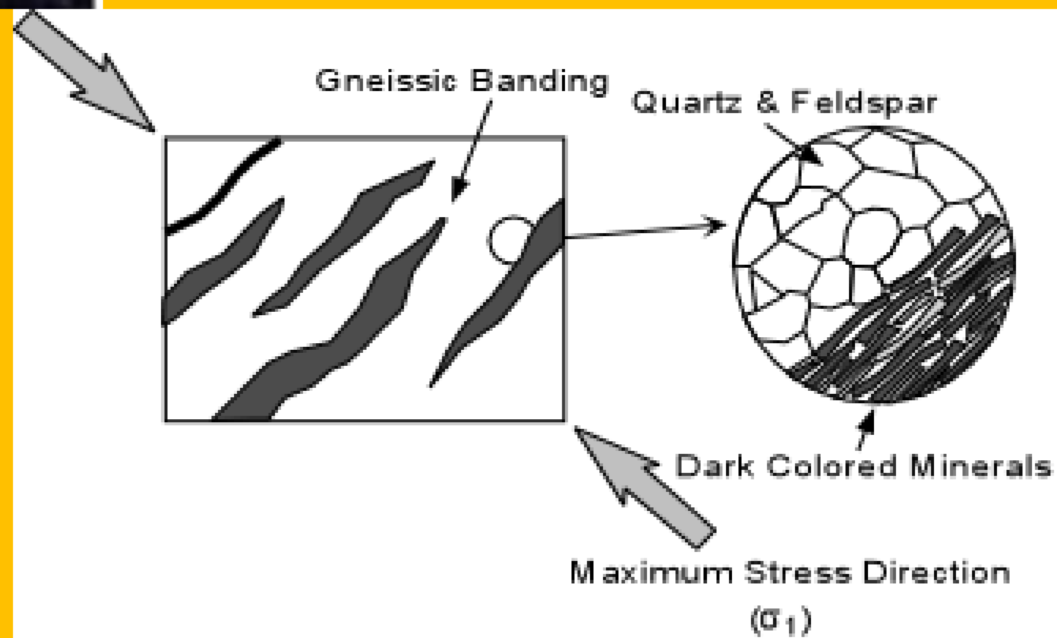
Classification of metamorphic rocks

Rock Name		Texture		Grain Size	Comments	Parent Rock
Slate	Increasing Metamorphism	Foliated		Very fine	Excellent rock cleavage, smooth dull surfaces	Shale, mudstone, or siltstone
Phyllite				Fine	Breaks along wavey surfaces, glossy sheen	Slate
Schist				Medium to Coarse	Micaceous minerals dominate, scaly foliation	Phyllite
Gneiss				Medium to Coarse	Compositional banding due to segregation of minerals	Schist, granite, or volcanic rocks
Marble		Nonfoliated		Medium to coarse	Interlocking calcite or dolomite grains	Limestone, dolostone
Quartzite				Medium to coarse	Fused quartz grains, massive, very hard	Quartz sandstone
Anthracite				Fine	Shiny black organic rock that may exhibit conchoidal fracture	Bituminous coal

Metamorphic Differentiation

- Redistribution of mineral grains and/or chemical component in a rock as a result of metamorphic processes is known as metamorphic differentiation. (OR)
- Metamorphic processes by which mineral grains or chemical components are redistributed in such a way to increase the modal or chemical anisotropy of a rock(or portion of a rock) without changing the overall chemical composition.
- As metamorphic grade increases, the sheet silicates become unstable and dark colored minerals like hornblende and pyroxene start to grow. These dark colored minerals tend to become segregated into distinct bands through the rock, giving the rock a ***gneissic banding***. This process is called metamorphic differentiation


b
Chl
Fsp +
Qtz
S2
2 cm


Gneissic Banding
Quartz & Feldspar
Dark Colored Minerals
Maximum Stress Direction
(σ_1)

Mineral Paragenesis

- **Paragenesis**, the sequence in which the minerals are formed in an ore deposit.
- Variations in the pressure and temperature and in the chemical constituents of a hydrothermal solution will result in the precipitation of various minerals at different times within the same ore deposit.
- The general sequence of deposition is gangue minerals (silicates and carbonates) first; oxide minerals next, with the sulfides and arsenides of iron, nickel, cobalt, and molybdenum contemporaneous with or closely following the oxides, and the lead and zinc sulfides following them; and last the native metals and tellurides followed by the antimony and mercury sulfides.
- The paragenesis at any particular location may be complicated if the ore deposit has been formed by more than one period of hydrothermal activity.

Mineral Paragenesis of Metamorphic rocks

Metamorphic rocks derived from sediments whose composition may not be the same even over a small volume. Therefore, it is well possible that all minerals observed in single thin section do not belong to a single metamorphic parangenesis, Rather, two or more mineral parangenesis.

In earlier petrographic work it was belived that the determination of all the minerals of a given rock is sufficient. That is not so. It now must be ascertained which of the minerals in a thin section are in contact. Only minerals in contact may be regarded as an assemblage of coexisting minerals,. i.e a parangenesis

Metamorphic mineral parangenesis refers to minerals in contact with each other.

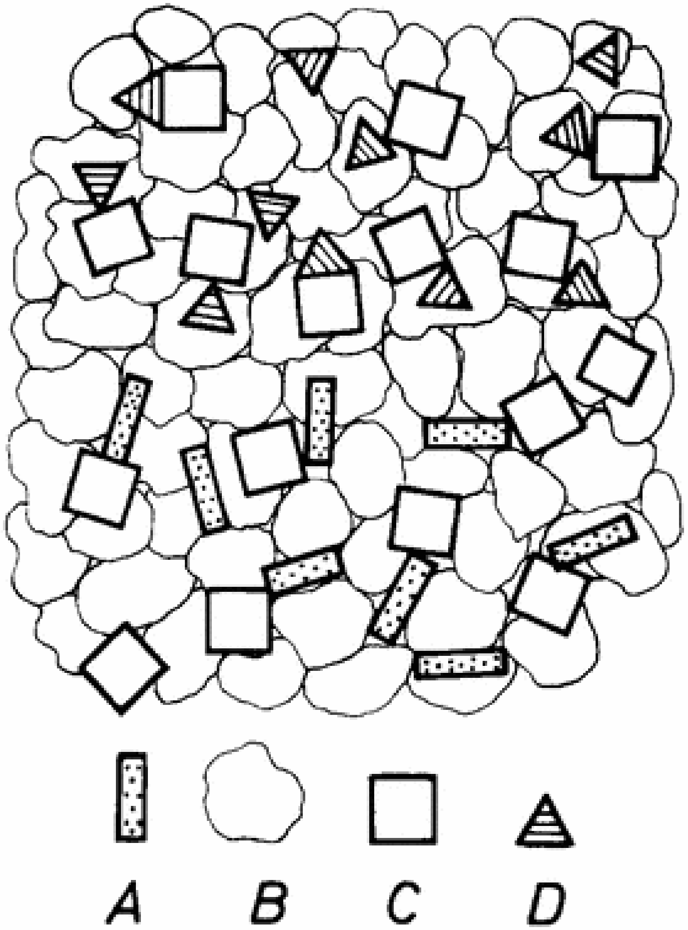


Fig. 4-1 Schematically shown are two different parageneses. They consist of (1) the minerals A,B, and C and (2) the minerals B,C, and D. Note that all four minerals together do not constitute a paragenesis because they are not in contact with each other.

- **Paragenesis,** the sequence in which the minerals are formed in an ore deposit.
- Variations in the pressure and temperature and in the chemical constituents of a hydrothermal solution will result in the precipitation of various minerals at different times within the same ore deposit.
- The general sequence of deposition is gangue minerals (silicates and carbonates) first; oxide minerals next, with the sulfides and arsenides of iron, nickel, cobalt, and molybdenum contemporaneous with or closely following the oxides.

- Then, the lead and zinc sulfides following them; and last the native metals and tellurides followed by the antimony and mercury sulfides.
- The paragenesis at any particular location may be complicated if the ore deposit has been formed by more than one period of hydrothermal activity.

Paragenetic Studies

- The goal of Paragenitic studies is to decipher the sequence of mineral formation.
- There is no "standard method" for carrying out paragenetic studies, because each ore deposit is unique.
- Samples must be representative of the whole deposit if they are to be useful in paragenetic studies.

- Conventional polished sections may be too small to display textural and paragenetic relationships in very coarse-grained ores, complex veins or bedded ores;
- This problem can be overcome by combining hand samples or oriented slabs of ore with polished and thin sections. and by the use of both high- and low-power objectives in microscopy.
- In some ores, the doubly polished thin section provides information superior to that provided by the conventional polished section for paragenetic studies.

Crystal Morphology and Mutual Grain Boundary Relationships

- The shapes of individual crystals and the nature of the contacts between adjacent grains have often been used as criteria for determining paragenesis.
- In general, euhedral crystals have been interpreted as forming early and growing unobstructed; grains with convex faces have been interpreted as forming earlier than those with concave faces.
- For example, calcite, quartz, fluorite, sphalerite, cassiterite, galena, covellite, and sulfosalts usually form well-developed euhedral crystals only in directions in which growth is unobstructed. The existence of such crystals, mixed with , or overgrown by, other minerals, indicates that the euhedra were the first formed.

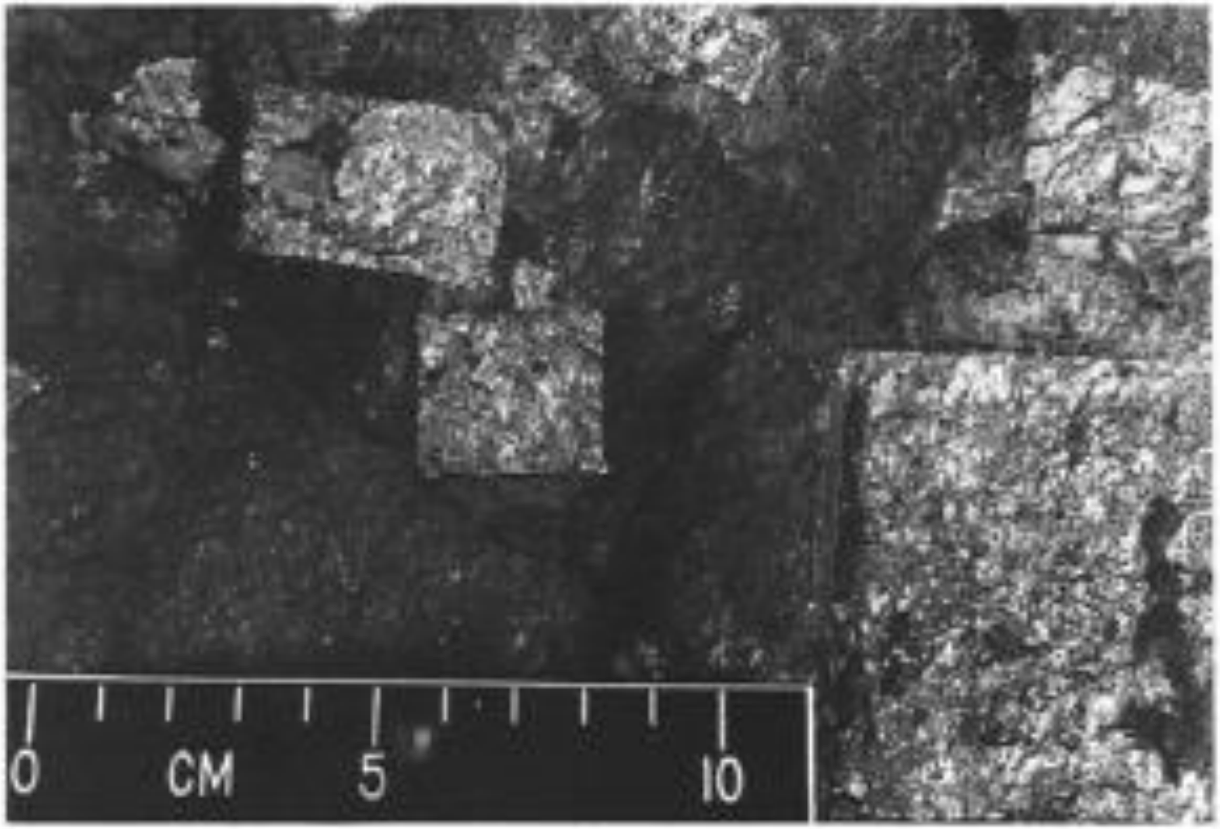


FIGURE 8.2 Porphyroblasts of pyrite grown in a matrix of pyrrhotite during regional metamorphism, Cherokee Mine, Ducktown, Tennessee (centimeter scale).

Crosscutting Relationships

- **In mineralogical examination. just as in geological field studies, crosscutting** relationships are a key to paragenetic interpretation.
- The *veinlet or other feature that crosscuts another is younger than that which it cuts across,* except when the older phase has been replaced, or when both features result from metamorphic remobilization .
- Therefore, the veinlet that cuts across an other veinlet or crystal, is later in the paragenetic sequence, whether it represents simple open-space filling or replacement.

