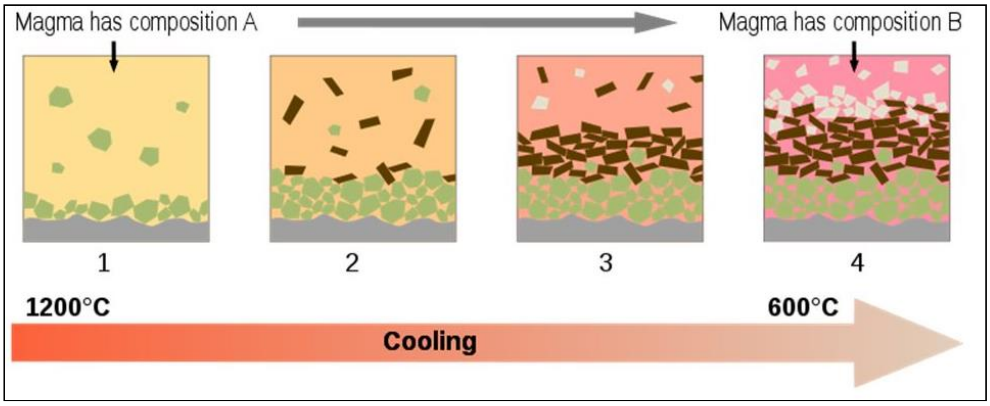
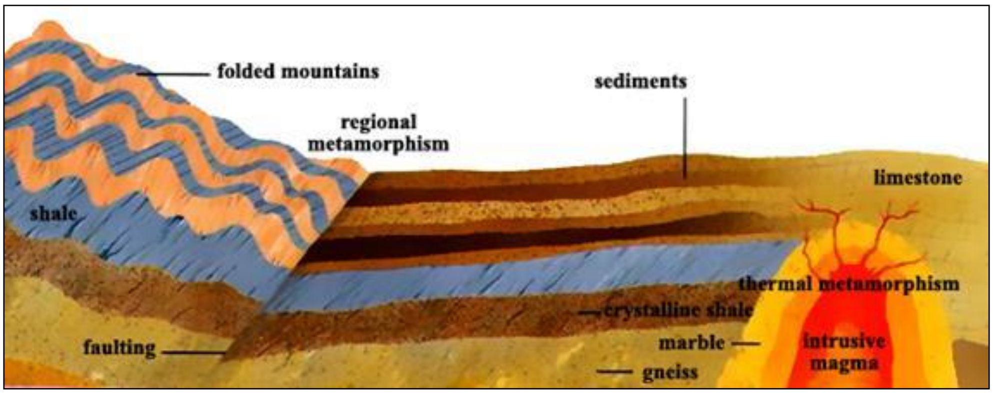
# GEOLOGY

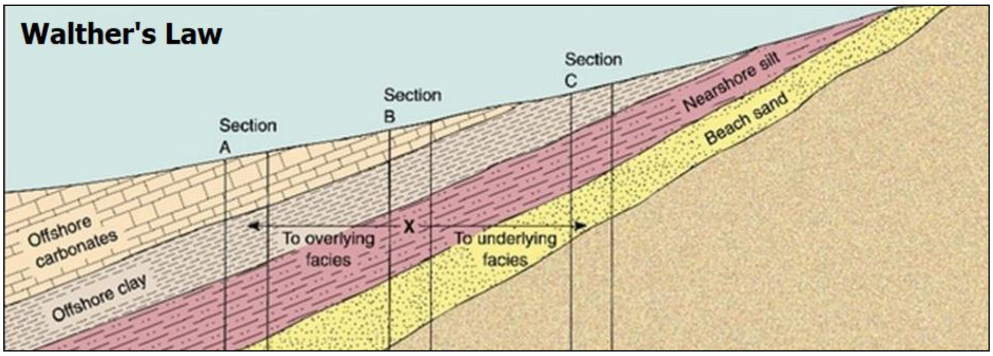
## A2 Level

## Interpreting the Geological Record

### Topic G1: Rock Forming Processes







A. Prickett

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# Key Idea 1: The generation and evolution of magma involves different processes

## Generation of Magma

The melting of solid rock to produce magma is controlled by three physical parameters; its **temperature**, **pressure** and **water content**.

### 1) Temperature:

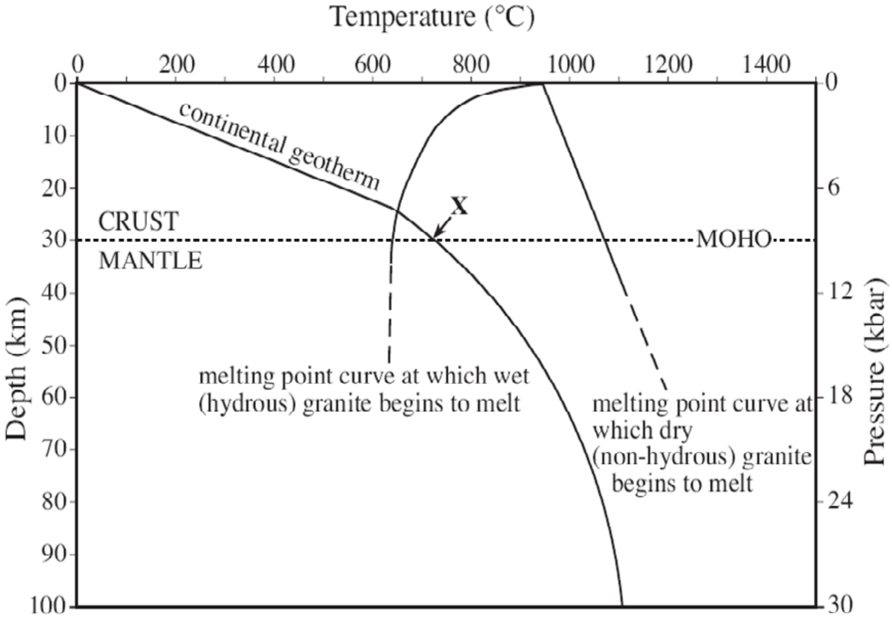
At any given pressure and for any given composition of rock, a rise in temperature past the solidus will cause melting. Within the solid earth, the temperature of a rock is controlled by the geothermal gradient and the radioactive decay within the rock.

### 2) Pressure:

Melting can also occur when a rock of a given temperature and composition rises through the solid earth. A sudden decrease in pressure can cause what is known as decompression melting. This may occur due to tectonic adjustments or from the rise of a volume of rock to a shallow depth in the Earth's crust.

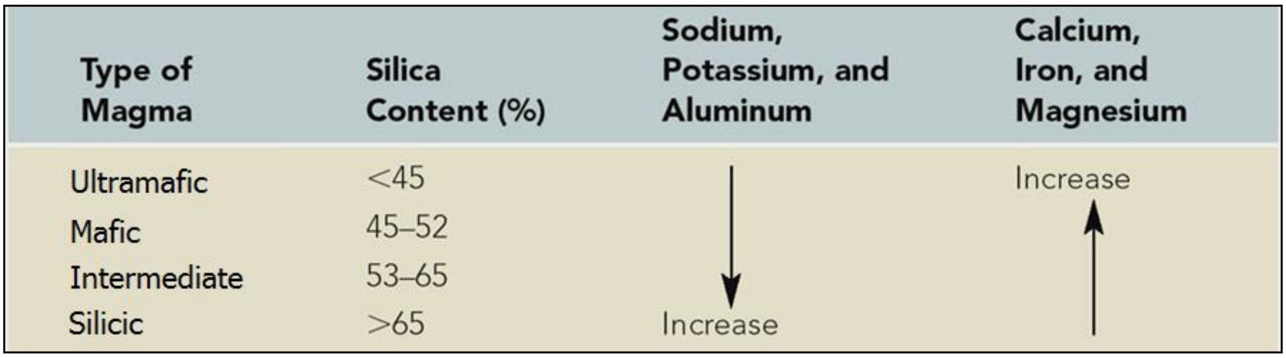
### 3) Water content:

It is usually very difficult to change the bulk composition of a large mass of rock, so composition is the basic control on whether a rock will melt at any given temperature and pressure. The composition of a rock may also be considered to include **volatile phases** such as water and carbon dioxide. The presence of volatile phases in a rock acts similar to a solvent, assisting in the break-down of the strong silicate bonds in the minerals of a rock. This is a very important process for generating melts, as the presence of even 1% water may reduce the temperature of melting by as much as 100°C. Conversely, the loss of water and volatiles from a magma may cause it to essentially 'freeze' or solidify.

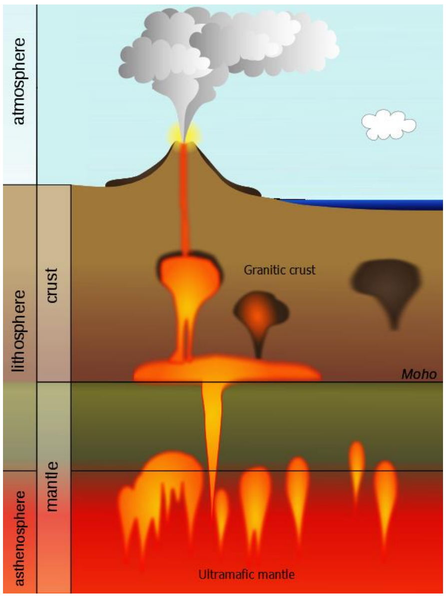


## Composition of Magma

As **Silicon** (silica) is the primary constituent of magma, geologists classify magma (a melt) based on its silica content. There are thus four main types of magma based on their silica content:



| Type of Magma | Silica Content (%) | Sodium, Potassium, and Aluminum | Calcium, Iron, and Magnesium |
|---|---|---|---|
| Ultramafic | <45 | ↓ | Increase |
| Mafic | 45–52 | ↓ | ↑ |
| Intermediate | 53–65 | ↓ | ↑ |
| Silicic | >65 | Increase | ↑ |

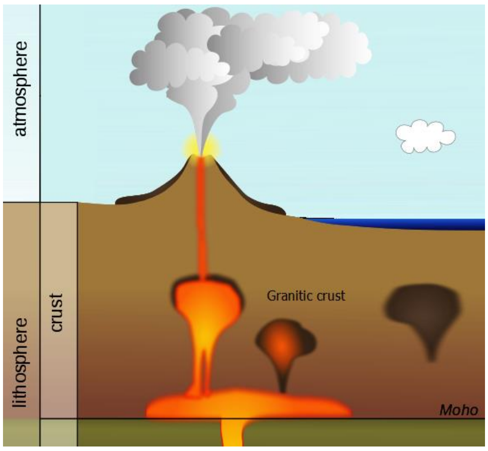


1) **Ultramafic** (Peridotite): Mantle composition (asthenosphere)
   - ➢ Less than 45% silica
   - ➢ High percentage of Fe, Ca and Mg
   - ➢ Melting points anywhere between 1300-1900°C
   - ➢ Contains high temperature minerals (Olivine, Augite, Plagioclase)

2) **Mafic** (Basaltic lava – Basalt, Dolerite, Gabbro)
   - ➢ Less than 52% silica
   - ➢ Silica poor, but contains much less Ca, Fe, and Mg than ultramafic
   - ➢ Melting points anywhere between 1000-1400°C
   - ➢ Contains high temperature minerals (Olivine, Augite, Plagioclase, Hornblende)

3) **Intermediate** (Andesitic lava - Andesite)
   - ➢ Between 53-65% silica
   - ➢ Melting points anywhere between 750-1000°C
   - ➢ Medium temperature minerals (Augite, Plagioclase, Hornblende, Biotite)

4) **Silicic** (Rhyolitic lava – Granite, Rhyolite)
   - ➢ Greater than 65% silica
   - ➢ Silica-rich with lots of Na, K, and Al and very little Ca, Fe, and Mg
   - ➢ Melting point between 600-750°C
   - ➢ Low temperature minerals (Biotite, Muscovite, Orthoclase, Quartz)

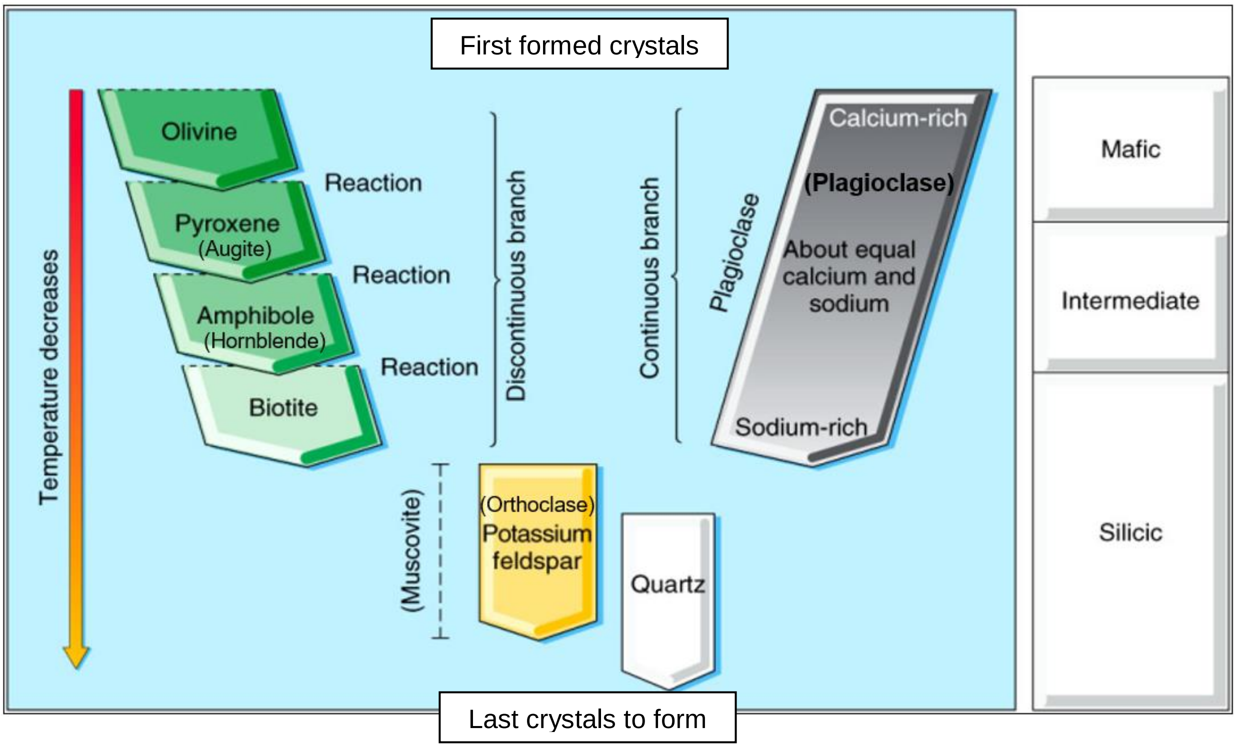


## The formation of magma at different tectonic settings

Magma is generated in the mantle at a number of different inter-plate and intra-plate tectonic settings. The composition of magma will change depending on the make-up of the rocks that it melts as it penetrates the Earth's crust to erupt in the form of lava. Fractional crystallization (differentiation), assimilation (contamination) and magma mixing are some of the processes by which a primary melt (magma) can change composition on its journey towards the surface.

