UNIVERSITY OF NICOSIA
DEPARTMENT OF OIL AND GAS ENERGY ENGINEERING

Lecture 4:"Igneous Rocks "

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Igneous Rocks

Observation 1:

Hot liquid lava spilling down from the volcano onto Earth's surface cooled and hardened into solid rock within a few hours ***(cooled fast).***

Observation 2:

sheets of rock that cut across other rock formations also formed by the cooling and solidifying of magma. In these cases, the magma ***cooled slowly*** because it had remained buried in Earth's crust

Magma solidification

- Before they reach the surface,
- Some break through and solidify on the surface.

Both processes produce igneous rocks.

Understanding the processes that melt and re-solidify rocks is a key to understanding the ***crust formation***.

Igneous rocks:

- Form at spreading centers (plates move apart) and
- At convergent boundaries (one plate descends beneath another)

Igneous Rocks

Understanding the ***Exact mechanisms*** of melting and solidification :

Answer the fundamental questions:

- How do igneous rocks differ from one another?
- Where do igneous rocks form?
- How do rocks solidify from a melt?
- Where do melts form?

Igneous processes in the Earth system

- Melted rock is transported from magma chambers in Earth's interior to volcanoes.
- A variety of gases are also carried along (carbon dioxide and sulfur gases)
- Affect the atmosphere and oceans

Igneous Rocks

How do Igneous rocks differ from one another ?

Classify rock samples by:

- Texture
- Mineral and chemical composition

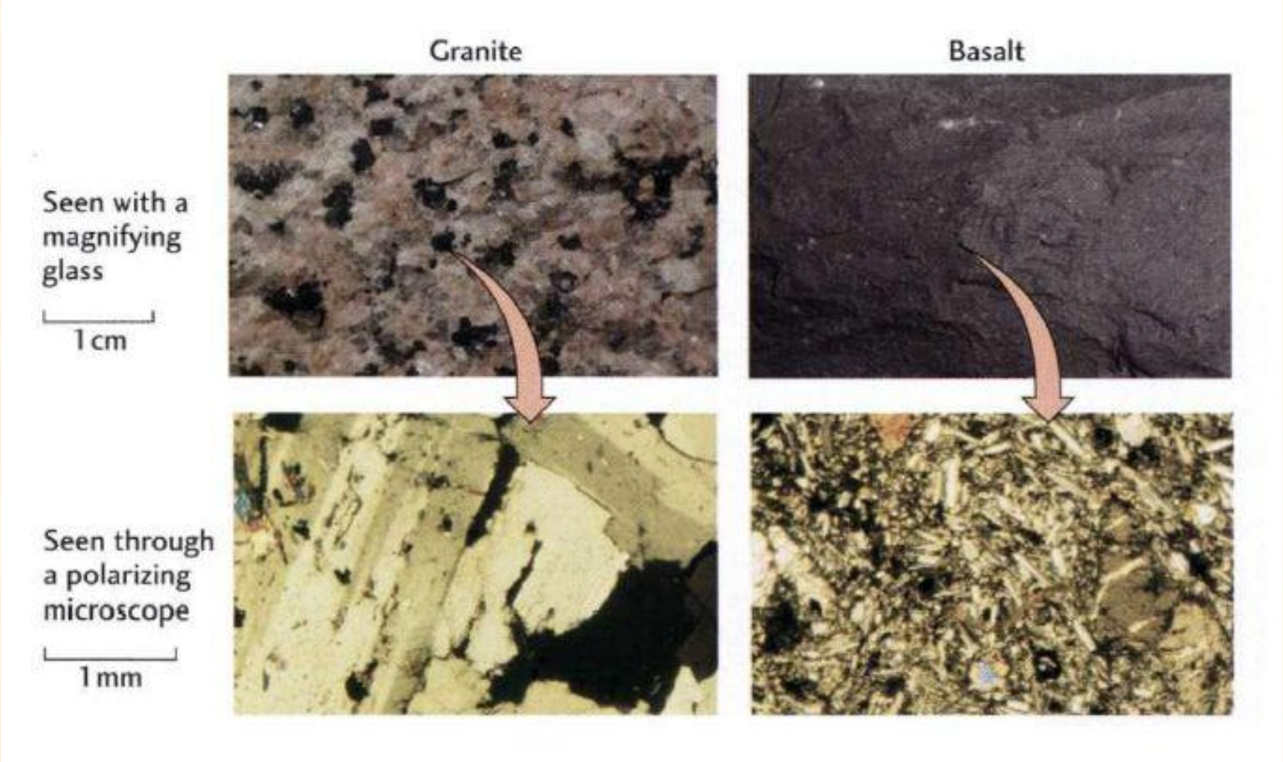
Igneous Rocks

A) Texture:

first division of igneous rocks is made on the differences in ***mineral crystal size*** easily see in the field.

Granite: is a ***Coarse-grained*** rock. It has separate crystals that are easily visible to the naked eye

Basalt: has ***Fine-grained*** crystals that are too small to be seen, even with the aid of magnifying lens.