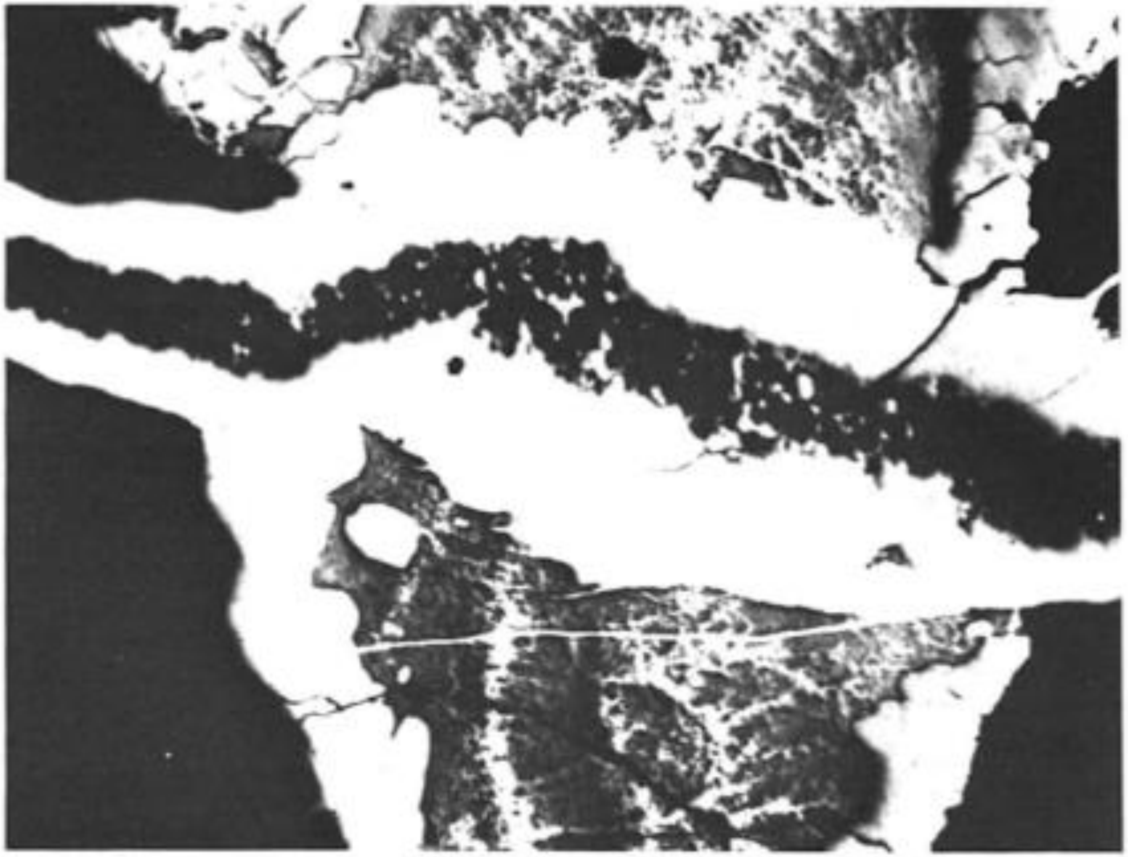


FIGURE 8.7 Crosscutting relationships shown in a manganese oxide ore in which early chalcophanite is cut by a later veinlet of the same mineral, Red Brush Mine, Virginia (width of field = 2,000 μm).

Replacement

Replacement features are very useful in the determination of paragenesis:

The mineral being replaced predates the one replacing it. Since replacement is generally a surface chemical reaction. it usually proceeds inward from crystal boundaries or along fractures.

In general. during advanced replacement, the replacing phase possesses convex boundaries.

whereas the replaced phase possesses concave boundaries and may remain as residual "islands" within a matrix of the later phase.

Twinning

- Twinning can be useful in the interpretation of both the paragenesis and the deformational history of an ore.
- Twinning may form during initial growth, through inversion or as a result of deformation.
- Since growth twinning is a function of temperature and degree of ore fluid super saturation and since kinetics are also influenced by the crystallization.
- the presence of twinning in only some grains of a specific mineral may be useful in distinguishing different generations of that mineral.

EXAMPLES OF PARAGENETIC STUDIES

Although it is difficult to generalize, the opaque minerals in many ores can be associated with one of four major divisions:

1. The host rock materials, which, if igneous, may contain primary oxides or which, if sedimentary, may contain detrital or authigenic opaques (e.g., framboidal pyrite, titanium oxides).
2. The main mineralization episode, which, although often multiphase, is usually one major introduction of fluids, volatiles, or magma that then undergo cooling.
3. A phase of secondary enrichment (in the zone of supergene alteration) resulting in overgrowths and replacement textures.
4. A phase of oxidation and weathering, again resulting in replacement textures and the formation of oxides, hydroxides, sulfates. carbonates.

Normally the sequence of mineral formation (paragenesis) would follow divisions (I) through (4). al though many deposits contain evidence of only divisions (1)and (2). **It is also impo rtant to note that many minerals may have** more than one paragenetic position, although different generations may have

different habits (e.g., very early pyrite framboidss pyrite cubes late colloform pyrite) or chemical compositions.

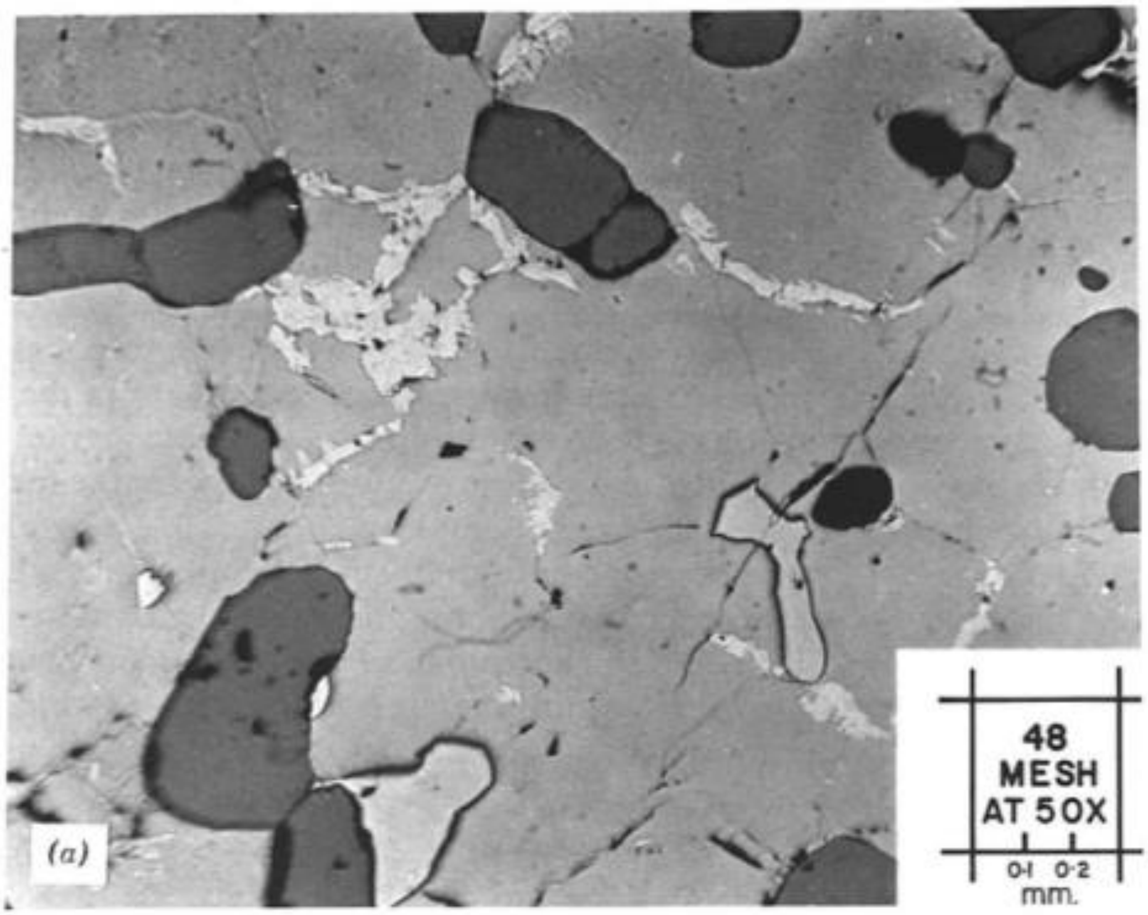


FIGURE 8.8 Nickel-copper ore from Sudbury, Ontario, Canada, illustrating the paragenesis of the ore. (*a*) Early-formed subhedral grains of magnetite (dark gray) within coarse granular pyrrhotite (medium gray), rimmed by granular pentlandite that has coalesced after exsolution. Also present are two anhedral grains of chalcopyrite (width of field = 1,700 μm). (*b*) Exsolutlon "flames" of pentlandite (light gray) in a

Bravoite with overgrowths of later pyrite in a veinlet
surrounded by carbonates

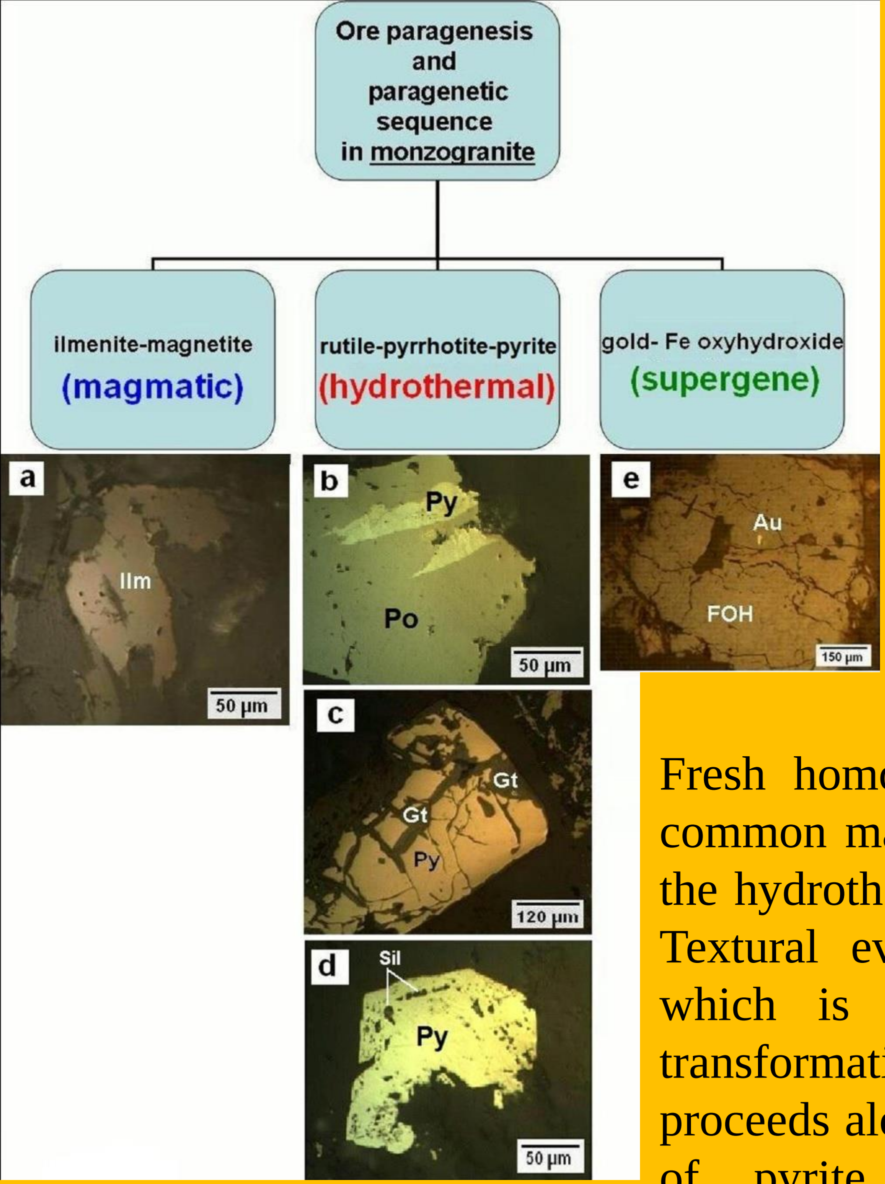


Figure 5: Ore paragenesis and paragenetic sequence in monzogranite. (a) Fresh homogeneous ilmenite (Ilm), P.R.L. (b) Pyrite (Py) replacing pyrrhotite (Po) along weak planes, P.R.L. (c) Pyrite (Py) replaced partly by goethite (Gt) along fractures, P.R.L. (d) Sub-idiomorphic pyrite (Py) showing zonal arrangement ofsilicate inclusions (Sil) at the peripheral zone, P.R.L. (e) Supergene ferric oxyhydroxide (FOH) with visible gold inclusion (Au), P.R.L.

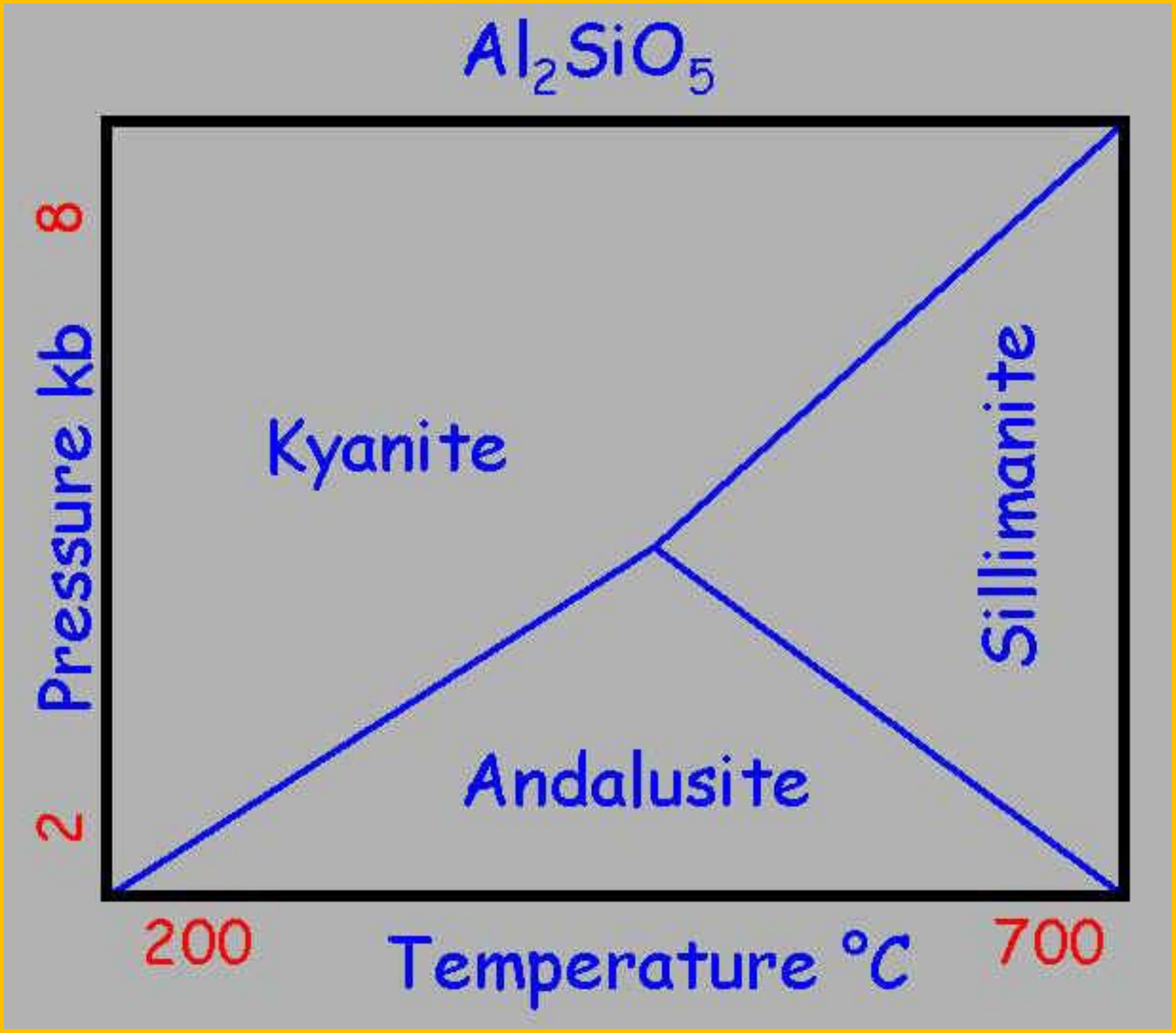
Monzogranite

Fresh homogeneous ilmenite Figure 5]a and magnetite are common magmatic ore minerals in the monzogranite whereas the hydrothermal ore minerals are rutile, pyrrhotite and pyrite. Textural evidence suggests earlier formation of pyrrhotite which is then followed by either partial or complete transformation into pyrite. This transformation obviously proceeds along cracks and cleavage planes [Figure 5]b. Cracks of pyrite itself contain goethite as a product of hydration [Figure 5]e. Some sub-idiomorphic pyrite crystals show zonal arrangement of rutile and silicate inclusions [Figure 5]f. Again, supergene visible gold is recorded in weathered

Mineral Stability

- Changes in temperature as well as in pressure, have important impacts upon the stability of minerals. Every mineral is stable over a range of pressures, if pressure conditions during metamorphism exceed a mineral's stability range the mineral will transform to a new phase.
- Many of these solid - state reactions involve polymorphic transformation –

.