### 1) Bowen's Reaction Series

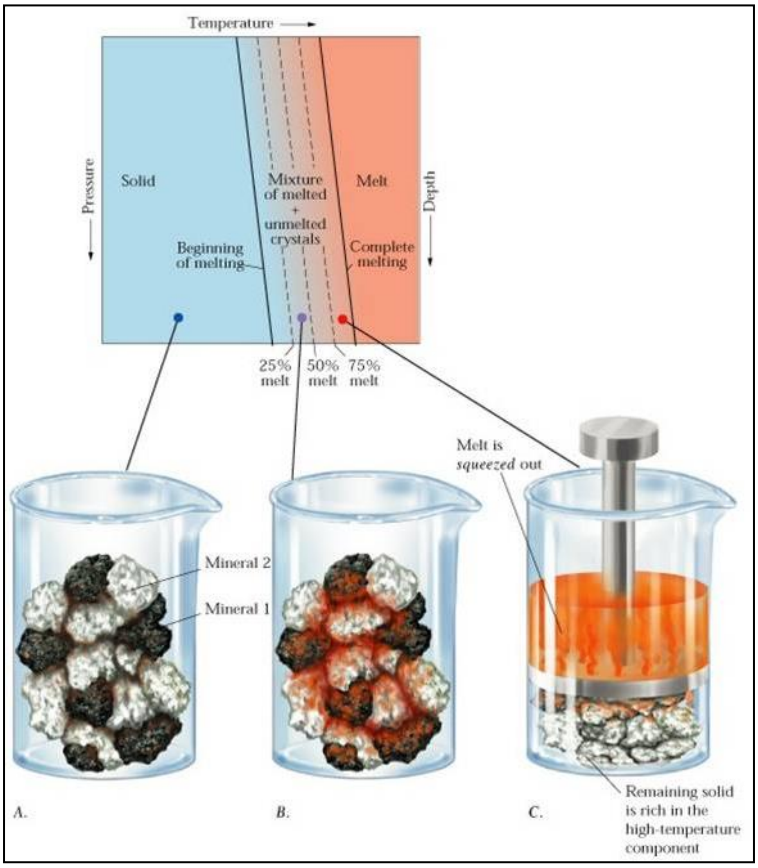
A mechanism, now called Bowen's Reaction Series, accounts for the origin of intermediate and silicic magma from their original ultramafic or mafic source material. Bowen's Reaction Series shows the sequence in which minerals crystallise from a cooling magma.

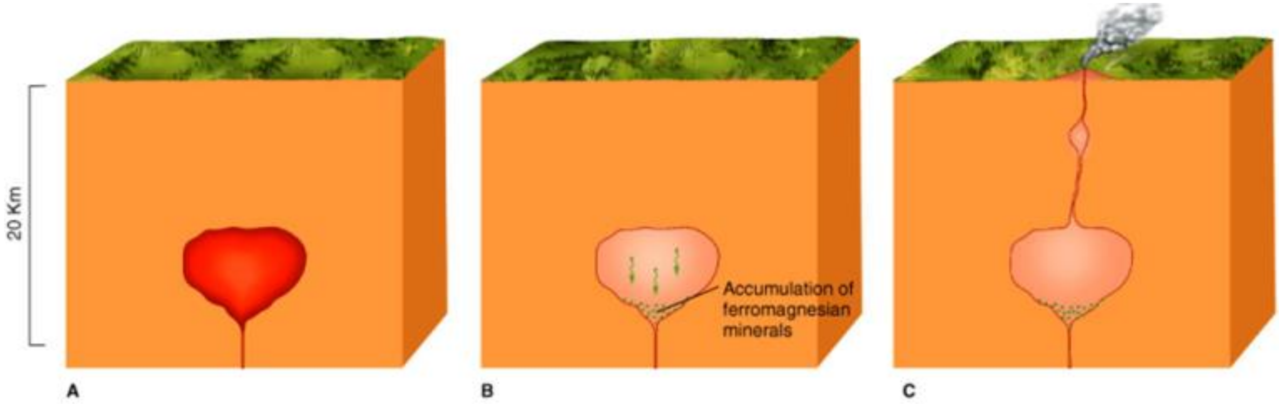


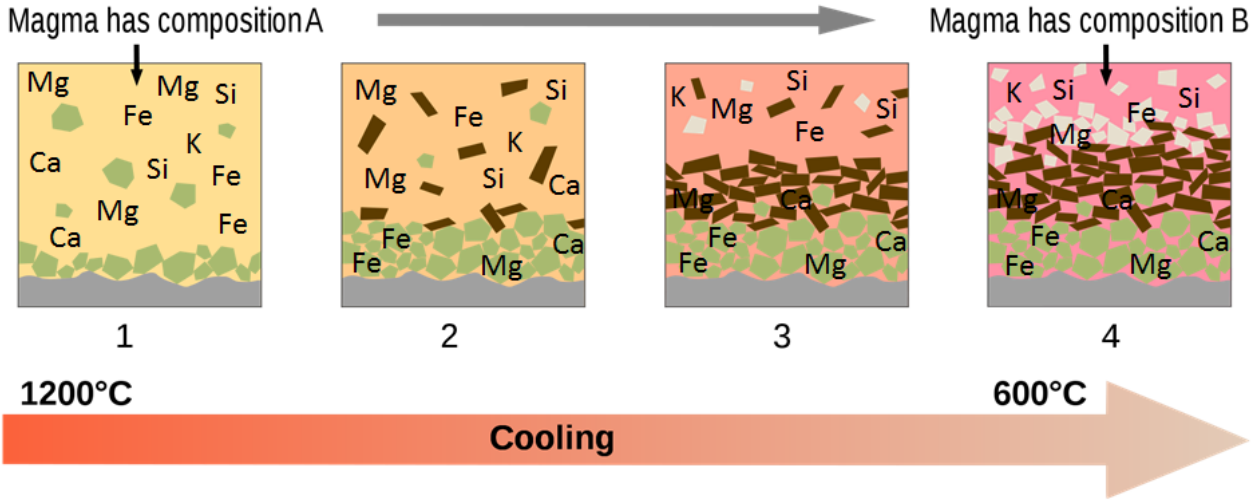
If a solid rock is heated, then the minerals in Bowen's Reaction Series will melt in reverse order from the bottom up as temperatures increase.

Bowen's Reaction Series also shows how **differentiation** and partial melting work to create and modify the composition of magma over time.

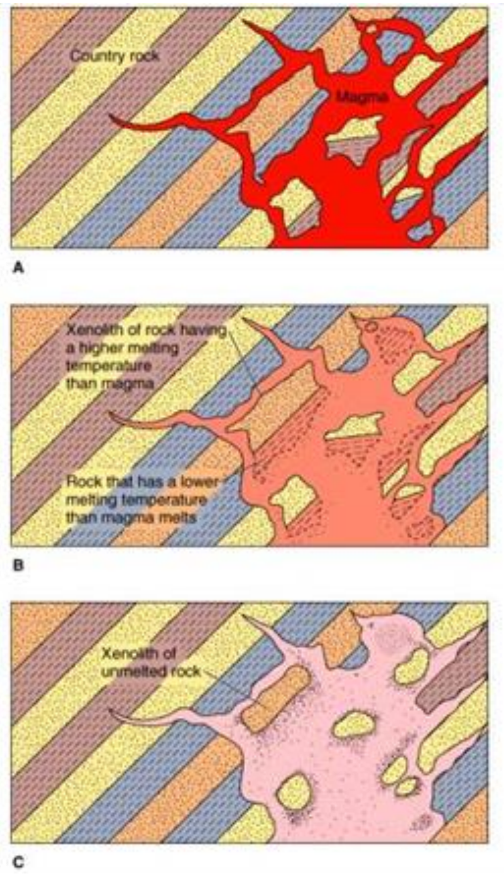
**2) Differentiation** (Fractional crystallisation) – this is the process by which ferromagnesian minerals separate from a magma leaving behind a more silica-rich magma. This process takes place in magma through crystal settling, which is the downward movement of solid, crystalline minerals that are denser than the remaining liquid magma (melt). These sink and settle (gravity settling) at the bottom of the magma chamber to form layers of dense, iron and magnesium rich minerals called cumulates. When a sufficient amount of mafic minerals are removed, the remaining magma, would now be intermediate in composition creating andesitic lava on the surface.







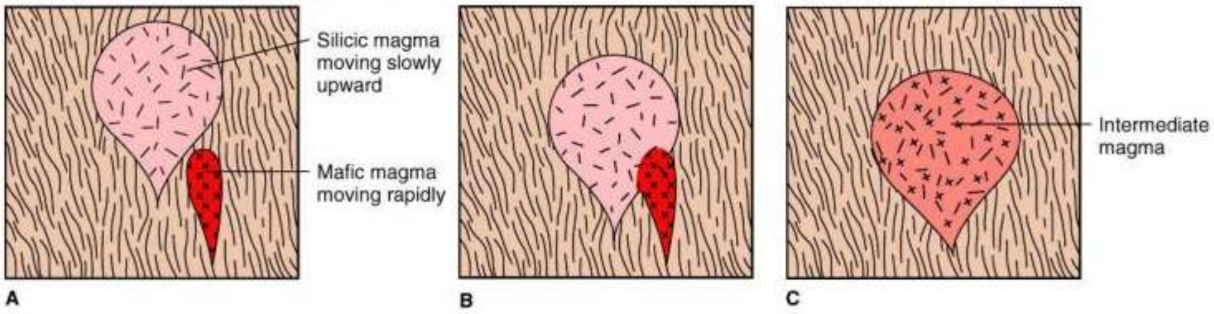
### 3) Magma contamination



This is a mechanism for explaining the increasing silica content of ultramafic and mafic magmas as they rise through the crust. This assimilation assumes that a hot primitive melt intruding into the cooler, silicic crust will melt the crust and mix with the resulting melt. This then alters the composition of the primitive magma. Very hot magma could melt some of the surrounding country rock and assimilate the newly molten material into the magma. Fragments of surrounding, country rock broken off and incorporated into the magma are known as **xenoliths**.

### 4) Magma mixing

This is where two magma types merge in the crust to produce a magma with a combined composition. Mixing equal amounts of mafic and silicic magma would result in an intermediate magma producing diorite if it solidified beneath the surface. However, if it erupted on the surface it would solidify as andesite (andesitic lava).



Incomplete magma mixing can lead to the formation of areas within a pluton with a different composition to the rest of the body. These areas are known as **enclaves**.

# Calculating the age of igneous rocks and samples

The age (time of final crystallisation) of an igneous rock can be calculated using radiometric dating. Igneous rocks contain trace amounts of various radioactive elements within certain minerals. The decay of these elements can be used to calculate the age of the mineral sample within the rock. For the age of a sample the decay rate equation is used. This defines the time (*t*) that a sample formed:

$$t = \frac{ln\left(\frac{N_D}{N_P} + 1\right)}{\lambda}$$

Where: $N_d$ is the number of daughter atoms present
$N_p$ is the number of parent atoms of the radioactive element
λ is he radioactive decay constant]
t is the time in years
ln is natural log

To calculate half-life, we can use:

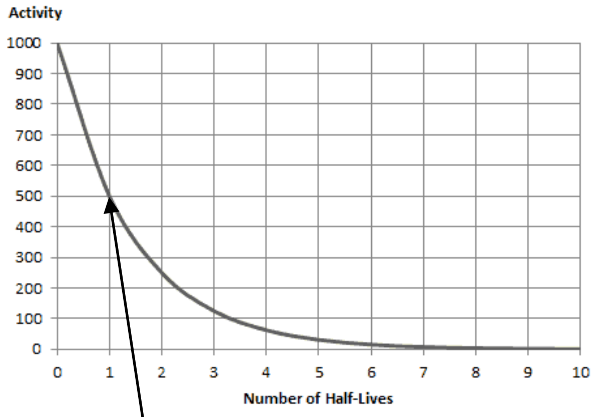
$$t_{1/2} = \frac{0.693}{\lambda}$$

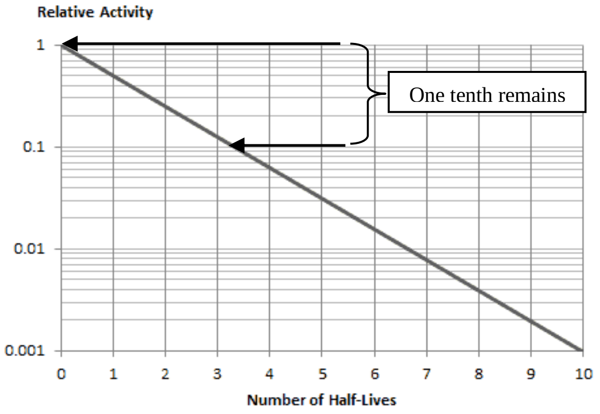
Where: λ is he radioactive decay constant]
$t^1/_2$ is the half-life

The **radioactive decay law** is a universal law that describes the statistical behaviour of a large number of nuclides (a specified nucleus with a set number of neutrons and protons). As can be seen to the right, radioactive decay is exponential (where the increase or decrease in something doubles or halves over a set unit of time).

| **Isotope** | **Half life** | **Decay constant (s$^{-1}$)** |
|---|---|---|
| Uranium 238 | 4.5x10$^{9}$ years | 5.0x10$^{-18}$ |
| Plutonium 239 | 2.4x10$^{4}$ years | 9.2x10$^{-13}$ |
| Carbon 14 | 5570 years | 3.9x10$^{-12}$ |
| Radium 226 | 1622 years | 1.35x10$^{-11}$ |
| Free neutron 239 | 15 minutes | 1.1x10$^{-3}$ |
| Radon 220 | 52 seconds | 1.33x10$^{-2}$ |
| Lithium 8 | 0.84 seconds | 0.825 |
| Bismuth 214 | 1.6x10$^{-4}$ seconds | 4.33x10$^{3}$ |
| Lithium 8 | 6x10$^{-20}$ seconds | 1.2x10$^{19}$ |

The decay constant is different for different radioactive elements (see above).