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1) Volcanic Rocks:

Volcanic rocks are formed from lava during volcanic eruptions.

{*Lava* is the term that we apply to magma flowing out on the Surface}.

When lava:

- ***Cools rapidly:*** it forms either:
  - A) a finely crystalline rock or
  - B) a glassy one in which no crystals could be distinguished.
- ***Cools slowly:*** Larger crystals were present.

B) Laboratory study of crystallization: **The Ice Cube Experiment**

Crystallization process of water: molecules take up fixed positions in the solidifying crystal structure (no longer able to move freely).

All other liquids including magmas crystallize the same way

Igneous Rocks

2) Laboratory study of crystallization: **Magma**

- The first tiny crystals form a pattern.
- Other atoms or ions in the crystallizing liquid also attach themselves and the tiny crystals grow larger.

Time influence:

It takes time for the atoms or ions to "find" their correct places on a growing crystal

- large crystals form only if they have time to grow slowly.
- Tiny crystals form if a liquid solidifies very quickly (no time to grow).

Result: Large number of tiny crystals form simultaneously

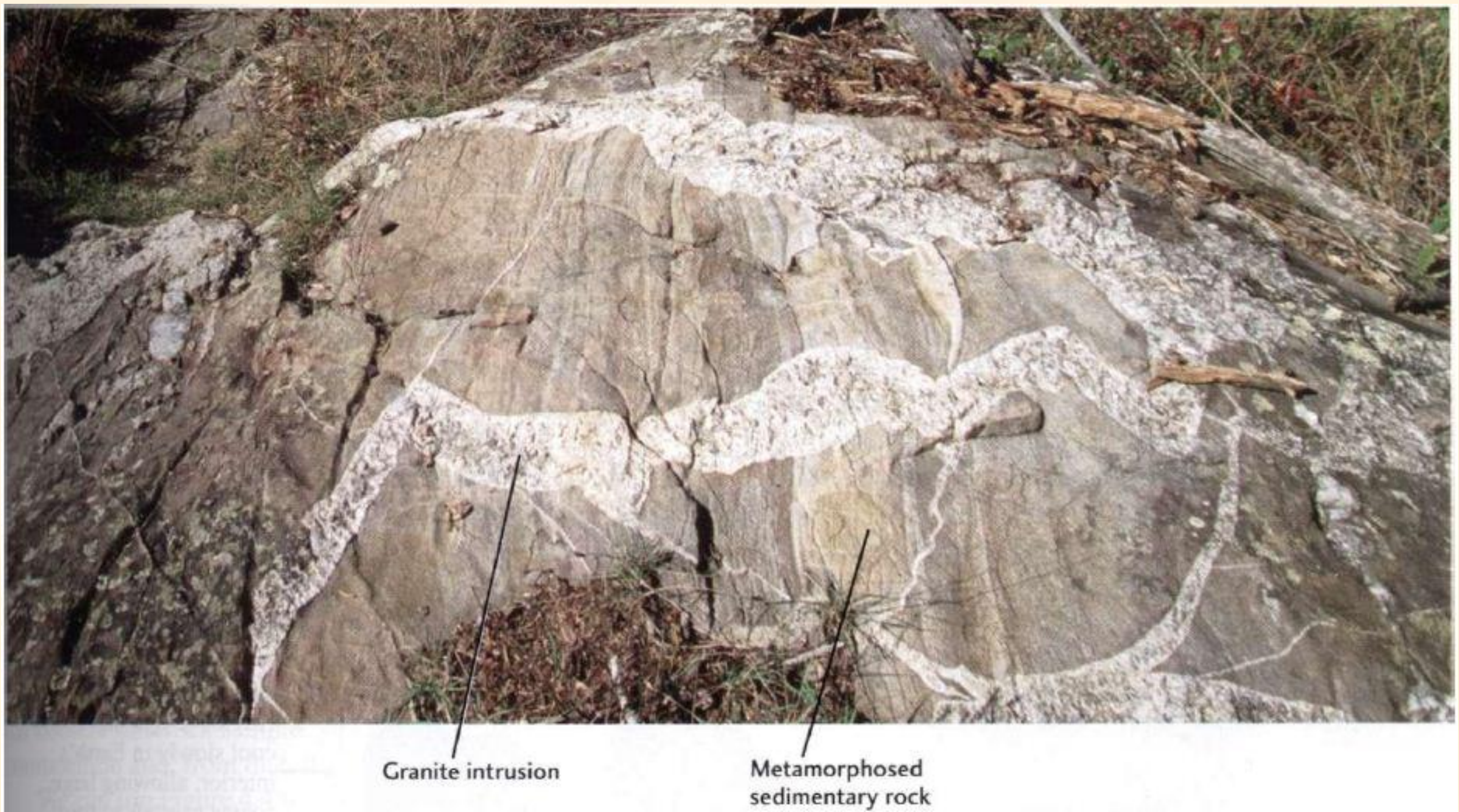
3) Granite: **Slow Cooling**

- Granites cut across and disrupt layers of sedimentary
- Can fracture and invade the sedimentary rocks (granite is forced into the fractures as a liquid).