Al_2SiO_5
Pressure kb
8
2
Kyanite
Andalusite
Sillimanite
200
Temperature °C
700

Anti-Stress and Stress Minerals

Anti-Stress (Uniform Pressure) Minerals whose formation is favoured by uniform pressure, and which are also well known as product of thermal and contact metamorphism, have been called as ***anti-stress minerals***, such minerals are anorthite, potash-feldspar, augite, pyroxene, olivine, andalusite, sillimanite, cordierite and sphine, which are unstable in the presence of stress.

Stress (Directed Pressure) Minerals

Minerals whose formation is favored by the directed pressure is known as **stress minerals**.

Stress in the rock is accomplished by internal movement and by recrystallization. Stress reduce with increased temperature and therefore in general, with depth in the crust. (fracture converted into shear while depth increases)

The minerals from mica group, sericite, muscovite and chlorite with albite among the feldspars, minerals of the epidote-zoisite group, the amphiboles, along with kyanite, staurolite, chlotitoid and talc all of which are grouped together as stress minerals.

FLUID INCLUSION STUDIES

A **fluid inclusion** is a microscopic bubble of liquid and gas that is trapped within a crystal.

The study of fluid inclusions although commonly carried out on nonopaque minerals using a transmitted-light microscope has become a major and important field of investigation that is commonly carried out simultaneously with conventional ore microscopy to provide vital information about the fluids associated with ore formation.

- Fluid inclusions are small volumes of paleofluids trapped in minerals which provide indispensable information about geological processes, from high temperatures at depth towards low temperatures near the Earth's surface.
- These inclusions are trapped gases, liquids or crystals, either trapped singularly (one-phase) or as a heterogeneous mixture of more than one phase (multi-phase) in a single cavity.
- Depending upon the timing of entrapment of liquid in the crystals, fluid inclusions are classified as primary, secondary or pseudosecondary.
- As minerals often form from a liquid or aqueous medium, tiny blebs of that liquid can become trapped within the crystal, or along healed crystal fractures.
- These small inclusions range in size from 0.1 to 1 mm and are usually only visible in detail by microscopic study.

- ➢The inclusions occur either as isolated, clustered, or trail bound; those occurring in groups form the Group of Synchronous Inclusions (GSI) having similar composition and time of entrapment.
- ➢The composition of trapped fluid varies greatly; commonly detected constituents include H_2O, CO_2, CH_2, H_2S, Cl, Br, F, I, N_2, S, Na, K, Ca, Mg and Fe.
- ➢There are several instruments used in the study of fluid inclusions, but the basic study is carried out using heating-freezing stages and Laser Raman Microprobe.
- ➢The study of fluid inclusions reveal geologically important information such as temperature, pressure, salinity, density and depth of trapping; and
- ➢Thereby providing direct information about the conditions at which given minerals and rocks are formed.

Hydrothermal ore minerals typically form from high temperature aqueous solutions.

The trapped fluid in an inclusion preserves a record of the composition, temperature and pressure of the mineralizing environment.

An inclusion often contains two or more phases.

If a vapor bubble is present in the inclusion along with a liquid phase, simple heating of the inclusion to the point of resorption of the vapor bubble gives a likely temperature of the original fluid.

If minute crystals are present in the inclusion, such as halite, sylvite, hematite, or sulfides, they provide direct clues as to the composition of the original fluid.

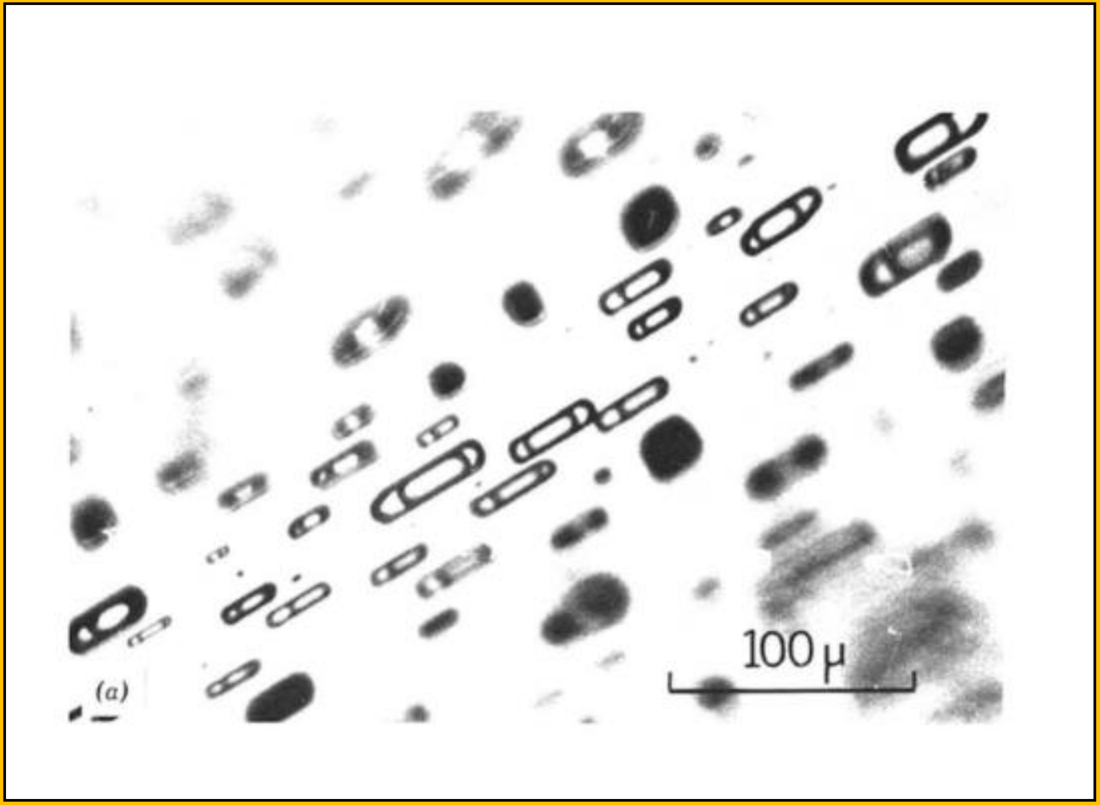
The Nature and Location of Fluid Inclusions

- Fluid inclusions are small amounts of fluid that are trapped within crystals during initial growth from solution or during total recrystallization (primary inclusions) or during localized recrystallization along fractures at some later time (secondary inclusions).
- Fluid inclusions are very abundant in common ore and gangue minerals. Sometimes occurring in quantities of a billion or more per cubic centimeter.

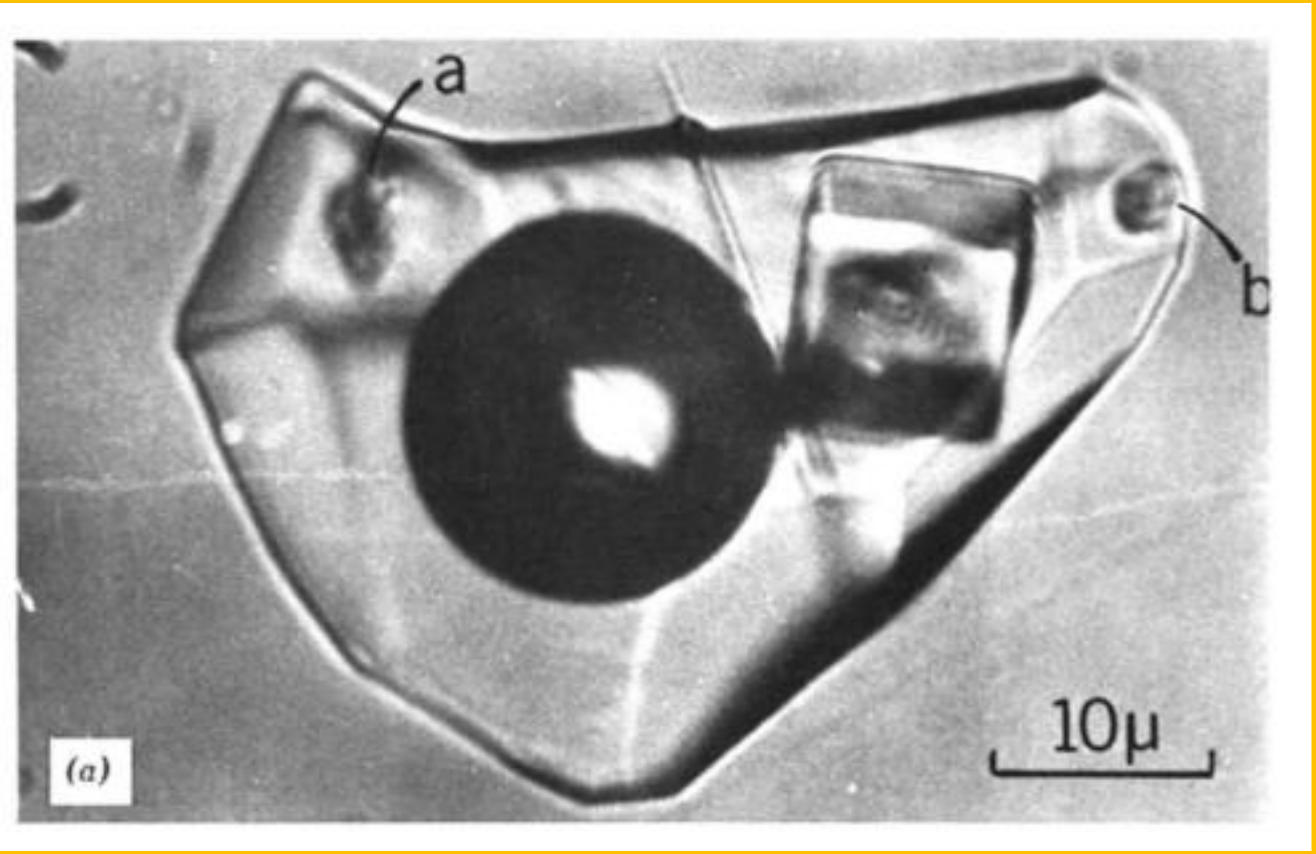
- Primary inclusions, those trapped during growth of the host mineral may be samples of the ore-forming fluid and may reveal important information regarding the conditions of ore transport and deposition .
- It reveal accurate information on entrapment conditions
- Some petrologists found that there has been alternation of ore and gangue mineral deposition in many ores without simultaneous deposition.
- If this has occurred, fluid inclusions in gangue minerals may not represent the fluids from which the ore minerals formed.

- Secondary inclusions must be used with care because they represent fluids passing through the rocks after the crystallization of the minerals in which these inclusions are found.
- Accordingly, they may contain fluids from a later stage of ore formation . a post ore fluid related to the ore forming episode. A metamorphic f1uid or even a late deuteric alteration or weathering fluid .
- If their position in the paragnesis can be established, they may still provide valuable information or the ore-forming process

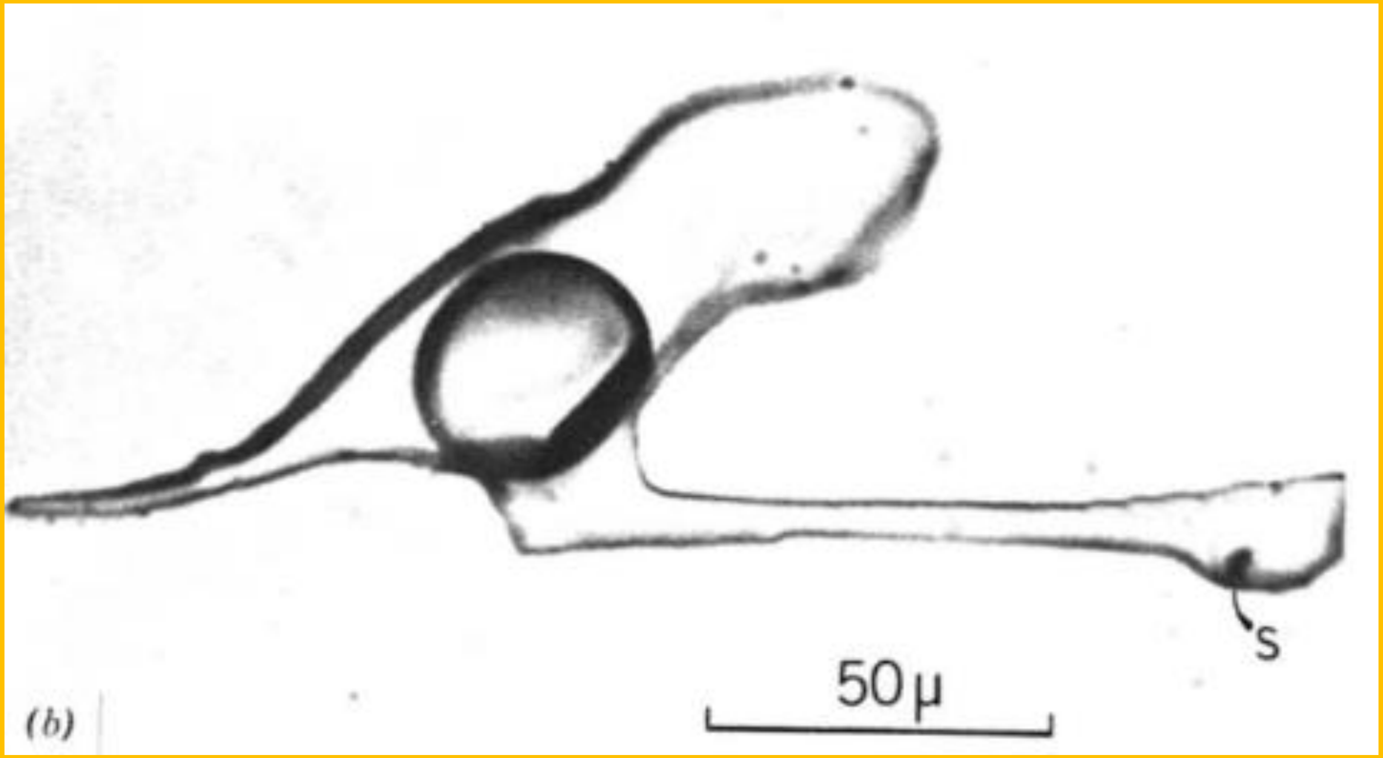
- Commonly, the fluids trapped along growing crystal faces are homogeneous: however, sometimes two or more immiscible liquid s (i.c.water and oil or water and CO_2), liquids and gases (i.e.. boiling water and steam). or liquids plus solids (i .e.water plus salts or other minerals) may be trapped together .
- Such inclusions (termed multiphase inclusions) are difficult to interpret geothermometrically but may provide considerable data on the nature of the ore-forming fluid .
- Typical host minerals in which fluid inclusions are observed include sphalerite, cassiterite, quartz, calcite, dolomite and f1uorite.