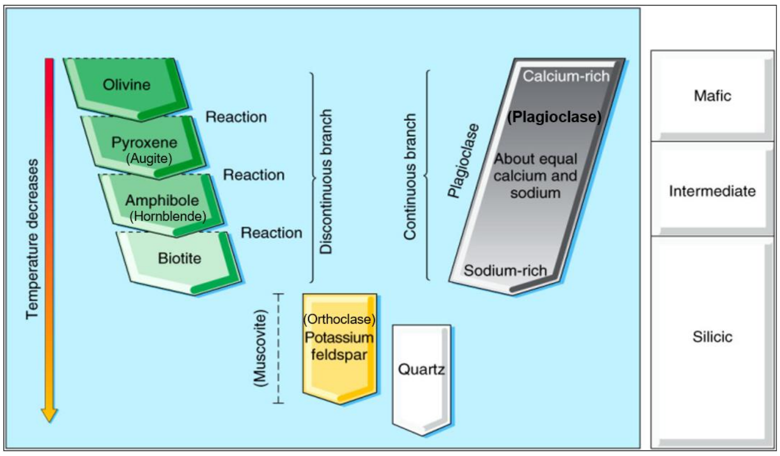




The number of atoms of the radioactive element remaining halves over each set unit of time. It also decreases ten-fold over a set unit of time. This is an **exponential** decrease.

# Continuous Reaction Series

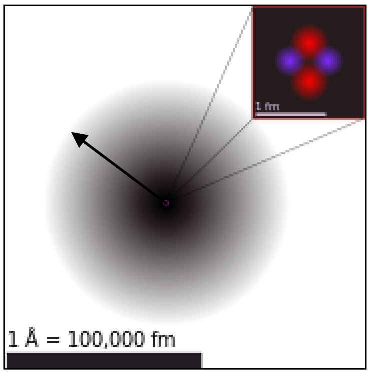
As can be seen from Bowen's reaction series, most minerals will form at a set range of temperature conditions. Once crystallised the composition of these minerals is set and will not change. However, some minerals form as a continuous reaction series. This means that their composition varies as the temperature changes. One element within the atomic structure of the mineral will substitute for another as the temperature drops. The two main examples of this are:



| | High temperature | | Lower temperature |
|---|---|---|---|
| Plagioclase Feldspar | Anorthite $Ca(Al_2Si_2O_8)$ | → | Albite $Na(Al_2Si_2O_8)$ |
| Olivine | Forsterite $Mg_2SiO_4$ | → | Fayalite $Fe_2SiO_4$ |

The substitution of one element for another in the crystal structure of a mineral depends upon two factors:

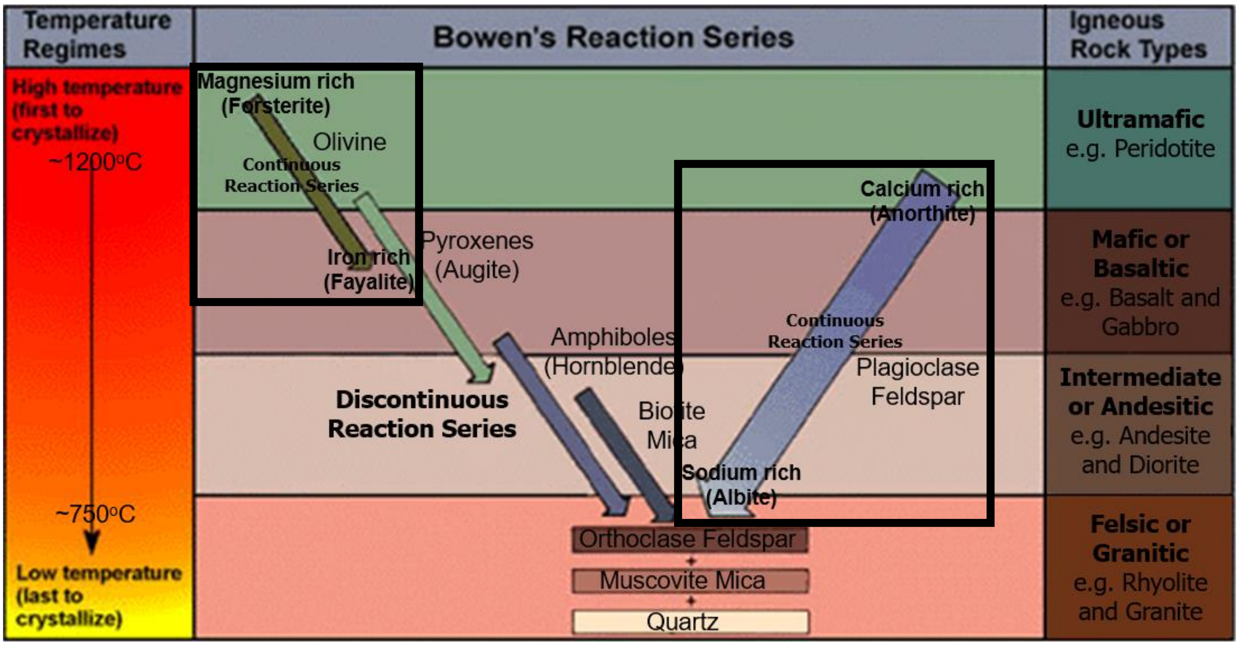
1) The **atomic radius** – this is the distance from the centre of a nucleus to the edge of the surrounding cloud of electrons. For one element to substitute for another, then they must have similar atomic radii.



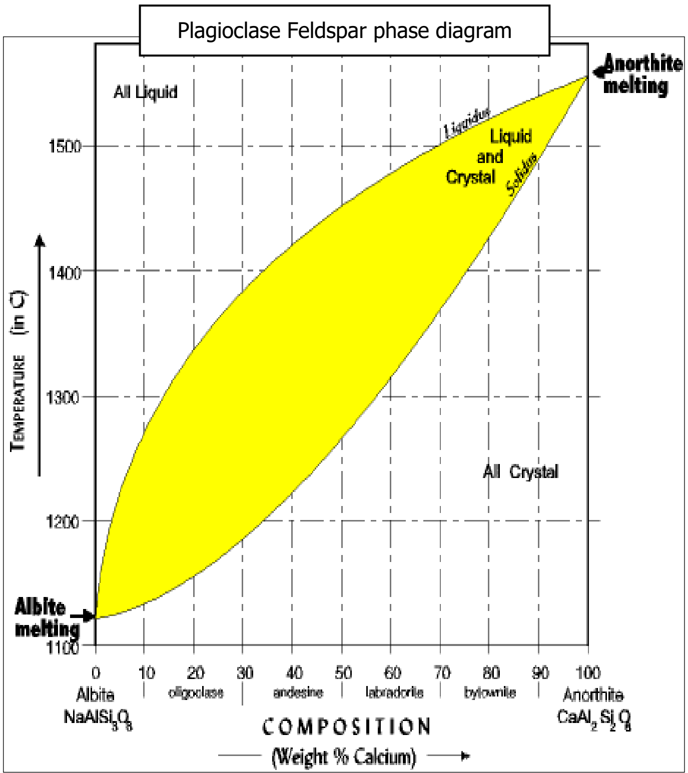
2) The **valency** – the affinity of an element to combine with others in a chemical compound. Only elements with similar valency can substitute for one another in a continuous reaction series. Therefore, Sodium (Na) and Calcium (Ca) with valency of 1 and 2 are similar enough to be able to substitute for one another in the Plagioclase Feldspar continuous reaction series. Likewise, Iron (Fe) and Magnesium (Mg) with valency of 3 and 2 can substitute for one another in the Olivine continuous reaction series (see above).

# Interpreting Continuous Reactions Series from Phase Diagrams

In Bowen’s Reaction Series there are two minerals which exhibit continuous reaction series. This means that the composition of the mineral changes as the temperature drops, due to it continuously reacting with the remaining magma (melt). As mentioned on the previous page the two minerals are **Olivine** and **Plagioclase Feldspar**.



To interpret and understand these continuous reaction series, geologists use phase diagrams. These show the different phases (liquid, part liquid/solid and solid) that magma will go through before finally crystallising. It is the partially liquid and solid phase where the exchange of ions takes place.

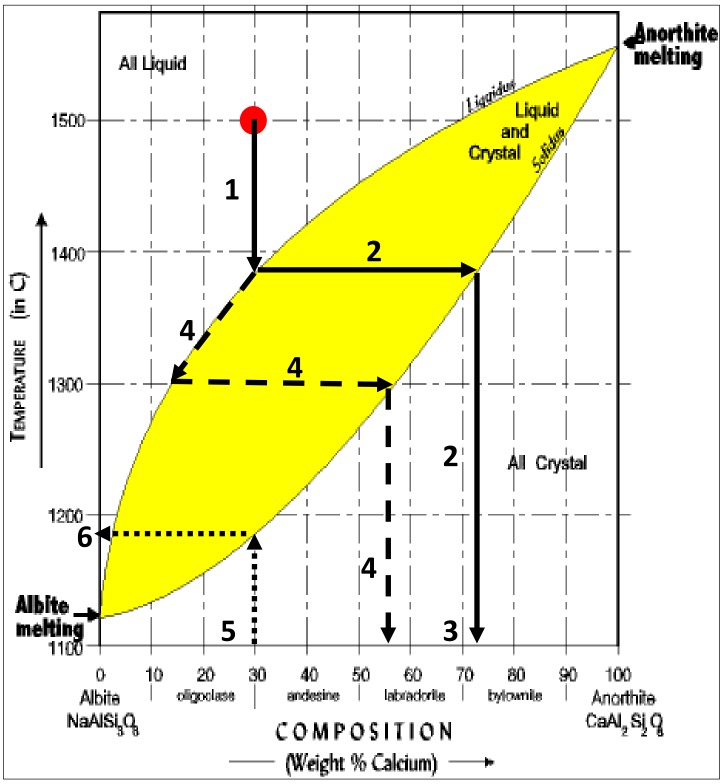


**Phase Diagrams:**

These show the liquid phase at the top, the liquid/solid phase in the middle and the solid (crystal) phase at the bottom. To read these there are a few basic rules:

- You must know the composition of the magma (melt) in terms of its Ca and Na ratio.
- In order to work out the Ca/Na composition of crystals forming at any given temperature you must read **down-across-down**.
- If continuous reaction takes place, then all of the final crystals formed will have the same Ca/Na composition as the original magma or melt did.

**Example:** Assume that a magma (melt) ● has a composition of 30% Ca and 70% Na and begins cooling at 1500°C.



1) This melt cools until it reaches the liquidus line where crystals begin to form.

2) The composition of the first formed crystals can be worked out by reading across and down.

3) They will be 72% Ca and only 28% Na in composition.

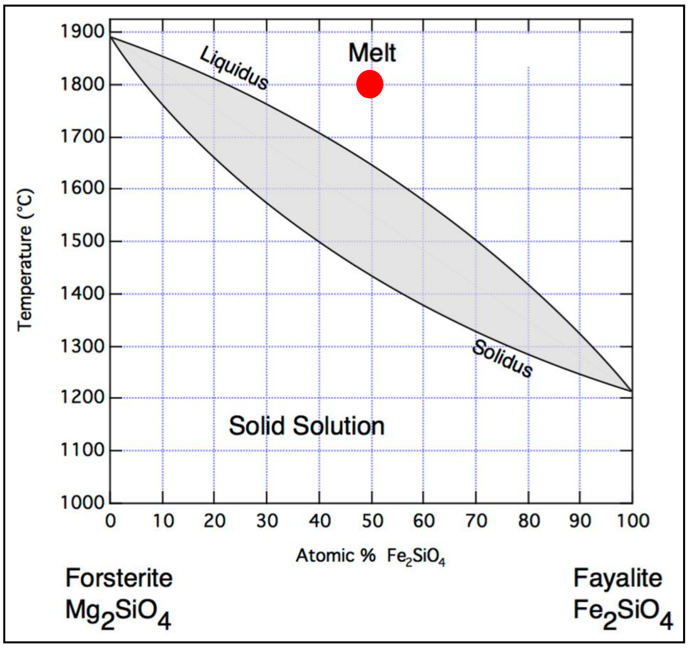
4) As the magma (melt) continues to cool so the composition of crystals formed will change. Also the first formed crystals will start to exchange high temperature Ca with lower temperature Na to match the crystals formed as temperature drops.

5) The final crystals formed will have the same composition as the original magma (melt): 30% Ca and 70% Na.

6) They will form at a temperature of around 1180°C. At this point the magma has entirely crystallised.

You may also see a phase diagram for the Olivine solid solution series in an exam.

**Exercise:** Assume that a magma (melt) ● has a composition of 50% Mg and 50% Fe and begins cooling at 1800°C. Work out the following in your book:



1) The initial crystallisation temperature.

2) The composition of the first formed crystals (%Mg/Fe).

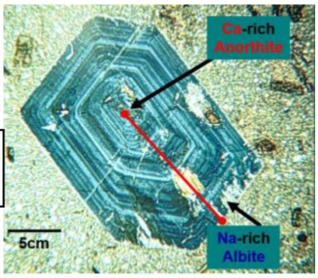
3) The composition of the crystals formed at 1500°C (%Mg/Fe).

4) The composition of the last drop of melt (liquid magma) in %Mg/Fe.

5) The composition of the final crystals assuming all of the ions have been exchanged (%Mg/Fe).

6) The temperature of the last crystallisation.

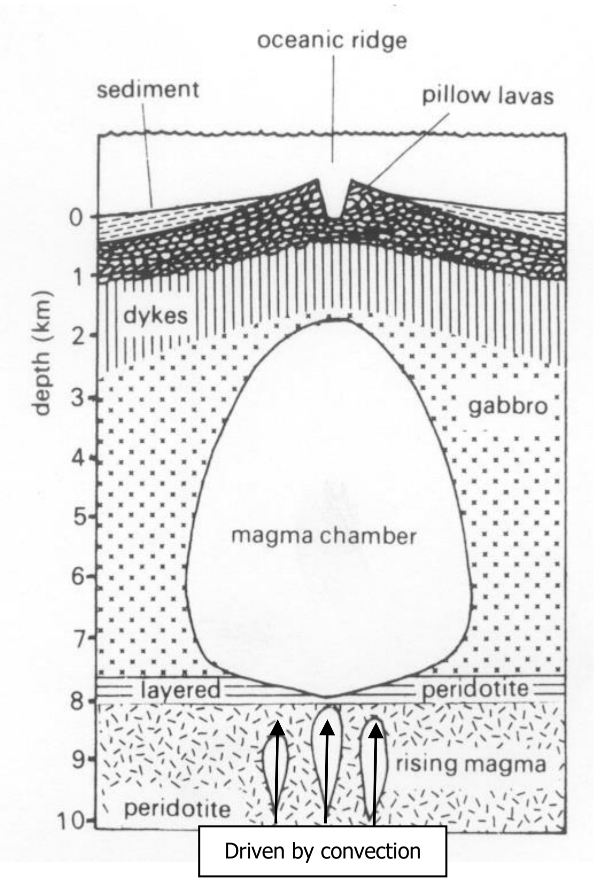
What are **zoned crystals** then and how do they form?



A 'zoned' crystal of Plagioclase Feldspar

# The Formation of Magma at Different Tectonic Settings

1) Divergent (constructive) plate boundaries – this is where rising and spreading convection currents are driving oceanic plates apart. As the plates are forced apart the mantle begins to melt as its melting point is lowered by decompression (a localised lowering of the pressure). This partially molten **Basaltic** magma is now less dense and free to rise towards the surface. Compositionally this type of magma is referred to as **Mafic**. This is magma rich in Fe, Mg and relatively low in Si <50%)
The diagram alongside shows how the rising magma will move upwards forming the distinctive layering of the oceanic crust. Some magma will cool before reaching the surface but some will make it to the top and erupt as **Basaltic** lava at the mid ocean ridge.



Driven by convection

## New Evidence from the JOIDES RESOLUTION 360 research cruise

**Objectives:**

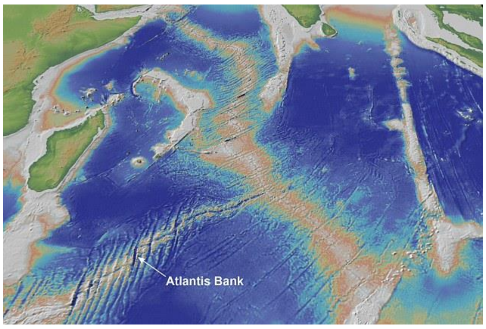
- To drill down to the Moho to understand the processes that operate at mid-ocean ridges.
- To test the types of rocks and materials at depth in the crust.
- To understand the processes of asymmetric seafloor spreading.

**The project:**

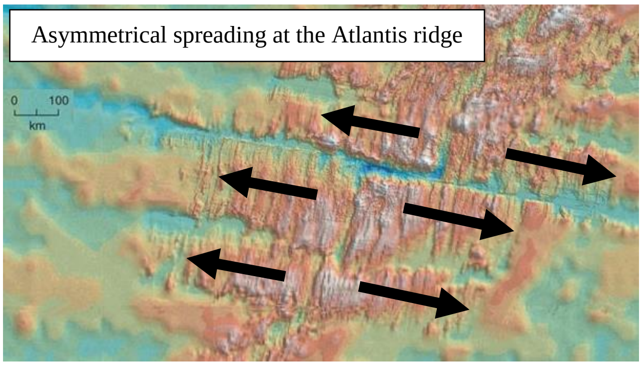
Geologists are to drill more than 3 miles (5km) into the Earth's crust beneath the Indian Ocean in an attempt to reach the super-heated rock of the mantle below for the first time. Using a drilling ship called JOIDES Resolution, the researchers will lower a drill through 2,296ft (0.4 miles) of sea water before beginning to penetrate the seabed below.

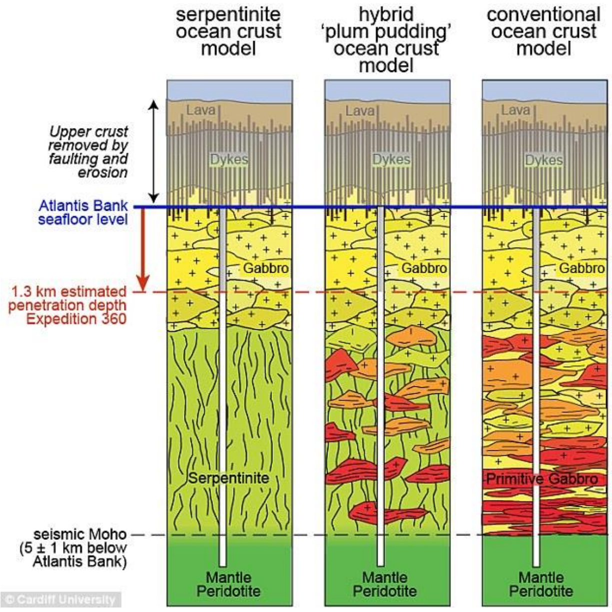
**What is the MOHO?**

The boundary between the mantle and the crust above is known as the Mohorovičić discontinuity or Moho. The Moho is thought to form a relatively rigid area of solid, but superheated rock where temperatures reach between 500°C and 900°C. The rock in this part of the mantle is known as peridotite. Sea water is thought to seep through cracks in the crust into the mantle, triggering chemical reactions that transform the mantle rock into serpentinite. Scientists have never been able to directly sample what lies at the boundary, however, instead relying upon information from seismic surveys and rock pushed to the surface through volcanoes. Scientists are hopeful the new attempt to drill into the Earth's mantle will be successful due to the location they have chosen. Their target site is the Atlantis Bank, an ocean ridge in the Indian Ocean. It is thought the crust is thinner here than in other areas.

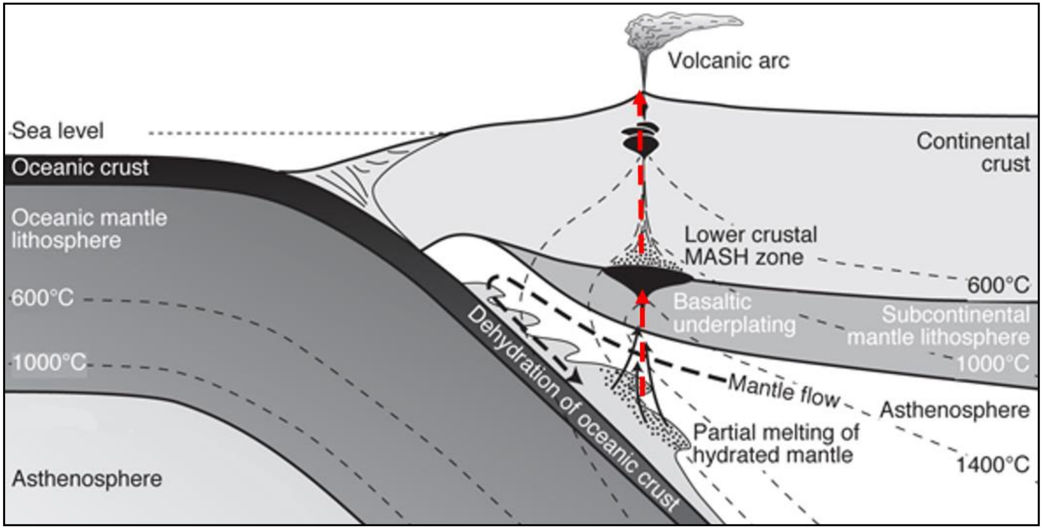


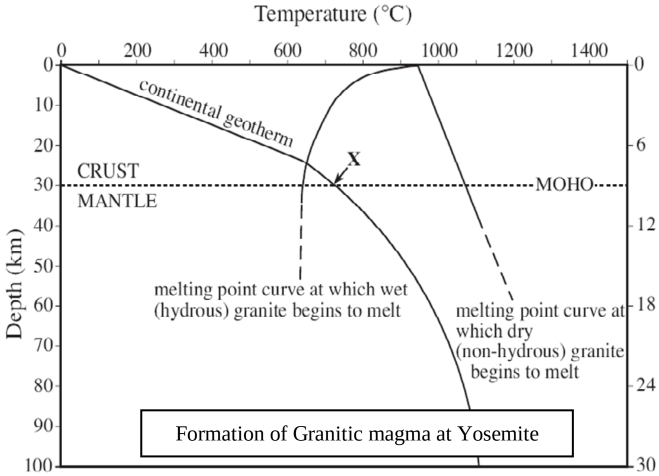
The researchers' estimate it will take them several years to reach the mantle, even from the Atlantis Bank in the Indian Ocean where faulting at the constructive plate boundary has left the crust thinner than elsewhere. One major discovery is that the two models proposed about the earth's lower crust are both wrong and that the middle model (see above) is most likely to be correct. They have also discovered that the constructive boundary spreads unevenly and is faulted (cracked) as it does so. This asymmetrical movement suggests that convection currents in the mantle vary dramatically from one location to another.


Asymmetrical spreading at the Atlantis ridge

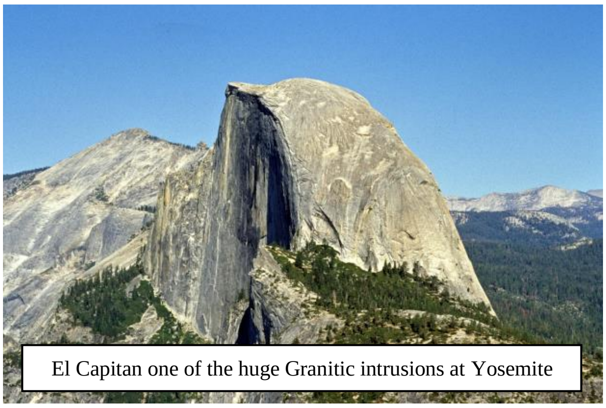


2) Convergent (destructive) plate boundaries – at this location parts of the Asthenosphere are partially melted due to the addition of water and other volatiles by subduction. These lower the melting point of the mantle and cause the buoyant, gassy magma to rise. This magma in turn will mix with material in the lower crust which has a low melting point anyway (as it is silica rich). The resulting magma is **Andesitic** in nature. Compositionally it is known as **Intermediate** magma (lower in Fe and Mg than mafic, but with Si ~60%.





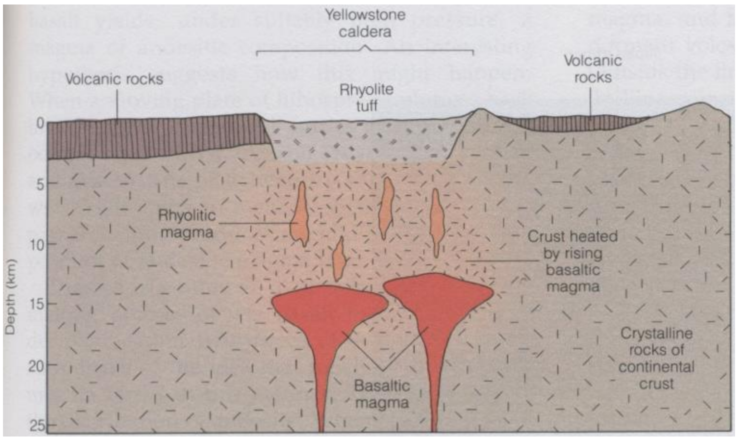
Formation of Granitic magma at Yosemite

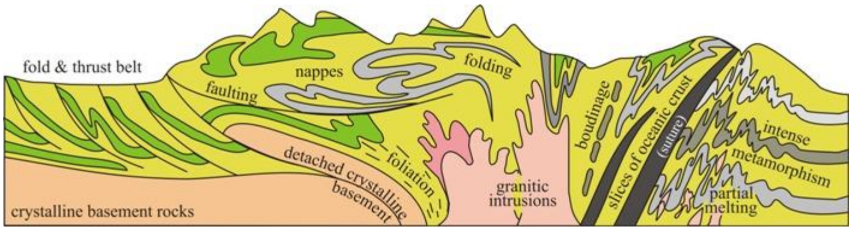


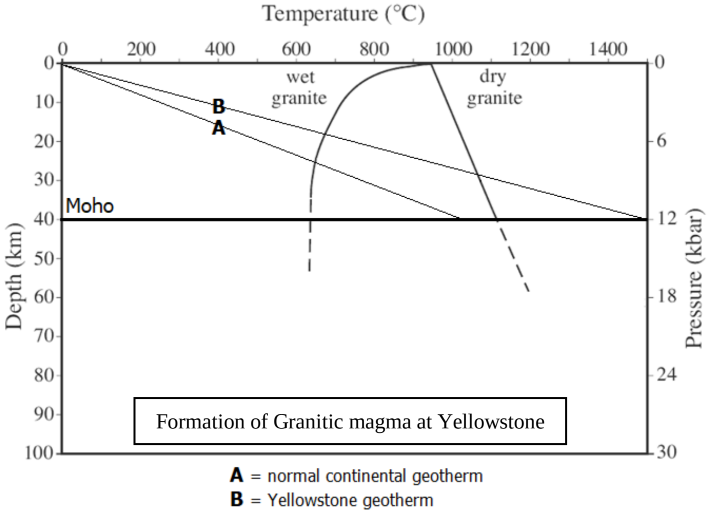
El Capitan one of the huge Granitic intrusions at Yosemite

The graph to the right show the melting points of both wet and dry granitic magma. At these convergent boundaries the subducted plate takes saturated sediment with it into the mantle. This additional water lowers the melting point of the surrounding mantle to a point where it is below the geotherm. Partial melting results. The resultant magma produced will be rich in the lower temperature minerals from Bowen's Reaction Series such as Quartz, Orthoclase and Muscovite. Hence it will be **Intermediate**. As this magma rises it lowers the melting point of material from the lower crust thus incorporating more silica. Therefore, over time the magma becomes more felsic, resulting in **Granitic** magma (cooling to form large plutons) under locations such as Yosemite National Park.