Fluid inclusions in cassiterite. *(a) Inclusions* lying along a healed cleavage plane. The gas phase fills the inclusions at 424-434"C



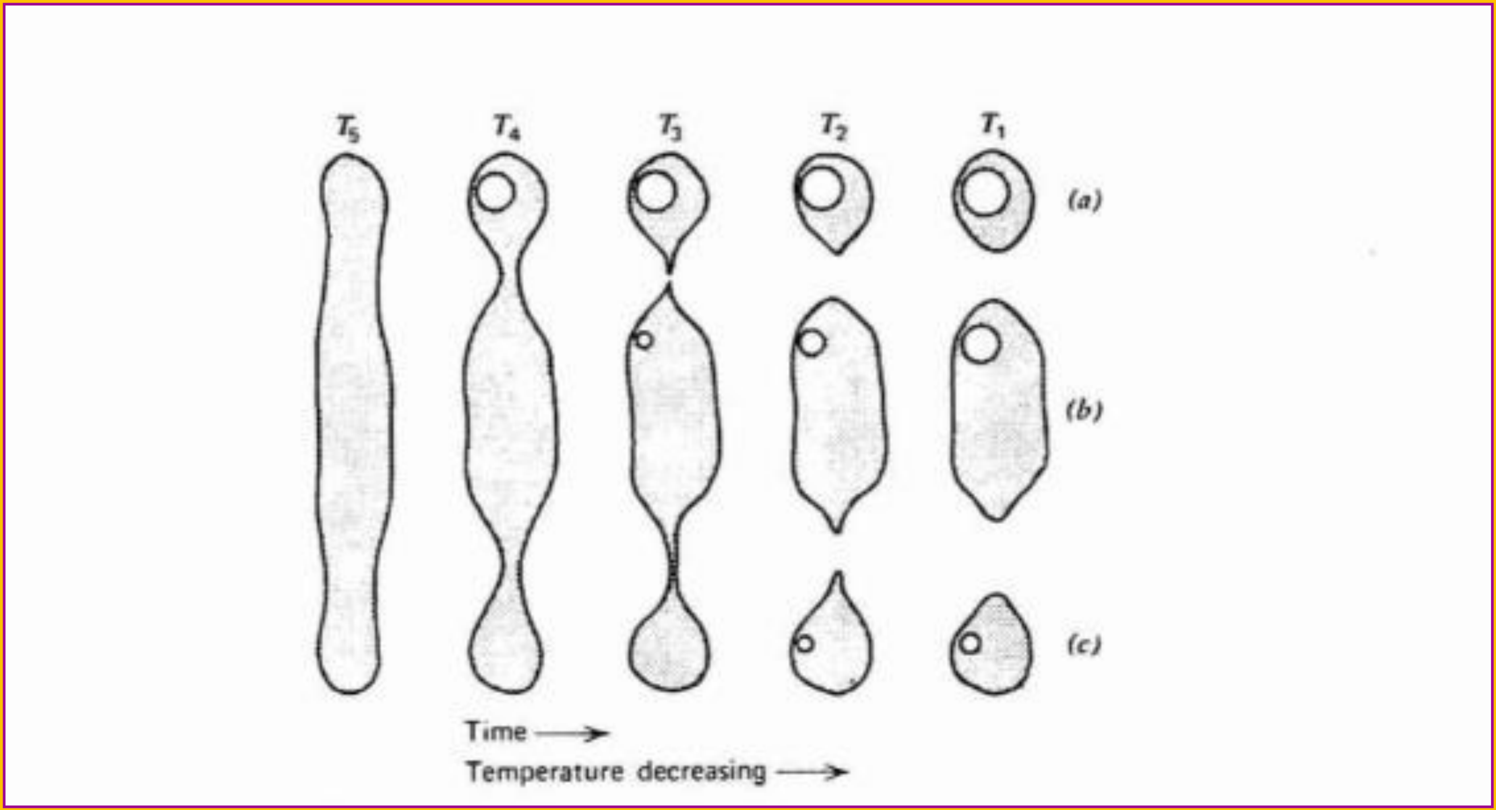
Inclusion in quartz with a large halite cube and unidentified daughter salts at *a and b.*



(b) Inclusion in apatite having an irregular form suggestive of necking down. A grain of an opaque inclusion at **s** lies in front of a small halite cube. The inclusion fills with liquid at 350°C:

Changes in Fluid Inclusions Since Trapping

- Most fluid inclusions were trapped as a homogeneous fluid at elevated temperatures and pressures.
- During the subsequent cooling, the fluid may have separated into liquid and vapor, because the fluid contracts much more than the solid host mineral. Immiscible fluids may separate on cooling, and daughter crystals, usually halite or sylvite, may precipitate as saturation of the fluid occurs.
- Many inclusions do not now have the shape they originally possessed because of solution and deposition in different parts of he inclusion cavity.



Necking down of a long tubular inclusion. The original inclusion, trapped at temperature T5 , breaks up during slow cooling to form three separate inclusions, a, b, and c.

Upon reheating in the laboratory, inclusion a would homogenize above the true trapping temperature T5 and inclusion b would homogenize between T4 and T5, inclusion c would homogenize above 2

The Compositions of Fluid Inclusions

- Fluid inclusions are extremely important in the study of ore deposits, because they often represent unaltered, or at least minimally altered samples of the ore-farming fluid.
- Most workers do not have facilities to determine the actual chemical composition of the inclusions that they observe, but they can determine the salinity of the trapped solution by measuring the freezing temperature.

Fluid Inclusion Geothermometry

- Fluid inclusion geothermometry, now recognized as one of the most accurate and widely applicable techniques for determining the temperatures at which a crystal formed or recrystallized, consists of determining the temperature at which a heterogeneous fluid inclusion homogenizes.
- In practice, a sample is heated while being viewed on a microscope stage until the liquid and a coexisting bubble that occupy the inclusion at room temperature homogenize and fill the inclusion as a single fluid.
- Filling is usually accomplished by disappearance of the bubble. but it may also occur by conversion of the liquid phase to vapor.

Applications of Fluid Inclusion Studies

- Fluid inclusion geothermometry has been extensively employed in determining the temperatures of ore mineral formation.
- However, Roedder (1977. 1979.1984) has pointed out that there are several other uses for fluid inclusion studies, including mineral exploration and even the determination of geologic age relations

- In such cases, the temperature differences observed may be employed either to locate "blind" ore bodies or to extend known ones.
- Variations within a mineralized zone may also serve to define directions of ore fluid movement,
- To aid in the interpretation of paragenesis, and as records of the changing nature of the ore fluid as a function of time,
- Since ore-forming brines are often more concentrated than fluids not associated with ores, trends in salinity obtained from freezing-point measurements may supplement temperature data in the exploration or extension of ore deposits.

Migmatite and the origin of Granites

- For migmatised argillaceous rocks, the partial or fractional melting would first produce a volatile and incompatible-element enriched rich partial melt of granitic composition. Such granites derived from sedimentary rock protoliths would be termed **S-type granite**.
- These are typically potassic rich, sometimes containing leucite, and would be termed adamellite, granite and syenite. Volcanic equivalents would be rhyolite and rhyodacite.
- Migmatised igneous or lower-crustal rocks which melt to form a similar granitic **I-type granite** melt, but with distinct geochemical signatures and typically plagioclase dominant mineralogy forming monzonite, tonalite and granodiorite compositions. Volcanic equivalents would be dacite, trachyte and trachydacite.
- It is difficult to melt mafic metamorphic rocks except in the lower mantle, so it is rare to see migmatitic textures in such rocks.

Dating of Rocks

- Essentially all igneous rocks have radioactive isotopes (R) in some of their minerals. These change to non-radioactive isotopes (N) at a known rate. Thus, by measuring the amount of R and N in an igneous mineral grain – and taking a few other factors into consideration – it is possible to determine how many years have passed since the mineral formed. That – the time passed - is the age of the igneous rock.
- The magma itself may have come into existence much earlier in Earth's history, but not the rock. With these radiometric techniques we determine the time at which the magma froze.

- Metamorphic rocks form when igneous or sedimentary rocks are buried deep in the earth, compressed, and held for long periods of time at high temperatures. When this happens, new minerals may form, and older, pre-existing minerals grow and change shape, or shrink and even disappear completely.
- The "age" of a metamorphic rock often is defined by the time at which these changes – called "metamorphism" – took place.
- Metamorphism generally takes a very long time – sometimes millions of years. Under some circumstances the "age" discussed is not the age of metamorphism but rather the age of the "protolith" – the igneous or sedimentary material from which the metamorphic rock was made.
- Dating of metamorphic rocks also is usually accomplished using radioactive materials. The processes of determining the age of metamorphic rocks often can be fraught with formidable difficulties. .

The Age equation

The mathematical expression that relates radioactive decay to geologic time is

$$\boldsymbol{D = D_0 + N(\mathrm{t})\,(e^{\lambda t} - 1)}$$

where

t is age of the sample,

D is number of atoms of the daughter isotope in the sample,

D_0 is number of atoms of the daughter isotope in the original composition,

N is number of atoms of the parent isotope in the sample at time t (the present), given by $N(\mathrm{t}) = N_o e^{-\lambda t}$, and

λ is the decay constant of the parent isotope, equal to the inverse of the radioactive half-life of the parent isotope times the natural logarithm of 2.

The **strontium** (**Sr**) has four stable, naturally occurring isotopes: ^{84}Sr (0.56%), ^{86}Sr (9.86%), ^{87}Sr (7.0%) and ^{88}Sr (82.58%). It has a standard atomic mass of 87.62(1) u.

Only ^{87}Sr is radiogenic; it is produced by decay from the radioactive alkali metal ^{87}Rb, which has a half-life of 4.88×10^{10} years. Thus, there are two sources of ^{87}Sr in any material: that formed during primordial nucleo-synthesis along with ^{84}Sr, ^{86}Sr and ^{88}Sr, as well as that formed by radioactive decay of ^{87}Rb. The ratio $^{87}Sr/^{86}Sr$ is the parameter typically reported in geologic investigations;

Textures of Metamorphic Rocks

Metamorphic Textures

Texture: Is a term that describes the size, shape and orientation of the grains constituting a rock, as well as the relationship between these grains.

Elements of metamorphic textures:

1- Crystal size:

- <0.1 mm v. fine-grained
- 0.1-1mm fine-grained
- 1-5 mm medium-grained
- 5-10mm coarse-grained
- > 10 mm v. coarse-grained

2-Shape:

- Idioblastic: If the mineral grain is euhedral
- Subidioblastic: If the grain is subhedral
- Xenoblastic: If the grain is anhedral

3- **Macroscopic to mesoscopic textures (general textures):**

(i) Slaty

(ii) Schistose: A schist has a lepidoblastic foliation if this foliation is defined by oriented micas, and a nematoblastic foliation if such a foliation is defined by the orientation of prismatic minerals as amphiboles and pyroxenes.

(iii) Gneissic: A complex banded texture made of schistose layers or bands alternating with bands commonly characterized by a granoblastic texture.

(iv) Granoblastic: granular, interlocking equidimensional grains of subequal size; no preferred orientation or cleavage.

(v) Hornfelsic: Fine-grained, granular interlocking grains, possibly of variable shapes and sizes. No preferred orientation.

Types of metamorphic textures and mineral-mineral relations

Metamorphic textures can be grouped into three main groups:

A- **Relict textures** (palimpsest textures): are textures inherited from the original rock type, and which have survived metamorphism.

B- **Typomorphic textures**: textures characteristic of metamorphism

C- **Superimposed textures**: textures characteristic of a post-metamorphic event, e.g. alteration, weathering, ... etc.

Metamorphic Rocks

- What is Foliation:

General term that describes a planar fabric; typically defined by platy minerals such as mica or flattened grains such as quartz.