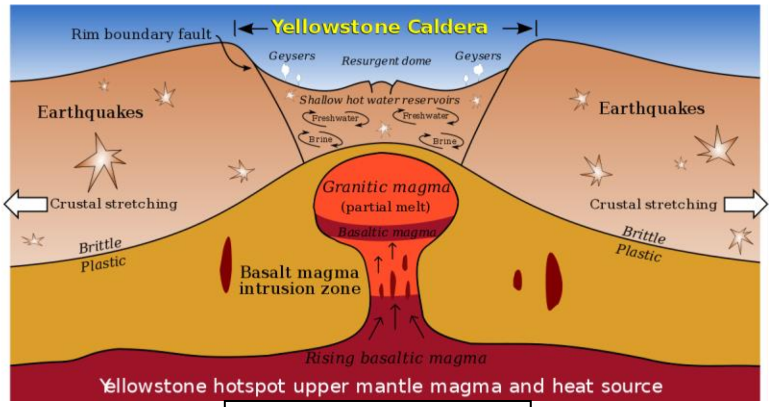
3) <u>Collision plate boundaries</u> – this is where continental collision occurs and mountain building events (orogeny) begin. At these collision zones (e.g. Himalayas today) the base of the continental plates can be partially melted as it is forced into hotter material. This can produce magma at depth. This basaltic magma then rises through the crust and melts many of the lower temperature minerals, adding more silica and making the magma **Granitic**. Compositionally this is **Felsic** magma (low in Fe and Mg but with over 70% Si content). This can produce very explosive rhyolitic eruptions as have happened at Yellowstone in the past. These collision boundaries can be extremely hard to interpret as their processes are complicated. It is thought that the geothermal gradient at Yellowstone is higher thus allowing even dry Granitic magma to begin to partially melt in the lower parts of the crust. As a result large amounts of magma are generated despite there being no additional water to lower the melting point. In conjunction with this Yellowstone today sits on a mantle hotspot. This makes the Yellowstone National Park an extremely active volcanic and magmatic area.





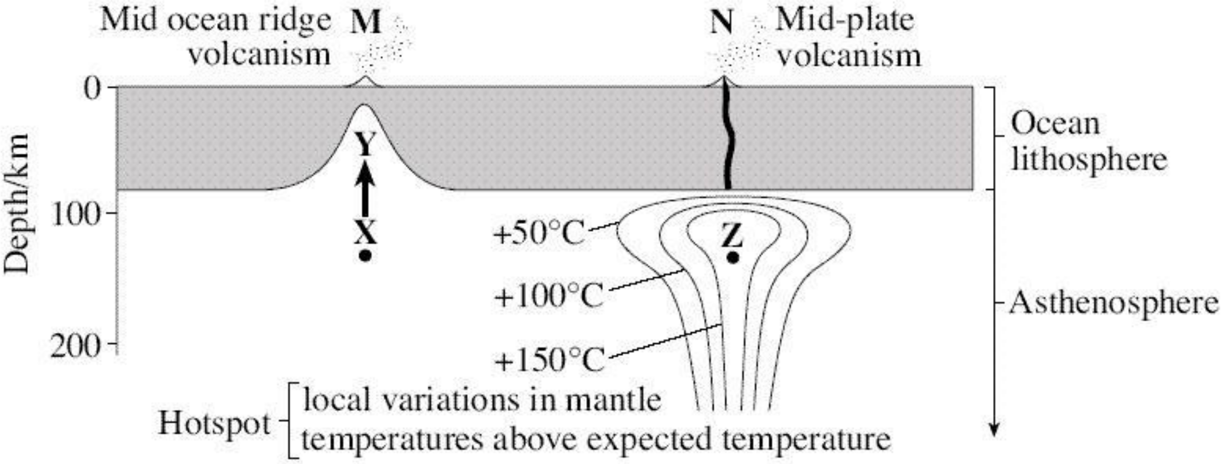


Formation of Granitic magma at Yellowstone



Yellowstone – mantle hotspot

4) Mantle plumes (hotspots) – where localised heating of the mantle by a plume or hotspot causes partial melting of the mantle material. See below:



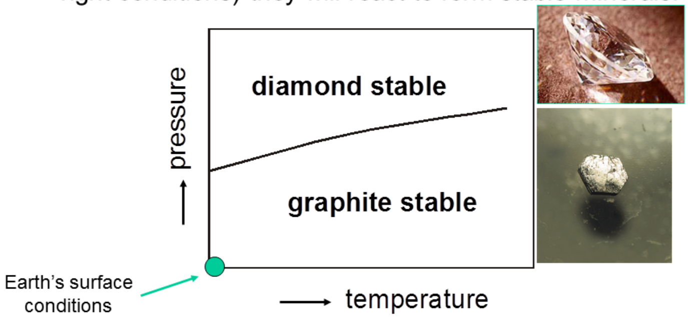
The most well-known example of this is in Hawaii. However, over 20 hotspots have now been discovered, with five of these being on land in locations as varied as Yellowstone in the USA and Cameroon in Africa. The magma here with its origins in the mantle is also usually **Basaltic**. Compositionally it is **Mafic**. However, Yellowstone, with its complicated 'plumbing' system is far more complex than this.

# Key Idea 2: The mineralogy and texture of metamorphic rocks are determined by the composition of the parent rock and the conditions of metamorphism

## Stable and Metastable minerals

Minerals which are chemically unreactive at the earth's surface are said to be **stable**. Most minerals are not chemically stable at the earth's surface and are thus referred to as **metastable**. It is generally those minerals which have formed under conditions closest to those found at the surface which are more stable e.g. Quartz. Minerals which have formed under conditions which are very different to those on the surface are metastable e.g. Olivine. Rocks which are metastable will react chemically until they eventually become stable under their new conditions. This is fundamental to all metamorphic processes.

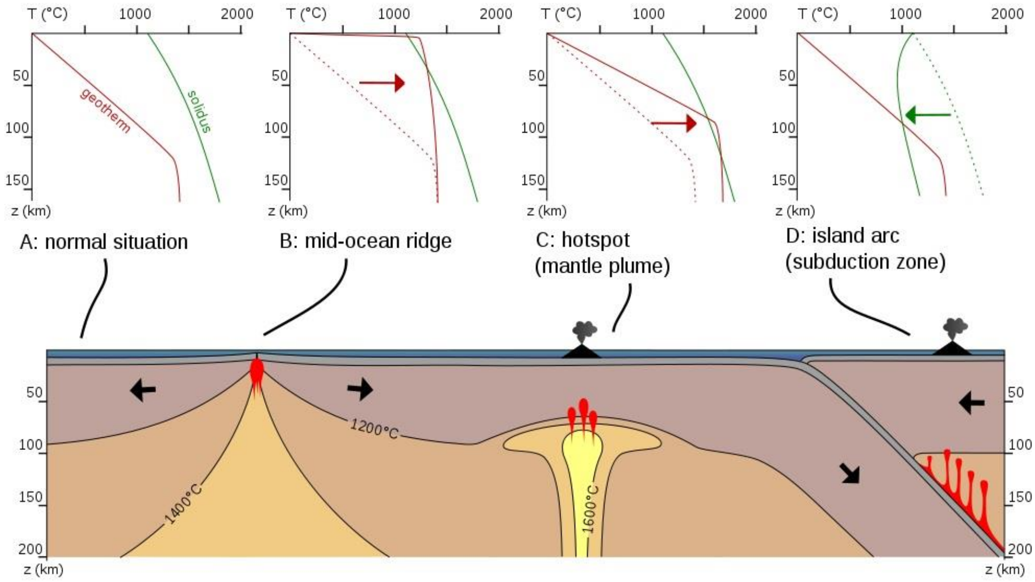
Minerals that persist in an environment in which they are not chemically stable are said to be *metastable.* Most of the minerals in the rocks at the Earth's surface are metastable. Given enough energy (or enough time and the right conditions) they will react to form stable minerals.



As rocks become buried the conditions that they experience will change. This can cause a stable mineral to become metastable.

### Changing conditions

We already know that **temperature** increases with depth inside the earth and within the lithosphere (geothermal gradient). This ranges from 25°C/km$^{-1}$ in the continental to lithosphere to between 10°C/km$^{-1}$ and 100°C/km$^{-1}$ in the oceanic lithosphere.



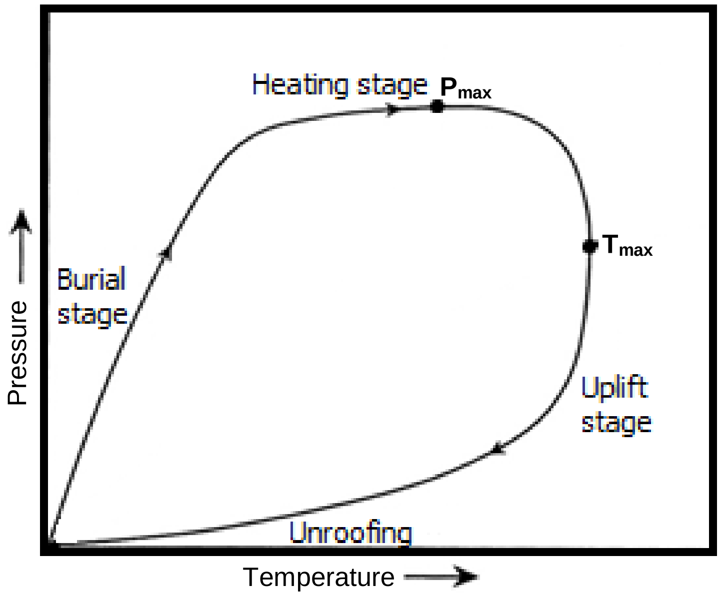
However, an important property of rocks to consider is their ability to conduct heat, On the whole, rocks are poor conductors of heat. Heat is far more efficiently transferred by convection in magma or partially molten material. This explains the high geothermal gradients at mid-ocean ridges.

**Pressure** also increases with depth at an average rate of 30MPa/km$^{-1}$. Therefore, rocks found at the base of the continental lithosphere may be experiencing very high pressures and temperatures over 900°C. It is logical to assume that minerals at this depth that formed from sedimentary processes on the surface may undergo changes to adjust to these new physical conditions.

## Pressure-Temperature-Time Paths

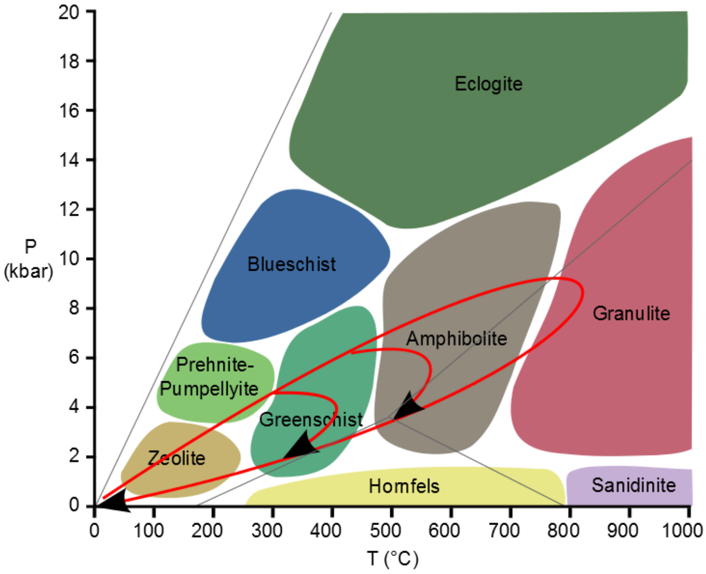
- "Typical" regional metamorphism takes **parent rocks** on a CLOCKWISE pressure (P) –temperature (T) – time (t) path.
- Remember that burial can be in a sedimentary basin, subduction zone or orogenic belt (tectonic crustal thickening).
- $P_{max}$ (maximum pressure applied) is reached before $T_{max}$ (maximum temperature reached) because the rock is buried faster than it can heat up by conduction. The downward bend of the path, approaching $T_{max}$, reflects the "catching up" of temperature by conduction of heat from below.
- "Uplift" can be accomplished by isostatic rebound, orogenic uplift and erosion.