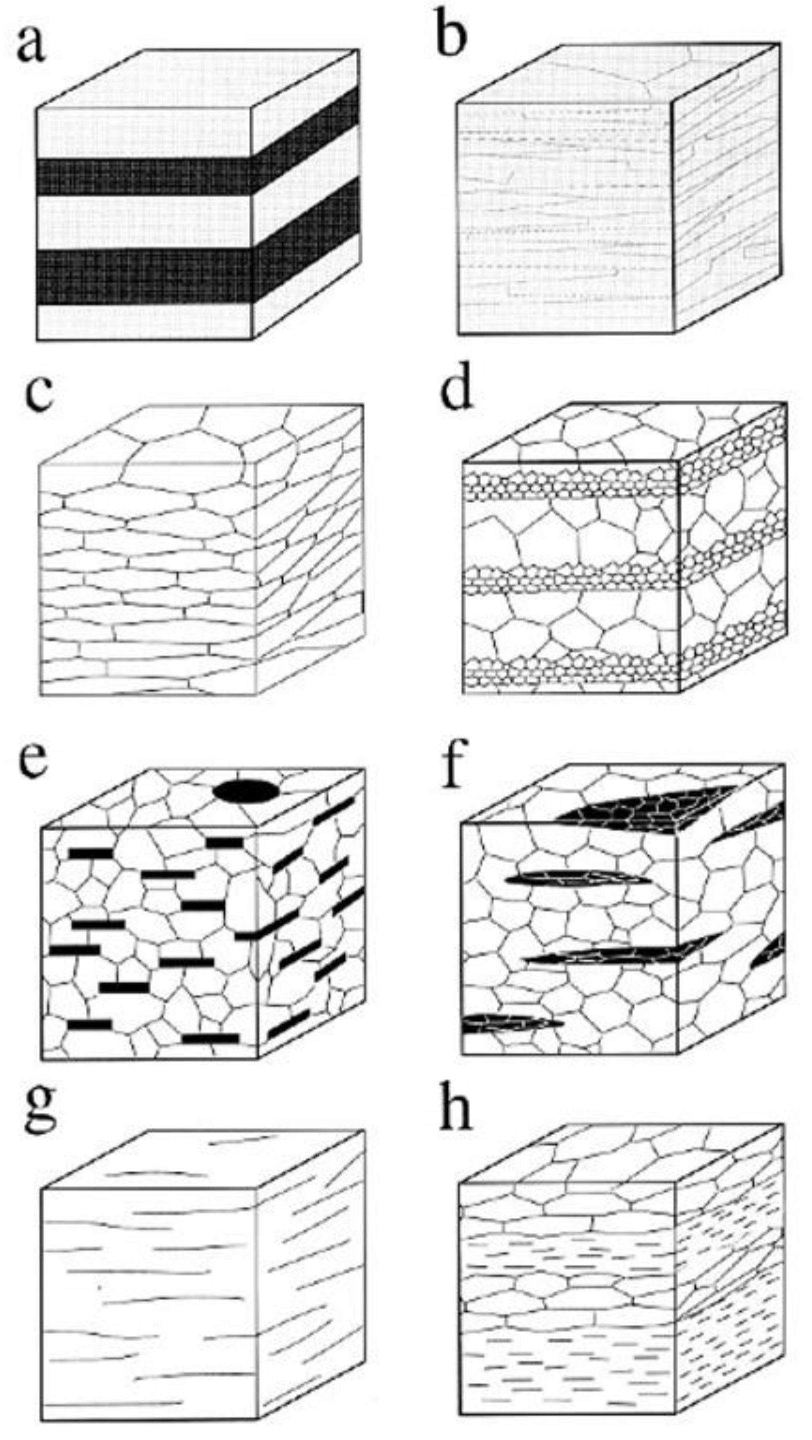


Fig. 4.1a–h. Diagrammatic presentation of various fabric elements that may define a foliation (after Fig. 5.1 in Hobbs et al. 1976). **a** Compositional layering. **b** Preferred orientation of platy minerals (e.g. mica). **c** Preferred orientation of grain boundaries and shape of deformed grains (e.g. quartz, carbonate). **d** Grain-size variation. **e** Preferred orientation of platy minerals in a matrix without preferred orientation (e.g. mica in micaceous quartzite or gneiss). **f** Preferred orientation of lenticular mineral aggregates. **g** Preferred orientation of fractures or microfaults (e.g. in low-grade quartzites). **h** Combination of fabric elements **a, b** and **c;** such combinations are common in metamorphic rocks

Passchier & Trouw, 1996

Foliated Metamorphic Rocks

STRUCTURES OF METAMORPHIC ROCKS

- The term Structure in a broad sense to include both **small scale** and **large scale features** seen in metamorphic rocks.

- Structures of metamorphic rocks developed in a solid medium by growth of crystals which recrystallize simultaneously.

Structures of Metamorphic rocks

1. Cataclastic structure
2. Schistose structure
3. Gneissose structure
4. Maculose structure
5. Granulose structure

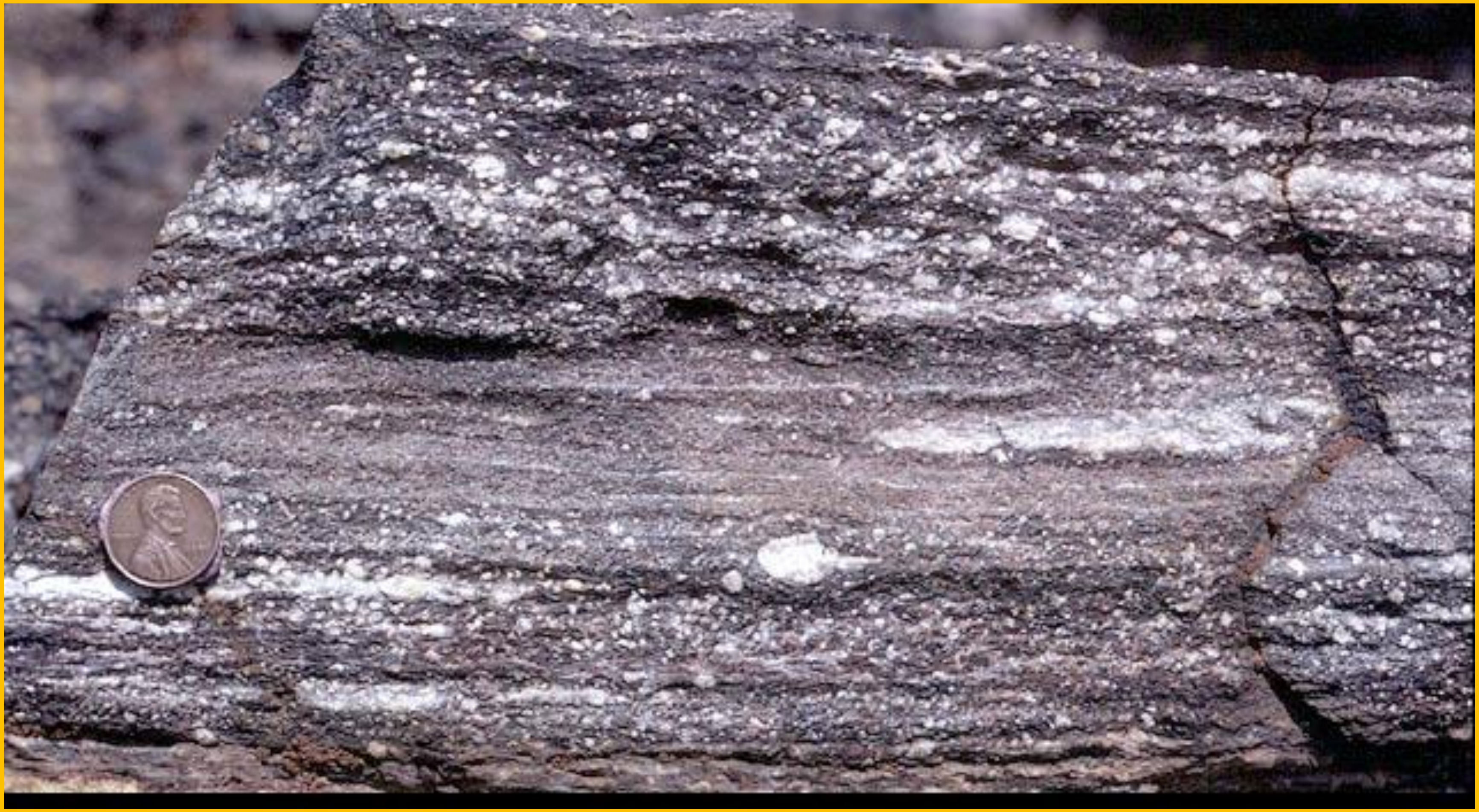
1. Cataclastic Structure :

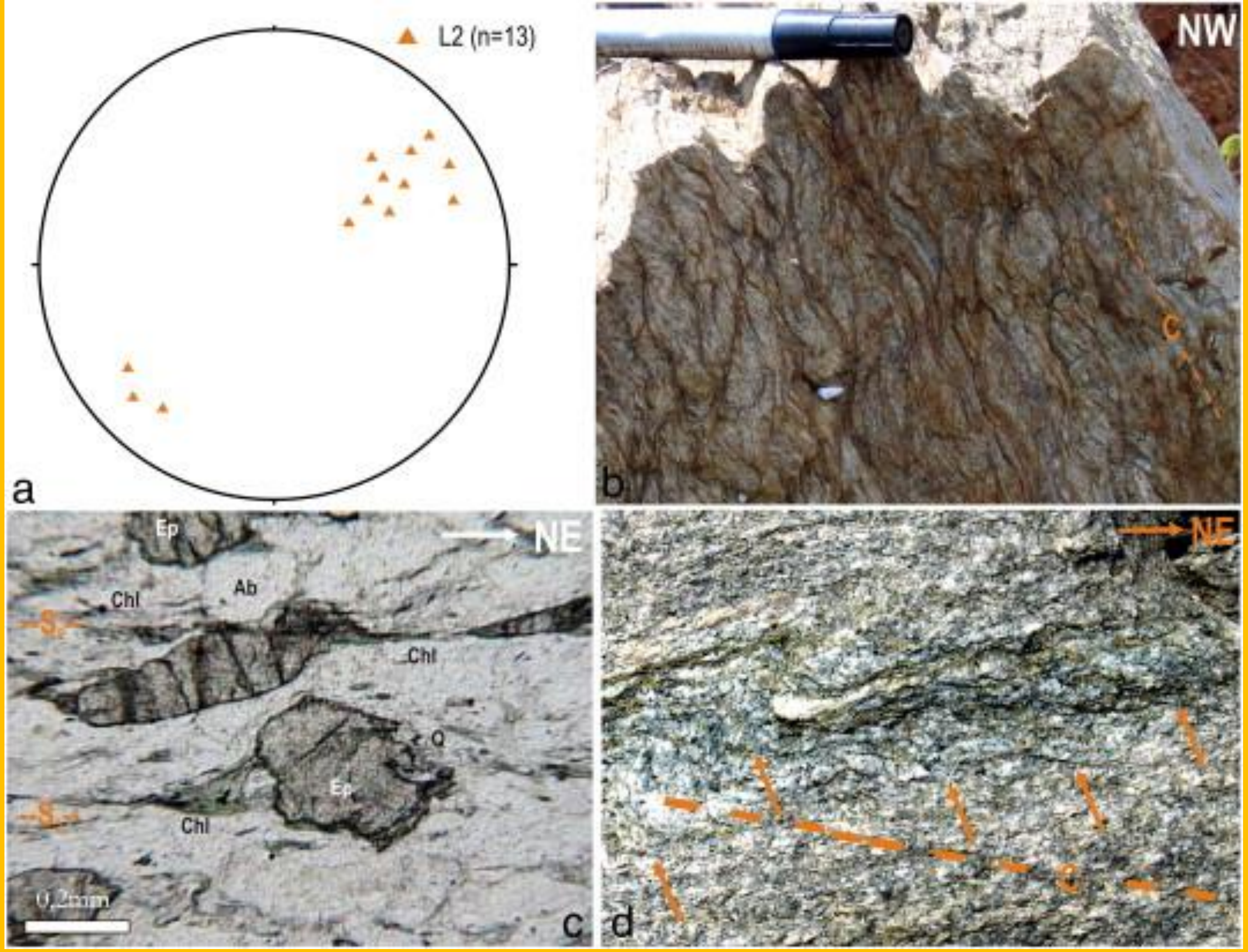
- Cataclastic structures are those of broken and fragmented rocks developed by mechanical deformation of hard brittle rocks due to cataclastic metamorphism.

- There is almost no new mineral formation.

- Initial stages of deformation simple crushing of rocks takes place producing structuraless aggregates, continued intense movement under stress results in the rolling of grains and finally the rock becomes a more or less streaky, pulverized rock.

Mylonitic and cataclastic rock in the southeastern San Bernardino Mountains





Mylonitic to cataclastic structures.

a) Stereographic projection of NE–SW L2 stretching lineation.

b) Composite C–S fabric developed in the quartz mica schists of Vari Unit, indicating top to NE sense of shear.

c) Microphotograph from a quartzofeldspathic sample, showing an epidote porphyroclast (Ep) with recrystallized tails of quartz (Q) and chlorite (chl). Sense of shear is top to NE.

d) Discrete C-surfaces in the quartzofeldspathic rocks (eastern part of Vari Unit).

2. Hornfelsic Structure :

- Hornfelsic structures also known as Maculose structure. It is one in which porphyroblasts of strong minerals like Andalusite, Cordierite, Chloritoid Biotite etc are well developed.

- An incipient banding or folia form at this stage and transitions to Granulose, Schistose and Gneissose structures.

- Hornfelsic structure is typically developed in Argillaceous rocks under Contact or Thermal Metamorphism.

3. Granular Structure :

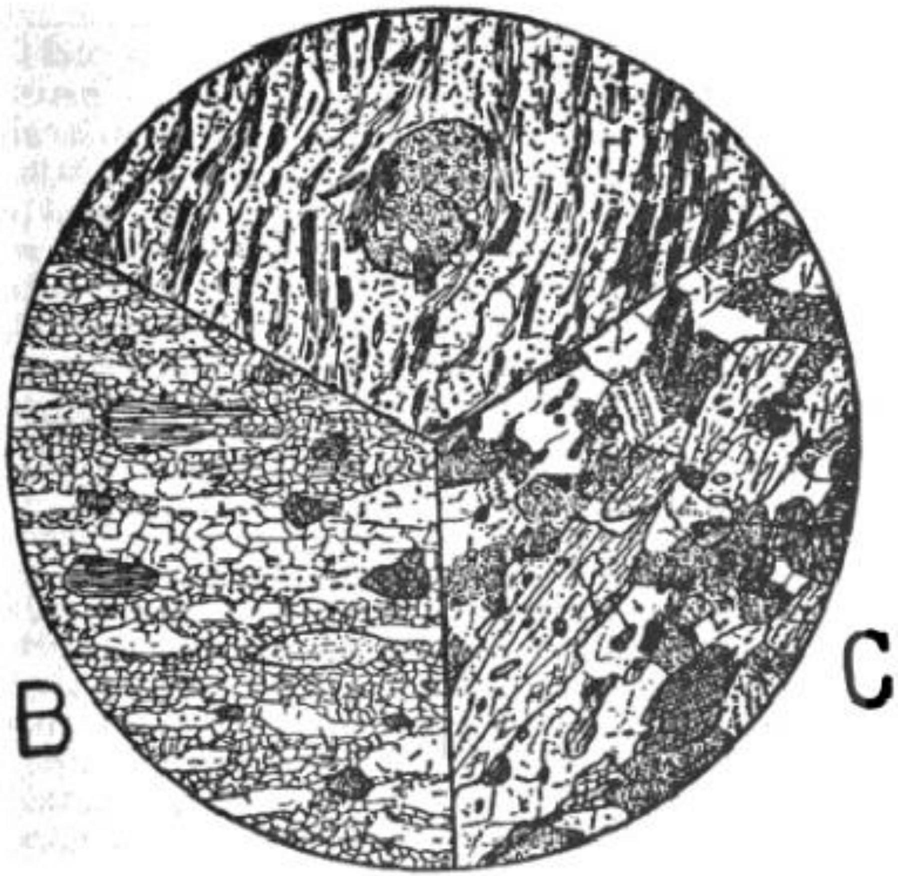
- This structures is developed largely in rocks with Granoblstic and equidimentional minerals like Quartz, Feldspar, Pyroxene, Granet, Calcite, Dolomite etc.
- Flaky or platy and linear minerals are either absent or present only in small quantities.
- Some times parallel, banded or streaky structures may be present due to alternation of patches differing in mineral composition or granularity.
- Granulose structures are common in products of Thermal and Plutonic metamorphism.