This diagram illustrates that a rock undergoing regional metamorphism will go through a series of heat and pressure changes as it is buried. At various temperatures and pressures different minerals are either stable or metastable. The depth and length of time that this journey takes will determine the final stable minerals that form and hence the final metamorphic rock formed

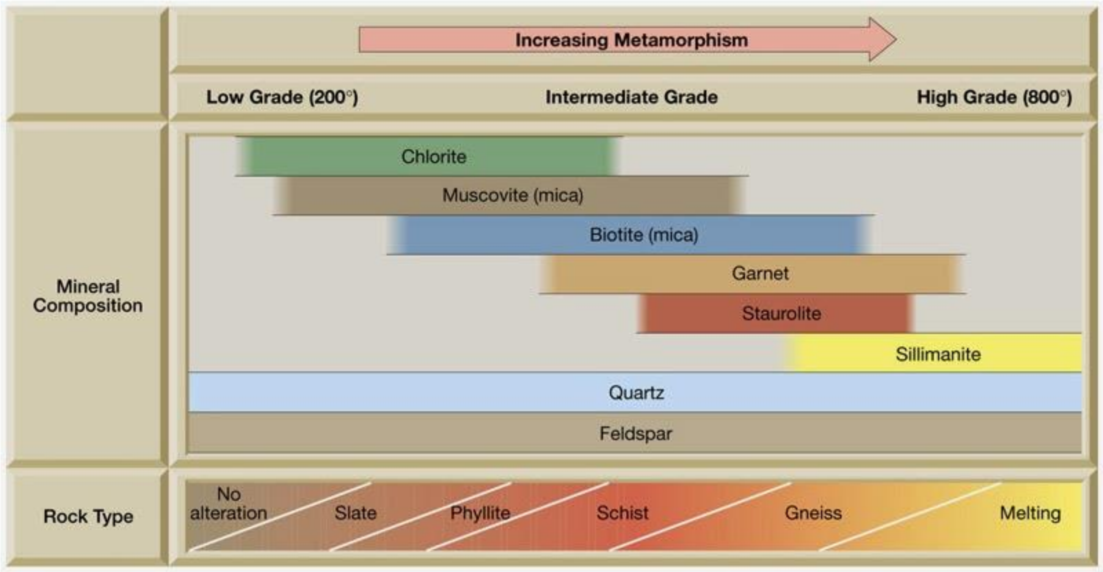


The result of these changes is that individual minerals have their own **stability fields** i.e. a range of temperatures and pressures at which they are stable.

This diagram depicts various **Metamorphic Facies** and their temperature and pressure environments. A metamorphic facies includes all of the rocks and minerals that form in a given metamorphic environment under specific temperature and pressure conditions. They are usually named for their most common rock type or mineral.

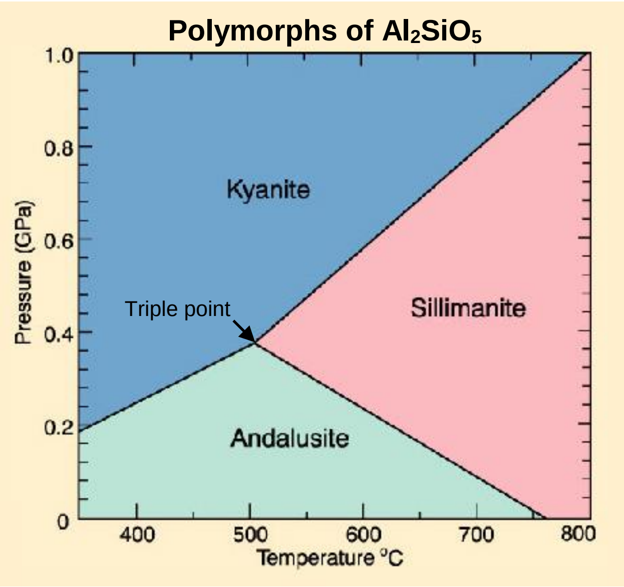


This next diagram correlates metamorphic intensity with metamorphic facies and their corresponding **index minerals**. These minerals are only stable or metastable at a given range of temperature or pressure conditions.



Therefore, many metamorphic rocks can be identified using their index minerals - those which mark a particular temperature and pressure of formation). Some minerals even have polymorphs or different forms of the same mineral that form at very specific pressure and temperature conditions.

Each mineral forms in metamorphic rocks at very specific conditions, although it is possible to find two or even all three in the same rock.

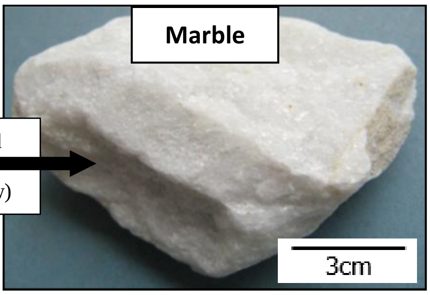


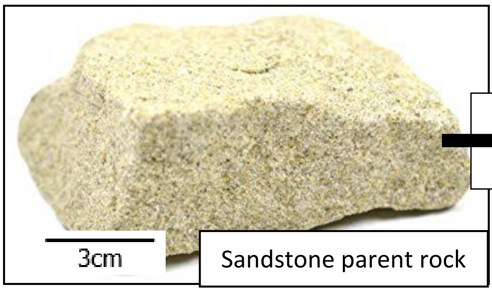
## Importance of the Parent Rock

Remember the analogy of the loaf of bread. A metamorphic rock is almost always **isochemical** (has the same chemistry as its parent rock). Therefore, the chemistry of the parent rock has a crucial role in determining the final metamorphic rock that can form.

Heated and recrystallised

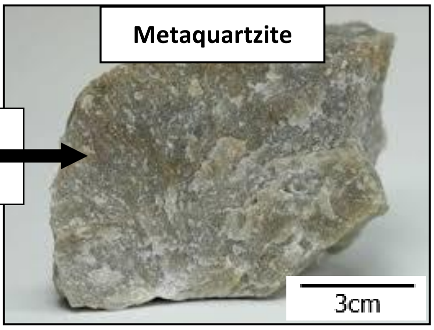
(New calcite crystals grow)





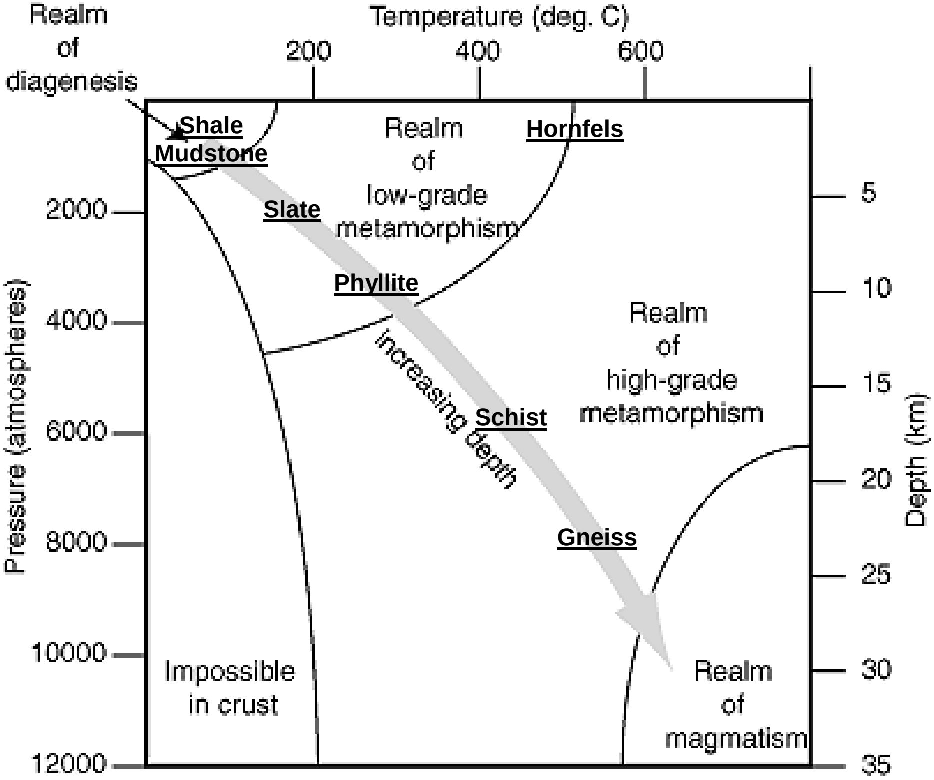
Heated and recrystallised

(New quartz crystals grow)



## The Metamorphism of Mudstone/Shale

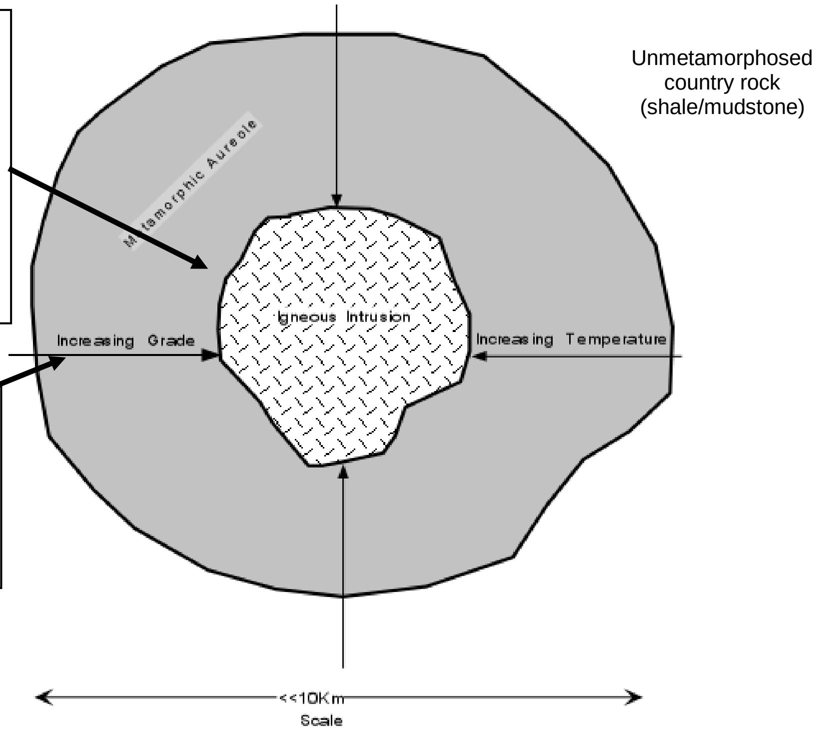
Both mudstone and shale are formed from a huge number of different clay minerals (Illite, Smectite and Montmorillonite). Therefore, both can have very complicated chemistry (e.g. Illite $(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$). This means that the resultant mineralogical changes seen can be extremely varied depending on the P and T conditions that the rock is exposed to. The intensity of changes to a parent rock is known as the **metamorphic grade**. Higher grade rocks show greater mineralogical and textural changes than lower grade ones.



There are three main types of metamorphism each with its distinctive textures associated

## Contact or Thermal Metamorphism

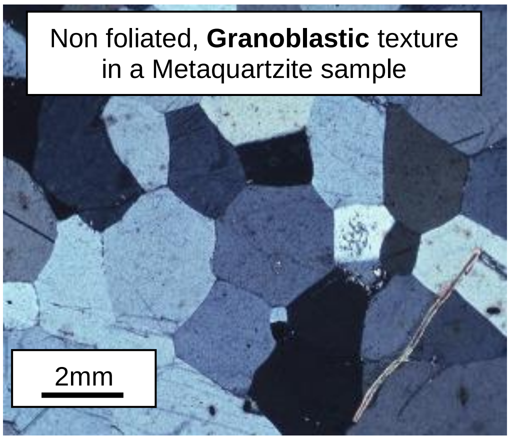
This involves the heating of the country rock surrounding an igneous intrusion. The area affected by heat from a large intrusion such as a pluton is known as the **metamorphic aureole**.



Near to the intrusion the country rock or parent rock (in this case shale) is heated intensely. Crystals of new minerals such as chiastolite and andalusite are formed. The rock formed from this recrystallisation is known as **hornfels**.

Further from the intrusion the rocks (shale) are simply spotted with a few small crystals. The rock formed at a lower grade is known as **spotted rock**.

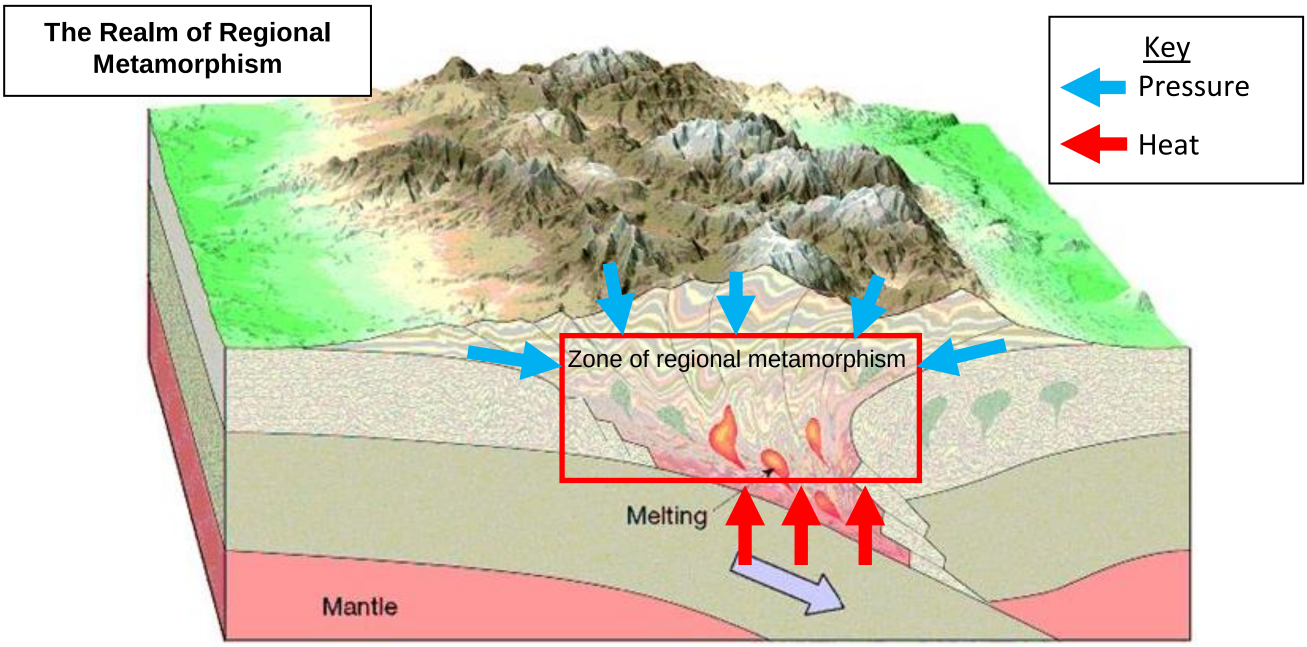
If the country (parent) rock is different, then the resulting metamorphic rock will also be different. See limestone and sandstone on the previous page. All of these resultant metamorphic rocks will be **non-foliated**. These rocks with tend to have **Granoblastic** texture. This is where grains mutually adjust their boundaries in the solid state in an attempt to achieve textural equilibrium. They will generally form triple junctions of 120° in order to achieve this equilibrium.