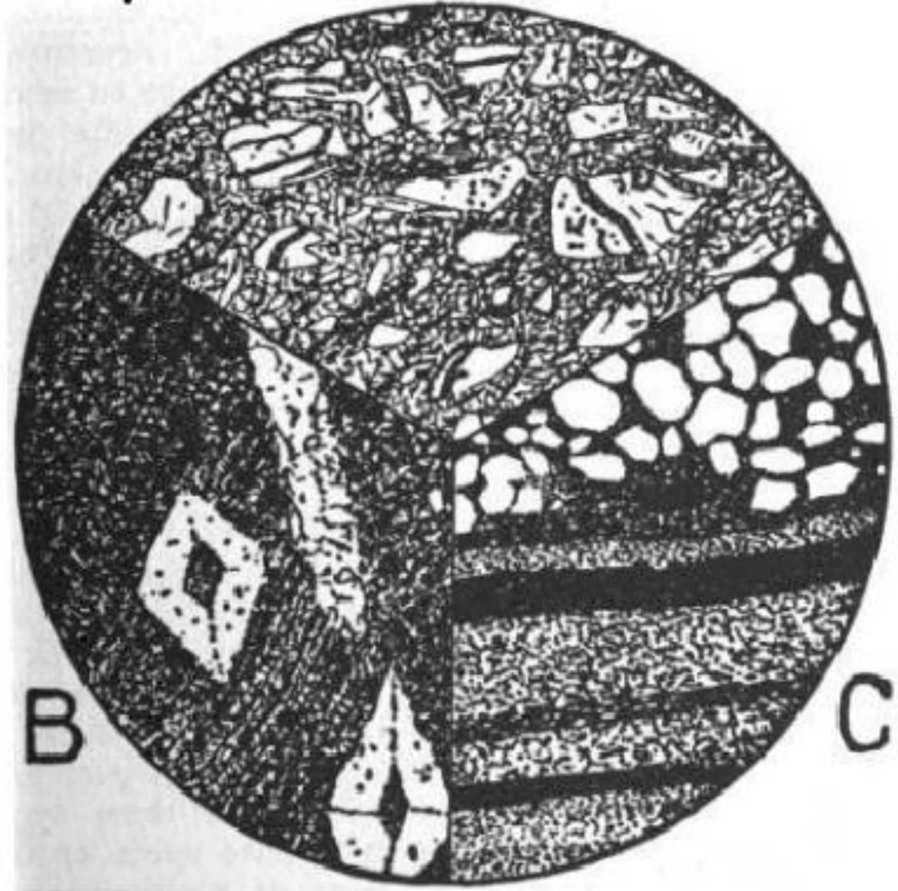
4. **Foliated Structure :**

- Foliated structures are by far the most common and important among metamorphic structures.
- The term Foliation or Schistosity is applied to cleavage or facility due to parallelism of platy or linear minerals in metamorphic rocks.
- Foliation may be subdivided according to the degree of perfection of the parallel surface as **Staty Cleavage** *(most perfect*) Schistosity and Gneissic structures *(least perfect)*.
- Foliation results from the parallel or subparallel arrangement of tabular, flaky and linear minerals.

Gneiss, a foliated metamorphic rock

A Structures of Metamorphic rocks A





A. Schistose structure

B. Granulose structure

C. Gneissose structure

A. Cataclastic structure

B. Maculose structure

C. Palimpsest structure

Large scale structural features

- Rock cleavage
  - Flow cleavage
  - Fracture cleavage
- Schistosity
- Foliation

Classification of Metamorphic rocks

- Foliated rocks – rocks that show parallelism in their mineralogical and structural constitution e.g. slates, phyllites
- Non-foliated rocks – characterized by the absence of foliation

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:

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

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, and gas) made of one chemical species only, is considered as one phase, thus, oxygen, benzene, and ice are all one phase.

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, liquid water and water vapour and the composition of all these phases is expressed in terms of one chemical individual water. H_2O, **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.**

DEGREES OF FREEDOM(F)

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.**

TRIVARIANT SYSTEM

A mixture of two or more gases is completely defined only when P, T and Composition are specified. If P and T be specified the third variable i.e. composition may be varied. Since it is necessary to specify three variables to define the system completely, it has three degrees. Thus it is **TRIVARIANT.**

NONVARIANT SYSTEM

For ice, water, water vapour system, F=0, In this system, the three phases coexist at the freezing point of water. Since the freezing temperature of water has a definite value, the vapour pressure of water has also a fixed value. Since both the variables are already fixed, the system is defined automatically and there being no need to specify any variable. Hence this system has no degree of freedom.

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.

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.

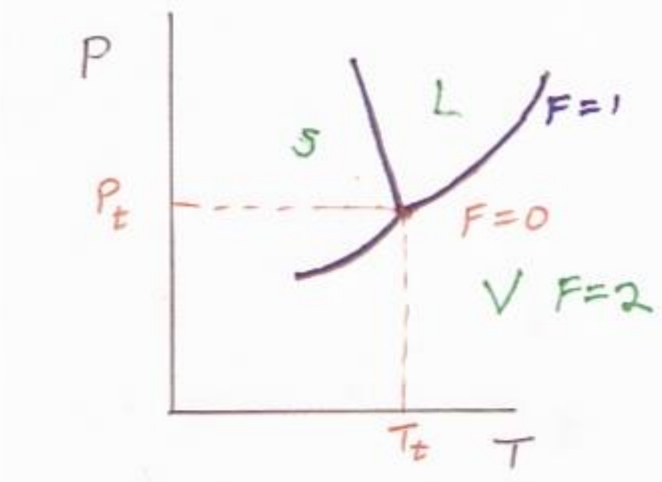
Phase Rule in One-Component Systems

➢ 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

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

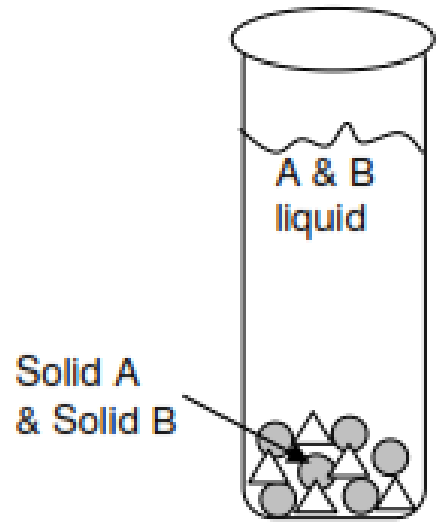
Solid-liquid 2-phase region:

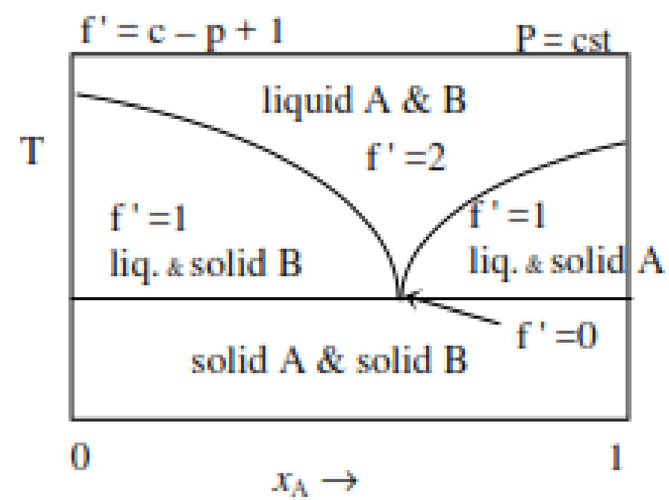
$f' = 2 - 2 + 1 \quad$ **= 1**

Eutectic:

$f' = 2 - 3 + 1 \quad$ **= 0**

invariant at cst P





The Water System

How many components do you have?

We have only one component which is H_2O.

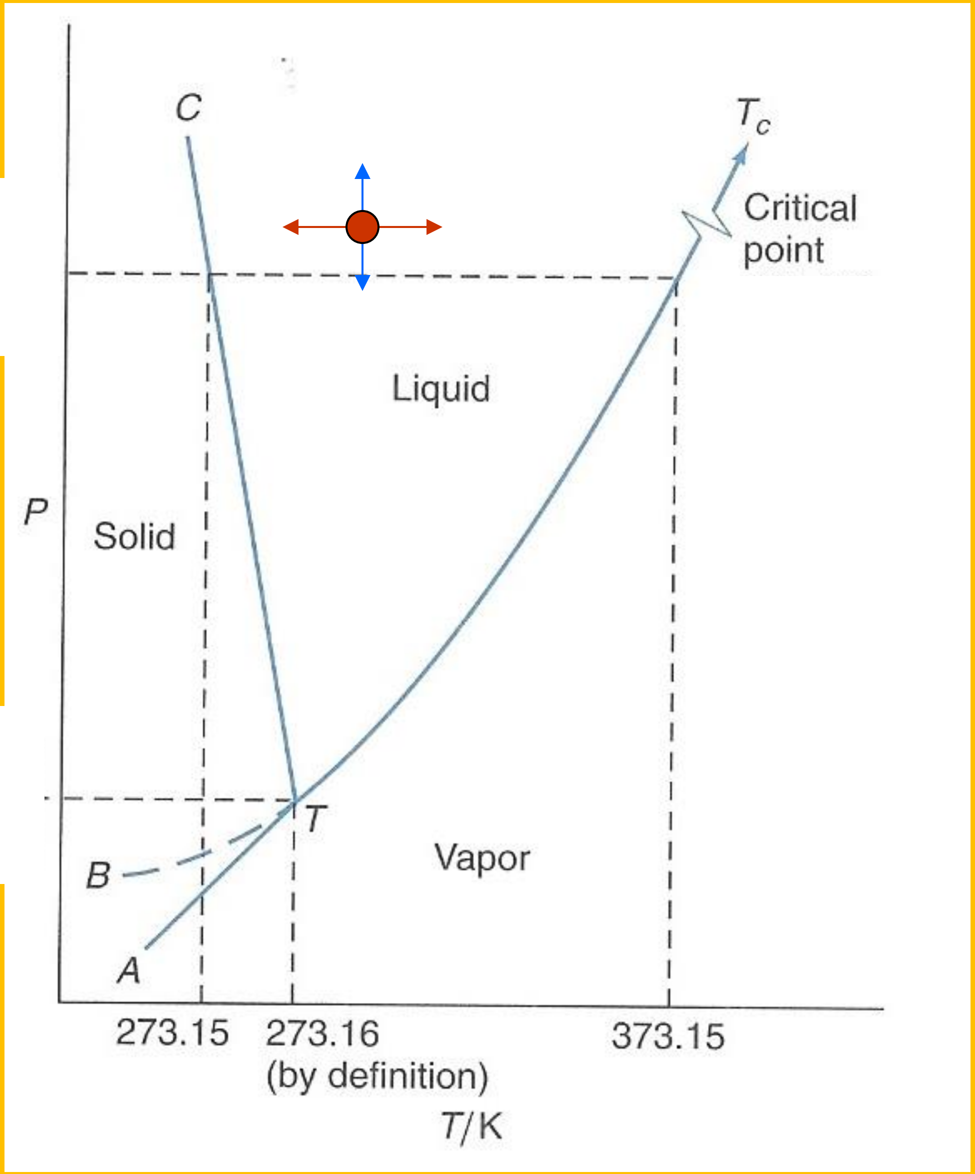
In the one-phase regions, one can vary either the temperature, or the pressure, or both (within limits) without crossing a phase line.

We say that in these regions:

$f = c - p + 2$

$= 1 - 1 + 2$

$= 2$ degrees of freedom.