Non foliated, **Granoblastic** texture in a Metaquartzite sample

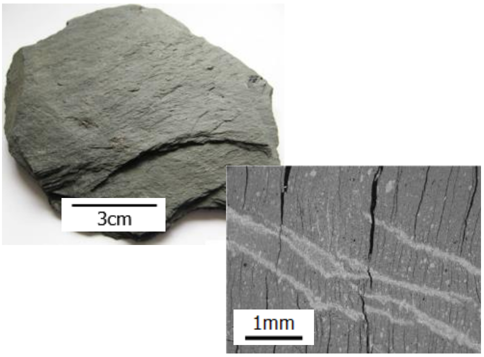
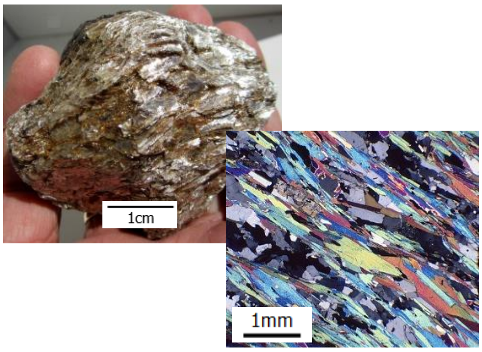
## Regional or Burial Metamorphism

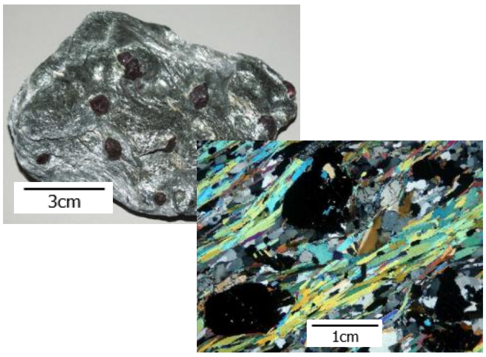
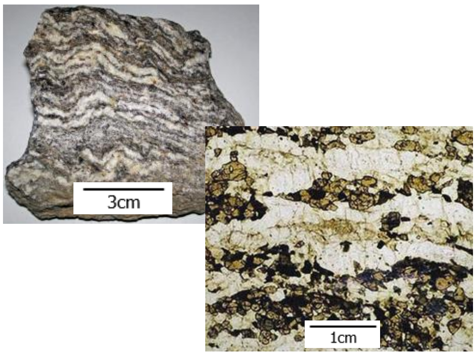
This is where rocks are buried deeply under other sediments, or by earth movements. This most commonly occurs deep inside young mountain belts formed by continental collisions. As the rocks are deeply buried increasing pressures and temperatures are exerted on them. This can cause dramatic changes to the rocks leaving them almost unrecognisable. There are various grades of metamorphic rock depending on the amount of heat and pressure that they are put under (see table on page 19).



The Realm of Regional Metamorphism

Regional metamorphism can lead to a variety of textural changes. However, the most common involve some form of foliation (alignment of particles).

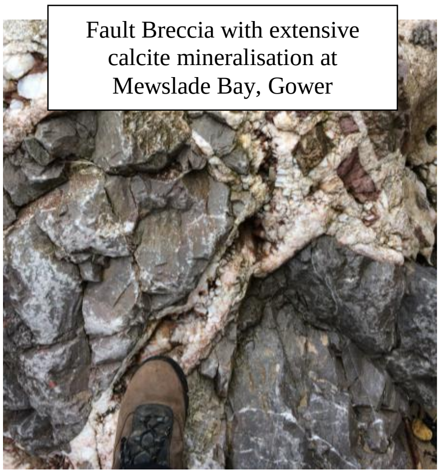
| Grade | Typical rock type | Textural and Mineralogical features | Picture/Photomicrograph |
|---|---|---|---|
| Low Grade (Low to medium P + low T) | **Slate** | At low grades rocks tend to exhibit **slaty cleavage**. Rocks will split easily along planes of weakness known as cleavage planes. This is due to increasing pressure causing alignment of the particles within the rock. Minimal recrystallization occurs as little heat has yet affected the rock. |  |
| Low to Medium Grade (Low to Medium P+T) | **Schist** | This rock will have less distinct cleavage planes. But now has a distinct wavy mineral foliation known as **schistosity**. These wavy layers are often folded or twisted. The rock has now also undergone extensive recrystallisation with clay minerals replaced by mica, quartz and feldspar. |  |

| | | | |
|---|---|---|---|
| Medium to High Grade (Medium to High P+T) | **Garnet Mica Schist** | This rock will continue to have distinctive schistosity. However, these wavy layers may now be folded around large, euhedral crystals of garnet. These large crystals are known as porphyroblasts and the texture is known as **Porphyroblastic**. |  |
| High Grade (High P+T) | **Gneiss** | The rock will now have recrystallised again and the new minerals are re-aligned in clear light and dark bands. This is known as **gneissose banding**. A totally new set of minerals will now be present as the previous ones have become metastable and recrystallised once again. |  |

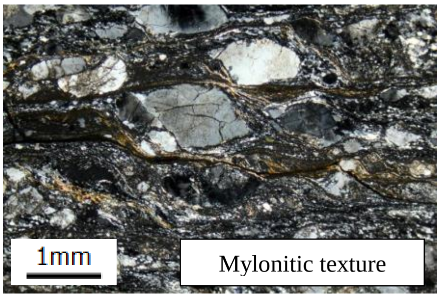
## Dynamic Metamorphism

The third type of metamorphism occurs is quite small areas where extremely high pressure conditions tend to occur for short periods of time. It tends to involve only a rearrangement of the components already present in the rock, and is largely a matter of breaking up the rock into smaller pieces. This tends to occur in areas of **shear deformation** along fault planes.

The product of this metamorphism depends on the depth at which faulting occurs as higher pressure deep in the crust increase the chances of **ductile** deformation. At shallow levels, **brittle** deformation dominates and is characterised by rocks which are shattered to form **fault breccia**. This occurs along fault planes where shearing of the rocks has occurred. This often creates an easy path for groundwater to flow, causing mineralisation (calcite and quartz are common) along the fault plane cementing the fault breccia together. At deeper levels, where ductile deformation is more important, the shearing action of fault movement produces a fine grained metamorphic rock called **mylonite**. It will often have lens shaped fragments in a streaky, fine grained matrix. This **mylonitic** texture is formed when the higher temperatures cause bonds between particles to breakdown and flowing to occur.



Fault Breccia with extensive calcite mineralisation at Mewslade Bay, Gower



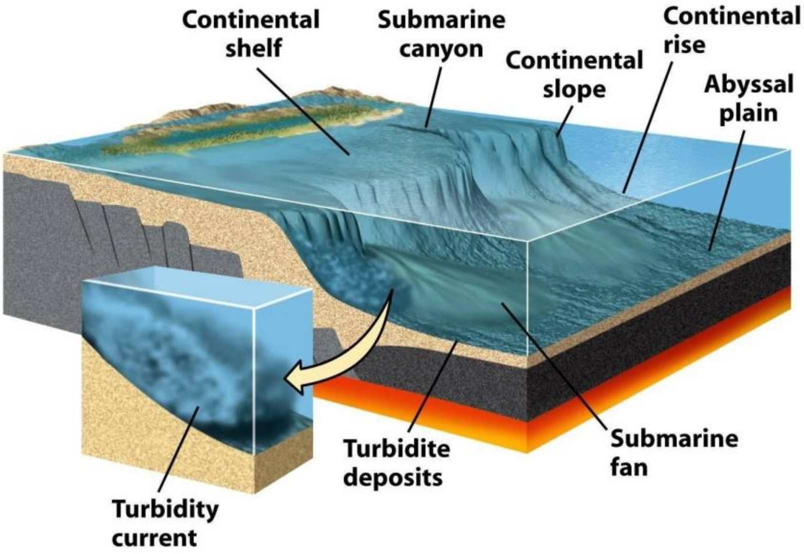
Mylonitic texture

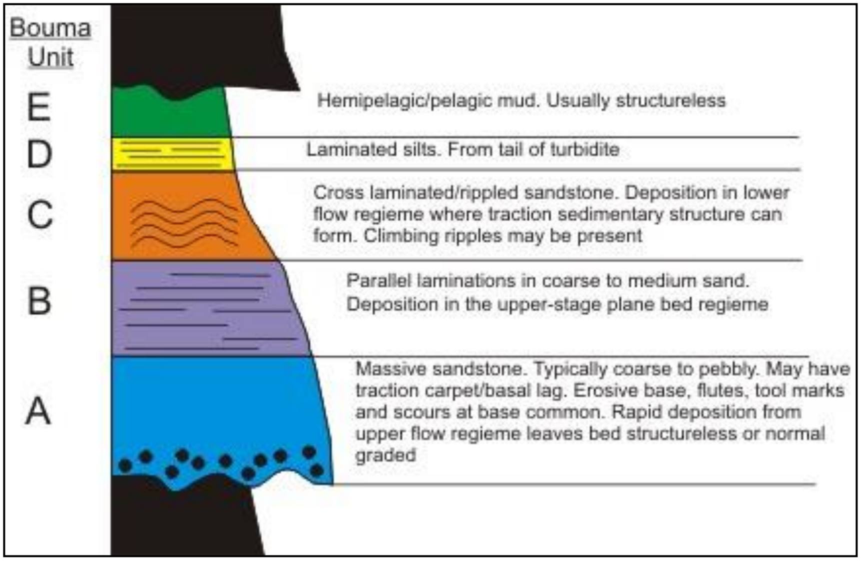
# Key Idea 3: Sedimentary processes can be understood using scientific modelling

## Understanding Unseen Geological Processes

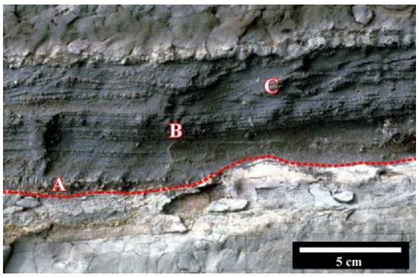
There are a number of sedimentary processes which are either infrequent or which are difficult to observe. In order to understand these, it is often necessary to model them in a laboratory.

**Turbidity currents** are a good example of an important sedimentary process which is difficult to observe due to their location. Therefore, if we are to fully understand these it is necessary to model them and try to understand the mechanisms involved. Turbidity currents are underwater currents of usually rapidly moving, sediment-laden water moving down a slope. Researchers from the Monterey Bay Research Institute in the USA found that as a layer of water-saturated sediment moves rapidly over the seafloor it also moves the top few metres of the pre-existing seafloor. Seafloor turbidity currents are often the result of sediment-laden river outflows, and can sometimes be initiated by earthquakes, slumping and other coastal disturbances. In terms of the more often observed and more familiar above sea-level phenomenon, they are thought to resemble flash floods. A typical sequence of sedimentation occurs as the result of a turbidity current. This is known as a **Bouma sequence**:

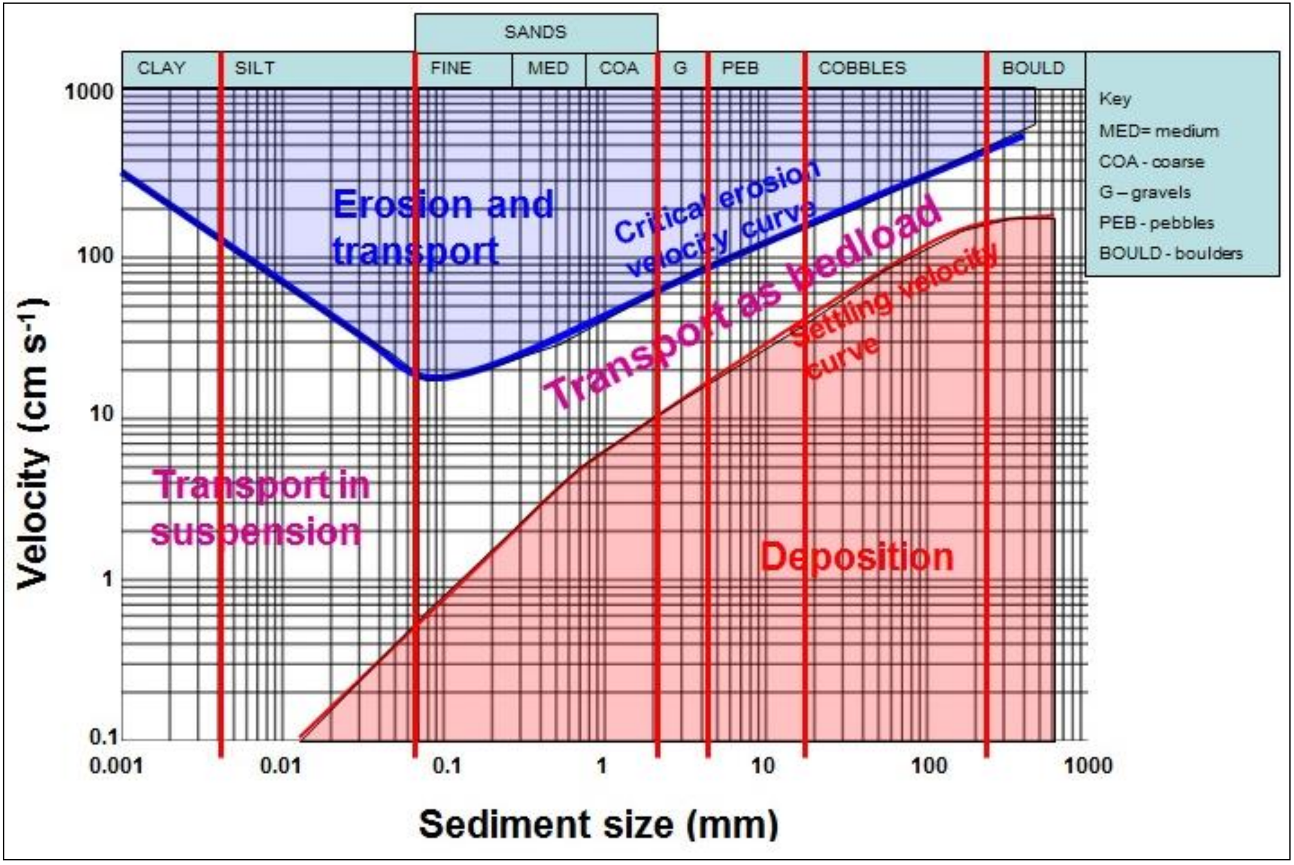




Although we do see these types of repeating deposits exposed on land today, this is still a theoretical sequence as they have never been observed forming under the ocean.



However, to fully interpret how this Bouma sequence is thought to form we need to apply another scientific model – the **Hjulström Curve**. It was originally designed by a geographer to determine whether a river will erode, transport, or deposit sediment.



The upper curve shows the critical erosion velocity in cm/s as a function of particle size in mm, while the lower curve shows the deposition velocity as a function of particle size. Note that the axes are logarithmic.

It is now often used by geologists to model erosion, transport and deposition in a variety of environments as similar rules are thought to apply. Is this of use in determining the formation of a Bouma sequence?

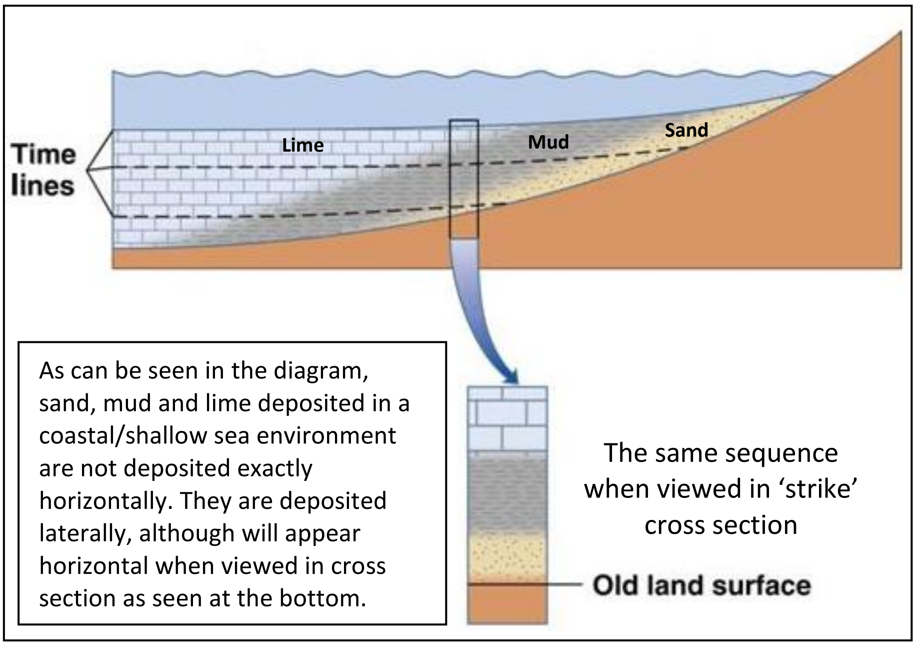
## Walther's Law

A **sedimentary facies** is a distinctive rock unit that forms under certain conditions of sedimentation, reflecting a particular process or environment. For example, a layer of limestone containing well preserved coral fossils could be termed a facies as it is most likely to have formed under shallow, tropical sea conditions.

**Walther's law** states that *'facies that occur in conformable vertical sections of strata also occur in laterally adjacent strata'*.

The key principles are:

- Sedimentary rock types record the environment of their deposition
- Depositional environments can shift laterally as conditions change
- When they shift, laterally related environments become superimposed
- Time-transgressive sedimentary formations are the result
- The vertical succession and lateral sequence of facies will be the same



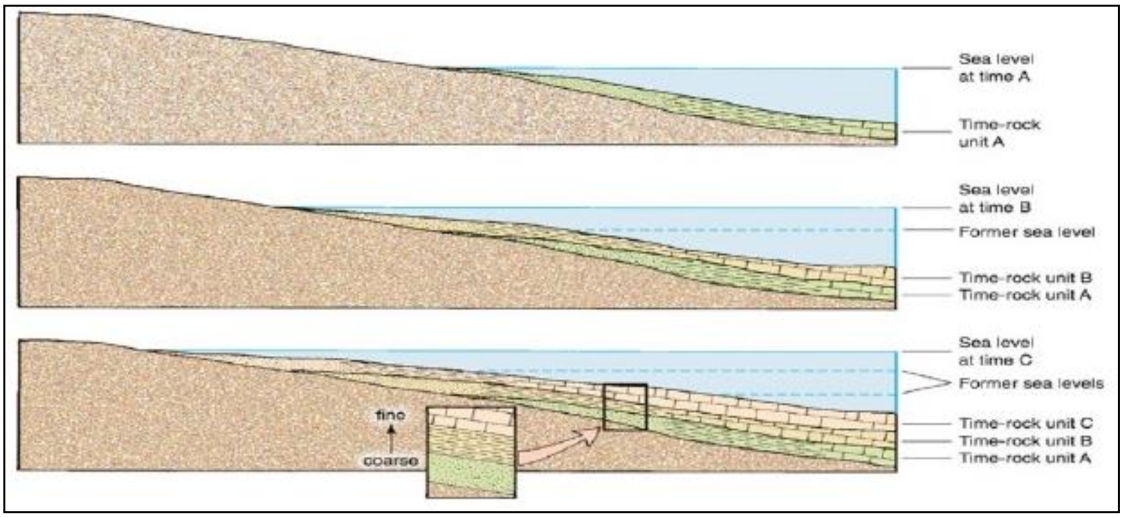
As can be seen in the diagram, sand, mud and lime deposited in a coastal/shallow sea environment are not deposited exactly horizontally. They are deposited laterally, although will appear horizontal when viewed in cross section as seen at the bottom.

The same sequence when viewed in 'strike' cross section

Essentially sedimentary sequences need to be viewed in three dimensions if they are to be fully understood. Sedimentary sequences and their lateral extent can also reveal vital information about past seal level changes and their rate of change.

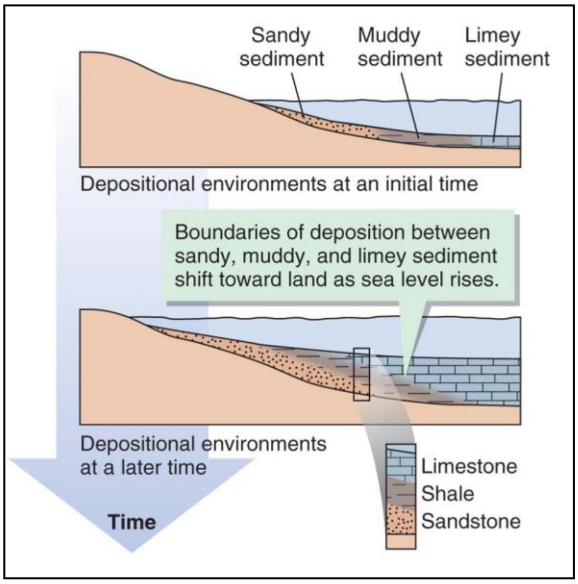
There are three possible patterns:

1) The rate of sedimentation is equal to the rate of sea level rise or fall. This would result in layers of sediment almost horizontal in nature and stacking up vertically.

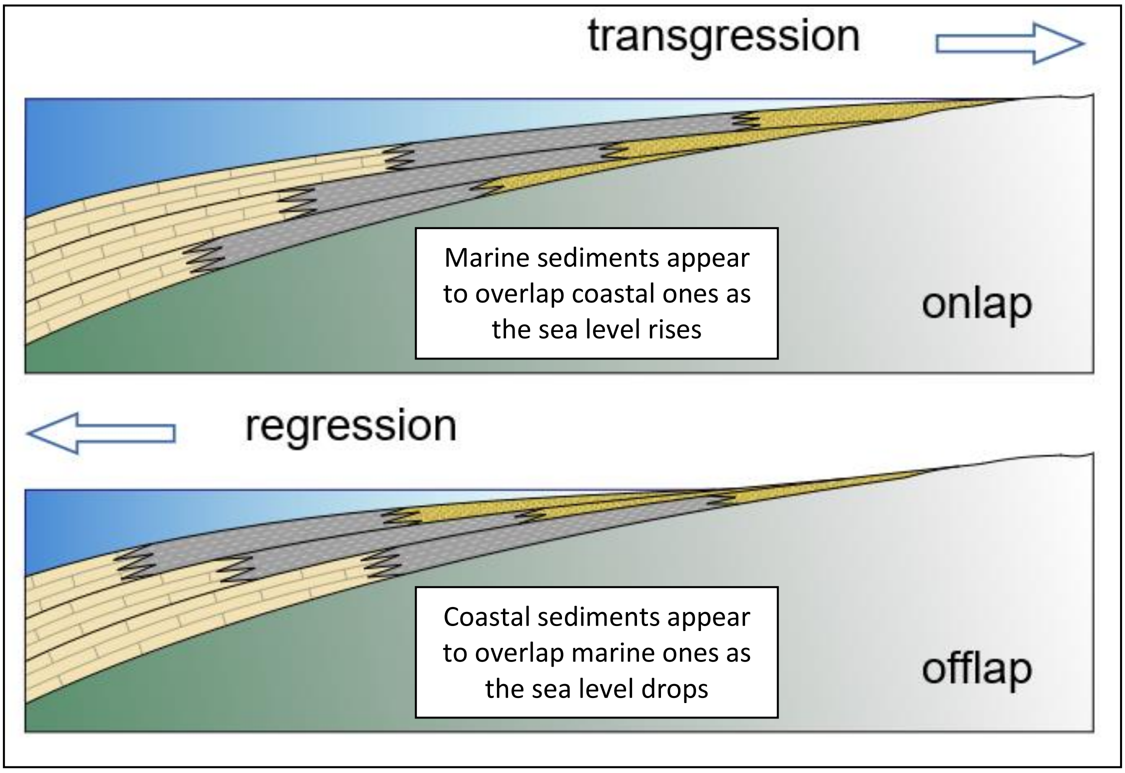


2) If there is a marine transgression (relative rise in sea level) and this is faster than the rate of sedimentation, then the shoreline sediments will move inland as seen in the diagrams.

3) If there is a marine regression (relative lowering of the sea level) and this is slower than the rate of sedimentation, then the shoreline sediments will move offshore away from the land.



Boundaries of deposition between sandy, muddy, and limey sediment shift toward land as sea level rises.



Marine sediments appear to overlap coastal ones as the sea level rises

Coastal sediments appear to overlap marine ones as the sea level drops

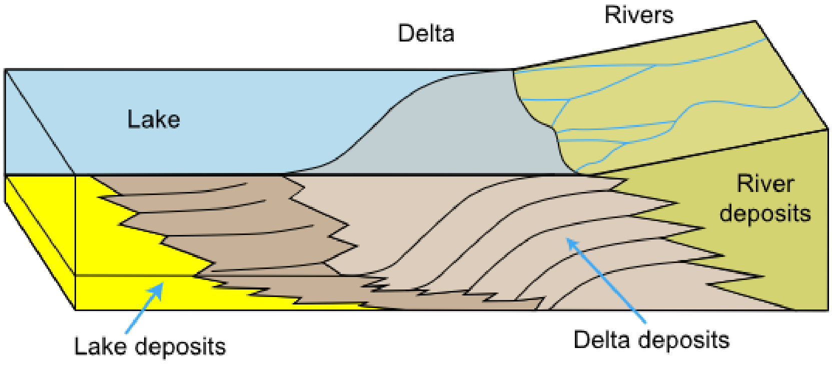
Remember that this sea level change can occur in one of two ways:

- Eustatic changes – these are due to global changes in the sea level often in response to large scale climatic changes. For example, sea levels are rising eustatically today due to rising temperatures. This causes ice caps to melt and the sea surface to expand as it heats up.
- Isostatic changes – these are more localised changes in sea level in response to isostatic rebounds or sinking. These are caused by the lithosphere being locally weighed down by the extra weight of ice or sediment. If this weight is removed the land can slowly rebound and rise. This will give the local impression than sea levels are falling.

## Interpreting Walther's Law

Interpreting sedimentary data can be difficult as Walther's law creates one or two problems. The main issue is that of interpreting **diachronous** strata. These are deposits of a sedimentary rock in which apparently similar material varies in age from place to place. Typically this occurs as a result of a marine transgression or regression, or the progressive development of a delta. As the shoreline advances or retreats, a succession of continuous deposits representing different environments (for example beach, shallow water, deeper water) may be left behind. Although each type of deposit (facies) may be continuous over a wide area, its age varies according to the position of the shoreline through time.

In this example the central delta deposits may appear in cross-section to be one sedimentary unit of rock formed over a relatively short period of time. However, as they have built up out into the sea, they may well have formed over a very long period of time. The top set of sediments might be considerably younger than the bottom ones and may actually be deposited tens of kilometres away as some deltas are huge.



The detection of diachronous beds can be quite problematic since fossil assemblages tend to migrate geographically with their environment of formation. They are generally revealed by the presence of marker species, fossils which can be dated reliably from other beds.