Phase Diagram of Water

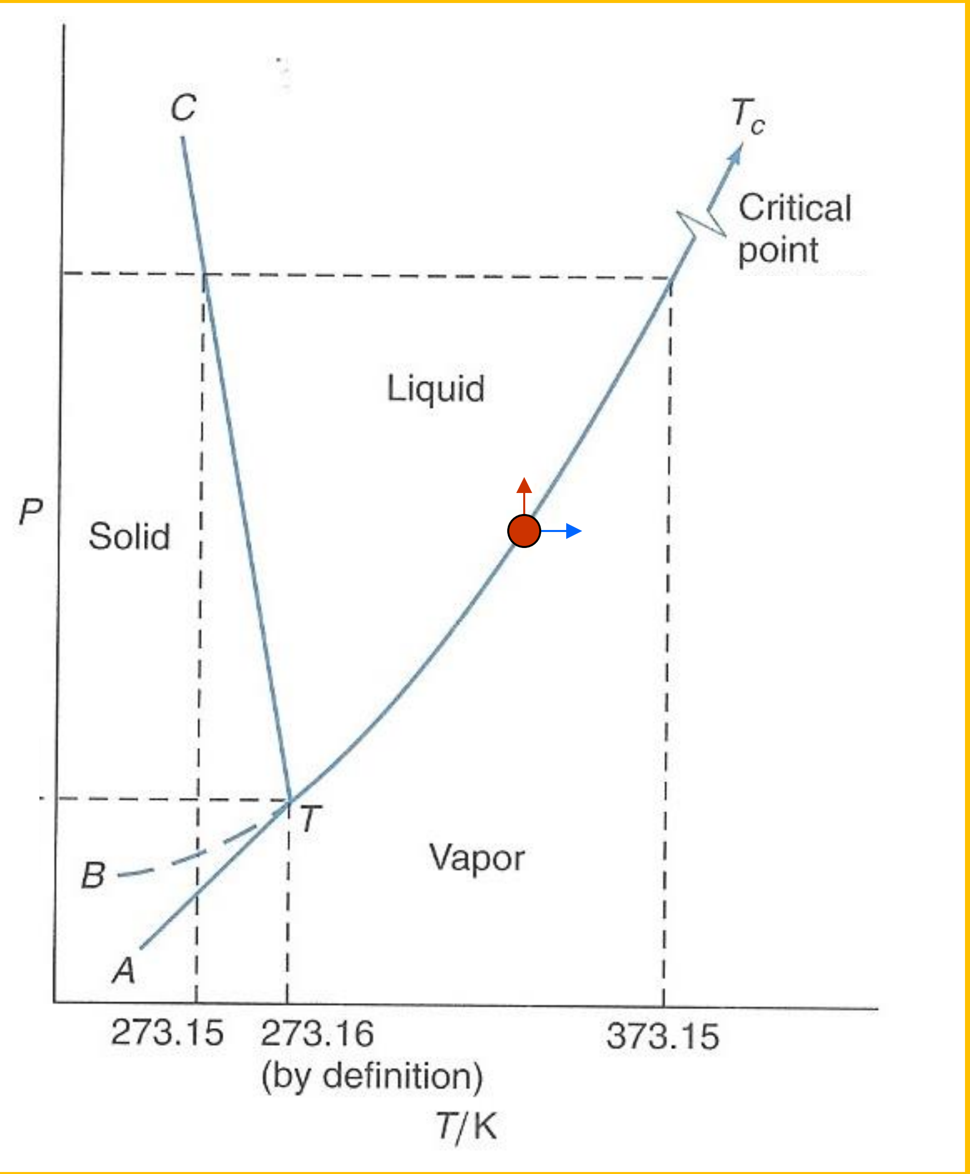
Along a phase line we have two phases in equilibrium with each other, so on a phase line the number of phases is 2.
If we want to stay on a phase line, we can't change the temperature and pressure independently.

We say that along a phase line:

$f = c - p + 2$

$= 1 - 2 + 2$

$= 1$ degree of freedom.



Contd…..

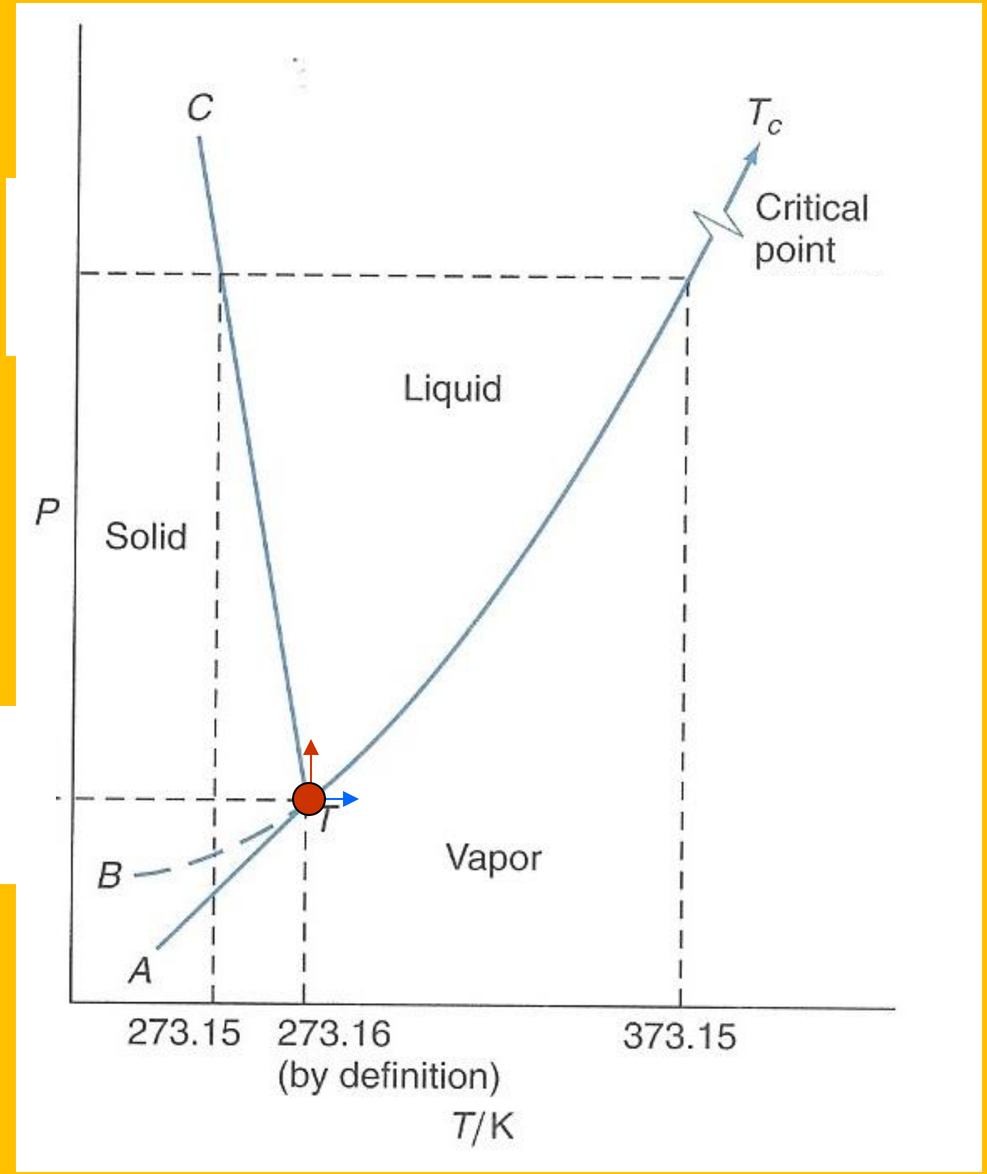
At the triple point there are three phases in equilibrium, but there is only one point on the diagram where we can have three phases in equilibrium with each other.

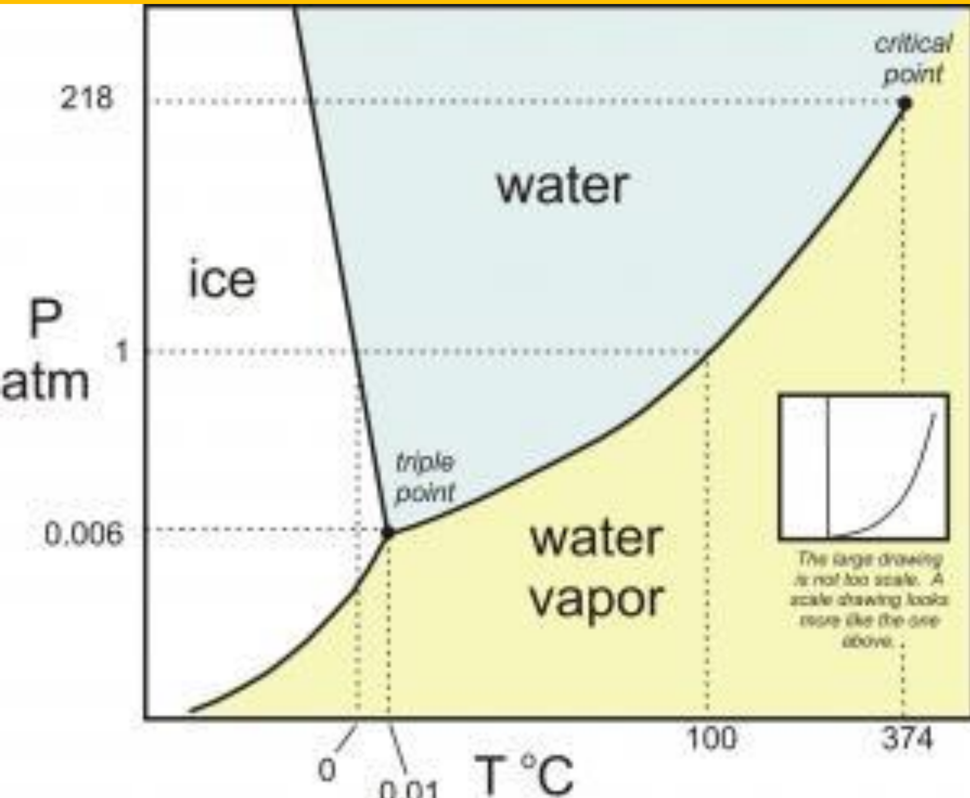
We say that at the triple point:

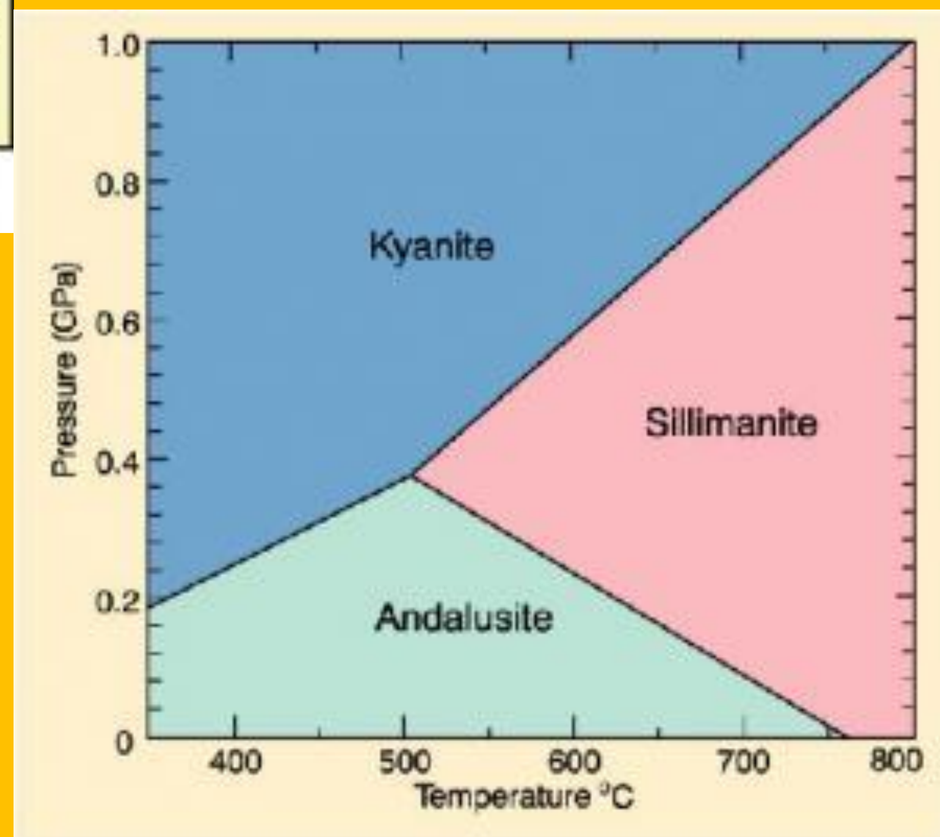
$f = c - p + 2$

$= 1 - 3 + 2$

$= 0$ 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


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

Petrogenesis of Amphibolite

Amphibolite?

Amphibolite is a coarse-grained metamorphic rock that is composed mainly of green, brown or black amphibole minerals and plagioclase feldspar. The amphiboles are usually members of the hornblende group. It can also contain minor amounts of other metamorphic minerals such as: biotite, epidote, garnet, wollastonite, andalusite, staurolite, kyanite and silimanite. Quartz, magnetite and calcite can also be present in small amounts.

How Does Amphibolite Form?

Amphibolite is a rock of convergent plate boundaries where heat and pressure cause regional metamorphism. It can be produced through the metamorphism of mafic igneous rocks such as basalt and gabbro or from the metamorphism of clay-rich sedimentary rocks such as marl or graywacke. The metamorphism sometimes flattens and elongates the mineral grains to produce a schistose texture.

Charnockite is a granofels that contains orthopyroxene, quartz, and feldspar.

Charnockite is frequently described as an orthopyroxene granite. Granites are felsic rocks that usually contain no or very little pyroxene. There is actually an entire array of rocks (mostly granitoids but also syenite, monzonite, etc.) that may contain orthopyroxene plus quartz. These rocks are collectively referred to as charnockitic rocks or charnockitic suite. All of these rock names refer to igneous rocks which makes it very logical to assume that charnockite is just an igneous rock with a somewhat unusual composition.

Such an interpretation (which seems to be prevalent) is very likely not true (at least not entirely). Igneous rocks are formed from magma but charnockites are found in high-grade metamorphic terranes (granulite facies). The transformation from the protolith to charnockite had probably no magma phase which means that in most cases we are dealing with true metamorphic rocks which have nothing to do with igneous processes. Charnockitic rocks are sometimes described as granulites but this term seems to be somewhat out of favor nowadays. Partly because it may be confused with metamorphic facies with the same name and I also guess that partly because too many different rock types have been called that way which have created great deal of confusion in the past.

Well, can we conclude that charnockite isn't a granite then? Perhaps we should but we probably can not do it because the term "granite" isn't reserved exclusively for igneous rocks. Some rocks that have been described as granites are almost certainly metamorphic rocks although they lack obvious foliation. Hence, we have to tolerate the situation that not all granites are igneous rocks and therefore we have no basis to demand that charnockite shouldn't be named granite anymore. However, if we want to use metamorphic terminology, then we should call it granofels. Charnockite is coarse-grained, and it lacks foliation. This is the definition of granofelsic metamorphic rocks.

I have one more thing to say which disturbs me when it is said that charnockites have granitic composition. Yes, they have according to the QAPF classification but only because we do not use pyroxenes in this classification scheme.

Charnockite from Ubatuba, Brazil (known by its trade name Ubatuba Green). The width of the view is 10 cm.

Charnockitic rocks are commonly green. Both feldspars and orthopyroxene tend to have a greenish or brown hue and quartz crystals may contain rutile needles which gives them bluish tinge. Charnockites are formed at high pressures in almost water-free conditions. That’s why we see only small amount of hydrous phases here (biotite, amphiboles) which are widespread in the rocks of amphibolite facies.
The name charnockite has an interesting origin. It was given to the rock type because it was first described as a tombstone of Job Charnock (1630–1692) in St John’s Churchyard in Calcutta (Kolkata). Job Charnock is known as the founder of the same city. Even today charnockite remains to be popular a tombstone material.

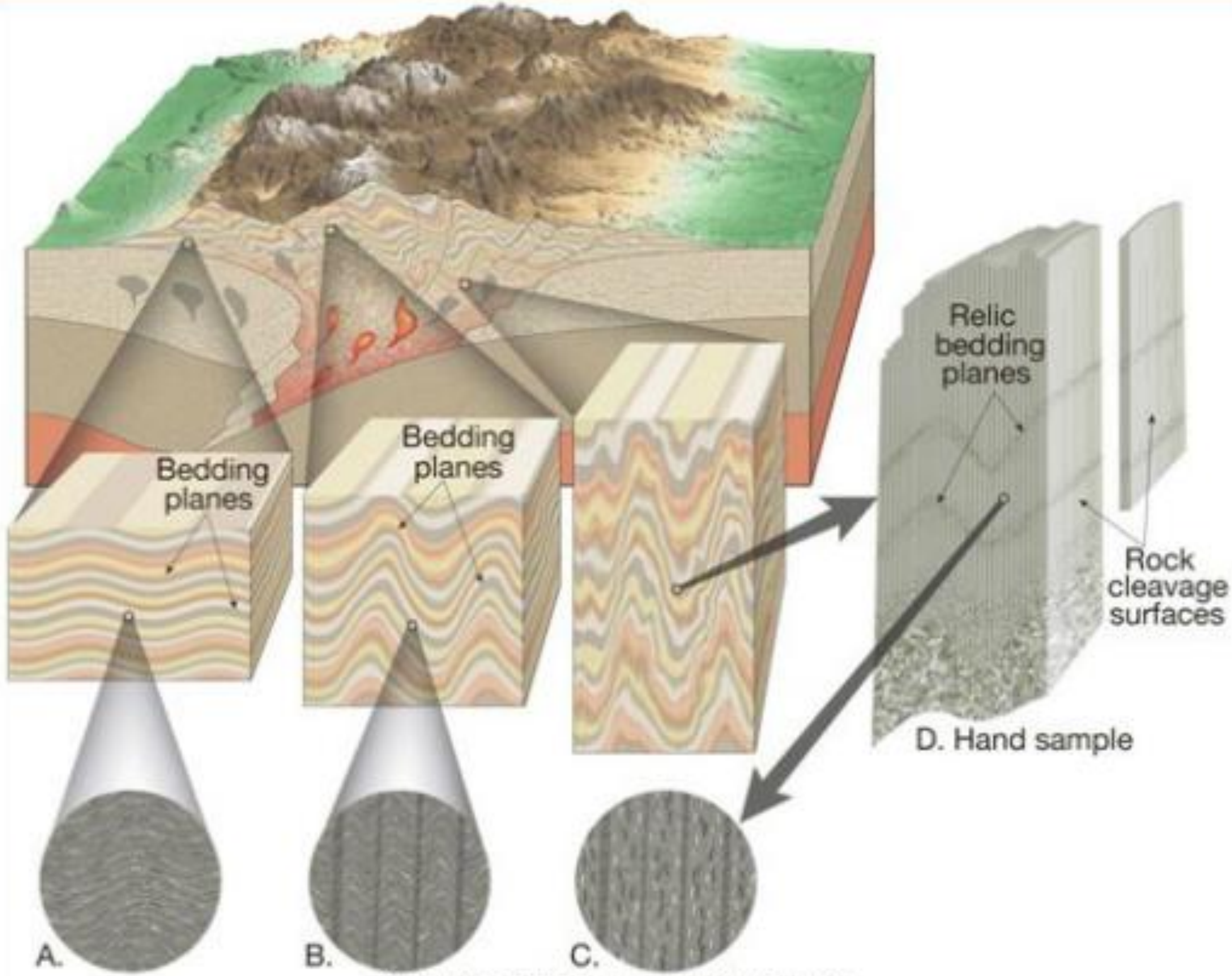
Nomenclature of metamorphic rocks:

- The nomenclature of metamorphic rocks is much easier than that of igneous or sedimentary rocks. Although you still need to know the texture and mineralogy of rock, you really do not need to learn any "new" names! In general, there are four different ways of giving a metamorphic rock a name:
- 1- **[minerals; listed *in reverse order of abundance*]** followed by the [general texture]. e.g.: "sillimanite - garnet - biotite - quartz schist" (where quartz > biotite > garnet > sillimanite)
- 2- **[minerals][ortho/para]-[general texture]** e.g. Biotite - feldspar - quartz paragneiss. (where the prefix "para" indicates that the protolith of the rock is sedimentary, whereas "ortho" indicates that the protolith is an igneous rock).
- 3- **Meta-[protolith],** e.g. metasandstone, metabasalt, metacarbonate, or metapelite.
- 4- S**pecial names**: e.g. marble, quartzite, granulite.... etc, which depend on the composition or the texture of the rock, as defined above (see Mason, 1978).
- In the literature, listing minerals in reverse order of abundance is not strictly followed, with some authors preferring to list the minerals in order of abundance!

Metamorphic textures

- Texture refers to the size, shape, and arrangement of mineral grains
- Foliation – any planar arrangement of mineral grains or structural features within a rock
  - Examples of foliation
    - Parallel alignment of platy and/or elongated minerals

UMR



- **Development of cleavage and foliated textures with increasing metamorphism. Note relict bedding planes.**

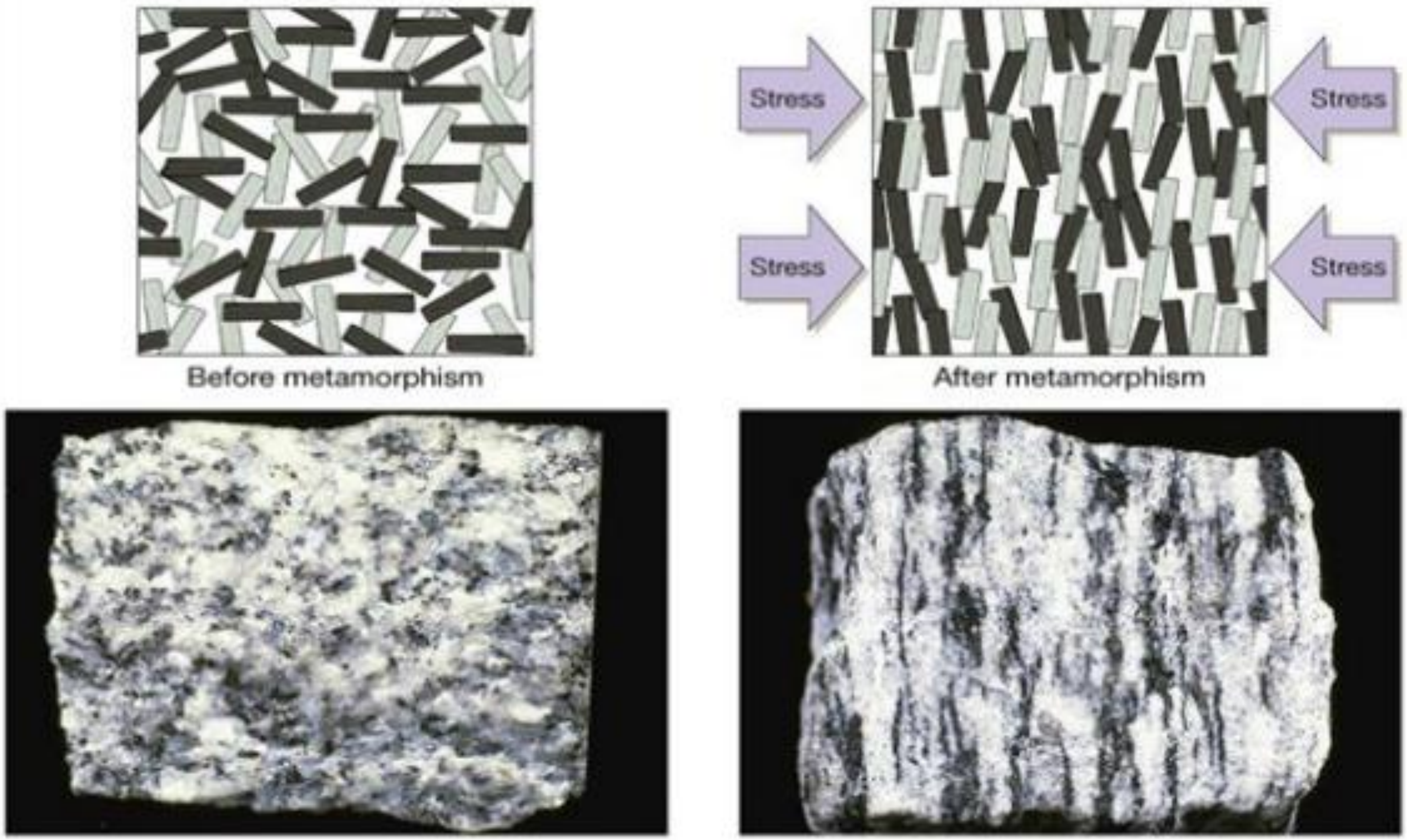
UMR

Metamorphic textures

- **Foliation**
  - **Foliation can form in various ways including**
    - **Rotation of platy and/or elongated minerals**
    - **Recrystallization of minerals in the direction of preferred orientation**
    - **Changing the shape of equidimensional grains into elongated shapes that are aligned**

UMR

Foliation resulting from directed stress



UMR

Metamorphic textures

- Foliated textures
  - Rock or slaty cleavage
    - Closely spaced planar surfaces along which rocks split
    - Can develop in a number of ways depending on metamorphic conditions and parent rock

UMR

- Slaty cleavage in quarry near Alta, Norway. Slate is used as dimension stone for roofing and billiard (pool) tables, among many other industrial and commercial applications.

UMR

Metamorphic textures

- Foliated textures
  - Schistosity
    - Platy minerals are discernible with the unaided eye and exhibit a planar or layered structure
    - Rocks having this texture are referred to as schist

UMR

Garnet-mica schist

- This sample of schist is comprised of muscovite and biotite.   Micaceous materials exhibit low shear strength between the tiny plates, often fomenting massive slope failures, such as landslides.

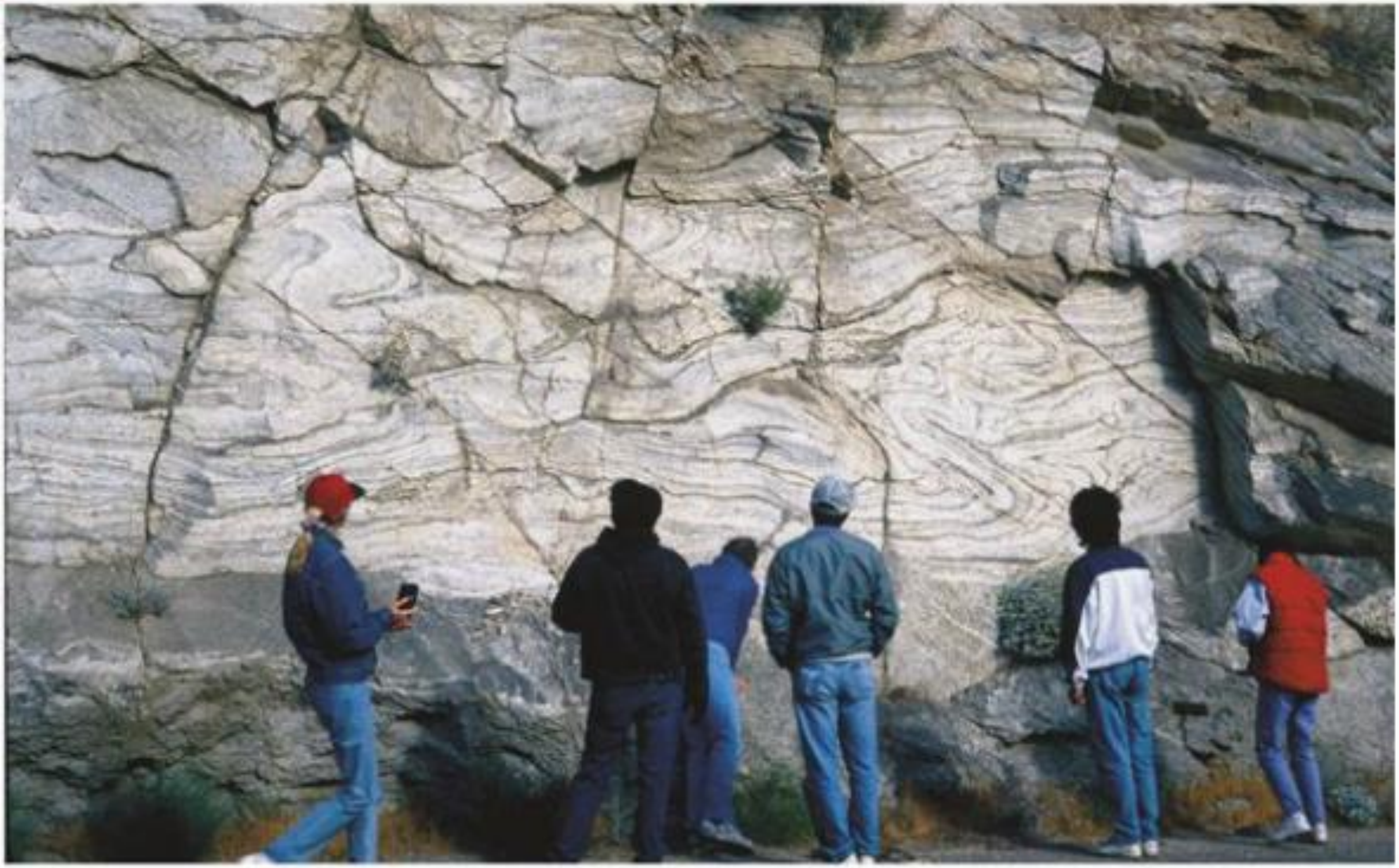
UMR

Metamorphic textures

- Foliated textures
  - Gneissic
    - During higher grades of metamorphism, ion migration results in the segregation of minerals
    - Gneissic rocks exhibit a distinctive banded appearance

UMR

- **Gneissic texture** created by banding of dark biotite flakes and lighter colored silicate minerals, giving the rock a banded, or layered appearance.



- **Deformed and folded gneiss in outcrop. Gneiss can be a very resistant rock, with highly undulatory structure.**

UMR

Metamorphic textures

- Other metamorphic textures
  - Those metamorphic rocks that lack foliation are referred to as nonfoliated
    - Develop in environments where deformation is minimal
    - Typically composed of minerals that exhibit equidimensional crystals
  - Porphyroblastic textures
    - Large grains, called porphyroblasts, surrounded by a fine-grained matrix of other minerals