Igneous Rocks

3) Granite: **Study surrounding sedimentary rocks**

- Minerals of sedimentary rocks in contact with the granite are different from those found in sedimentary rocks at some distance from the granite.
- The changes in the sedimentary rocks have resulted from great heat (from the granite liquid form)
- Granite is composed of interlocked crystals (evidence of slow crystallization)



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Huttons Proposal:

Granite forms from a hot molten material that solidifies deep in the Earth. The evidence is conclusive and no other explanation could accommodate all the facts.

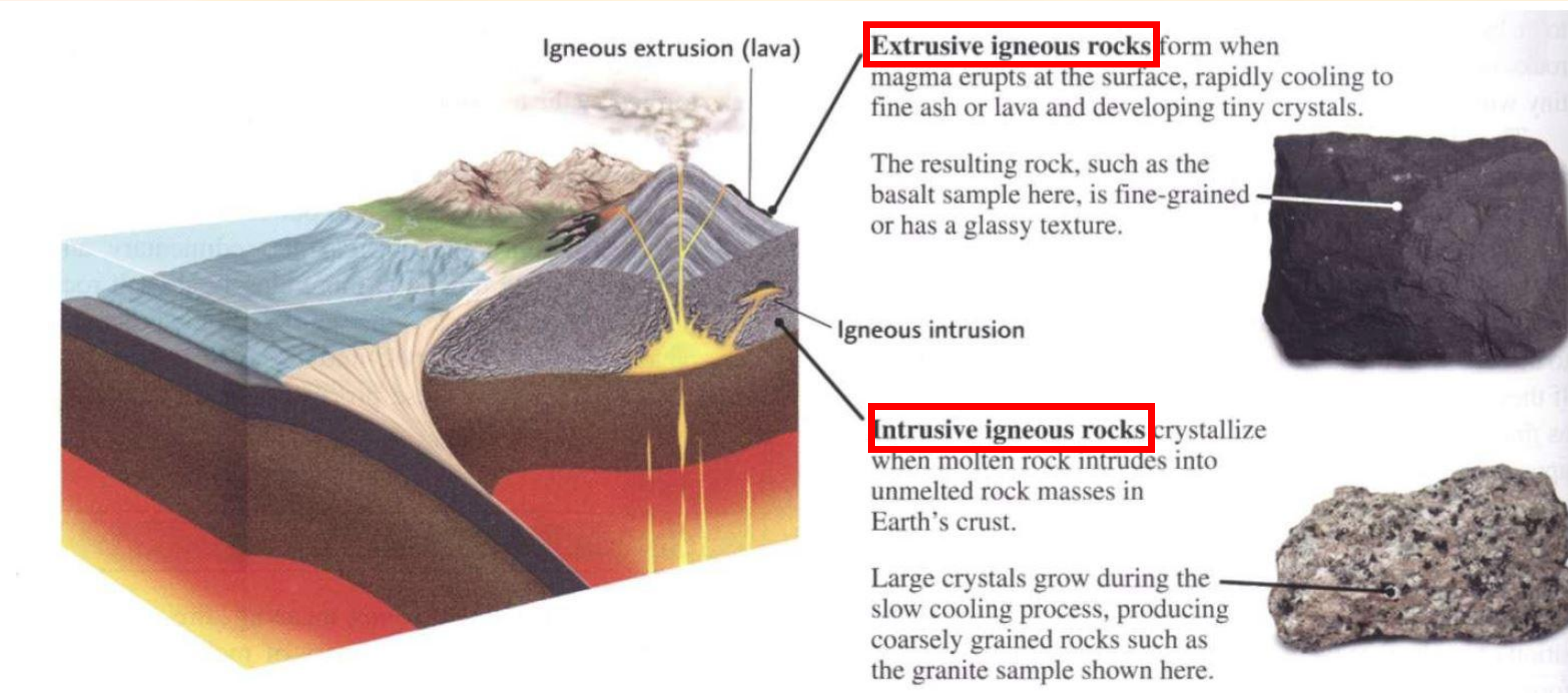
Today we recognize that:

Granite and many similar coarsely crystalline rocks were the products of magma that had crystallized slowly in the interior of the Earth.

Support the theory:

- **Intrusive Igneous rocks**
- **Extrusive Igneous rocks**

Igneous Rocks



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A) Intrusive Igneous rocks

Texture is ***linked to the rate and therefore the place*** of cooling.

Slow cooling of magma in Earth's interior allows adequate time for the growth of the interlocking of large coarse crystals that characterize intrusive igneous rocks.

An intrusive igneous rock: is one that has forced its way into surrounding rock.

Country rock: is the surrounding rock of an intrusive formation

B) Extrusive Igneous rocks

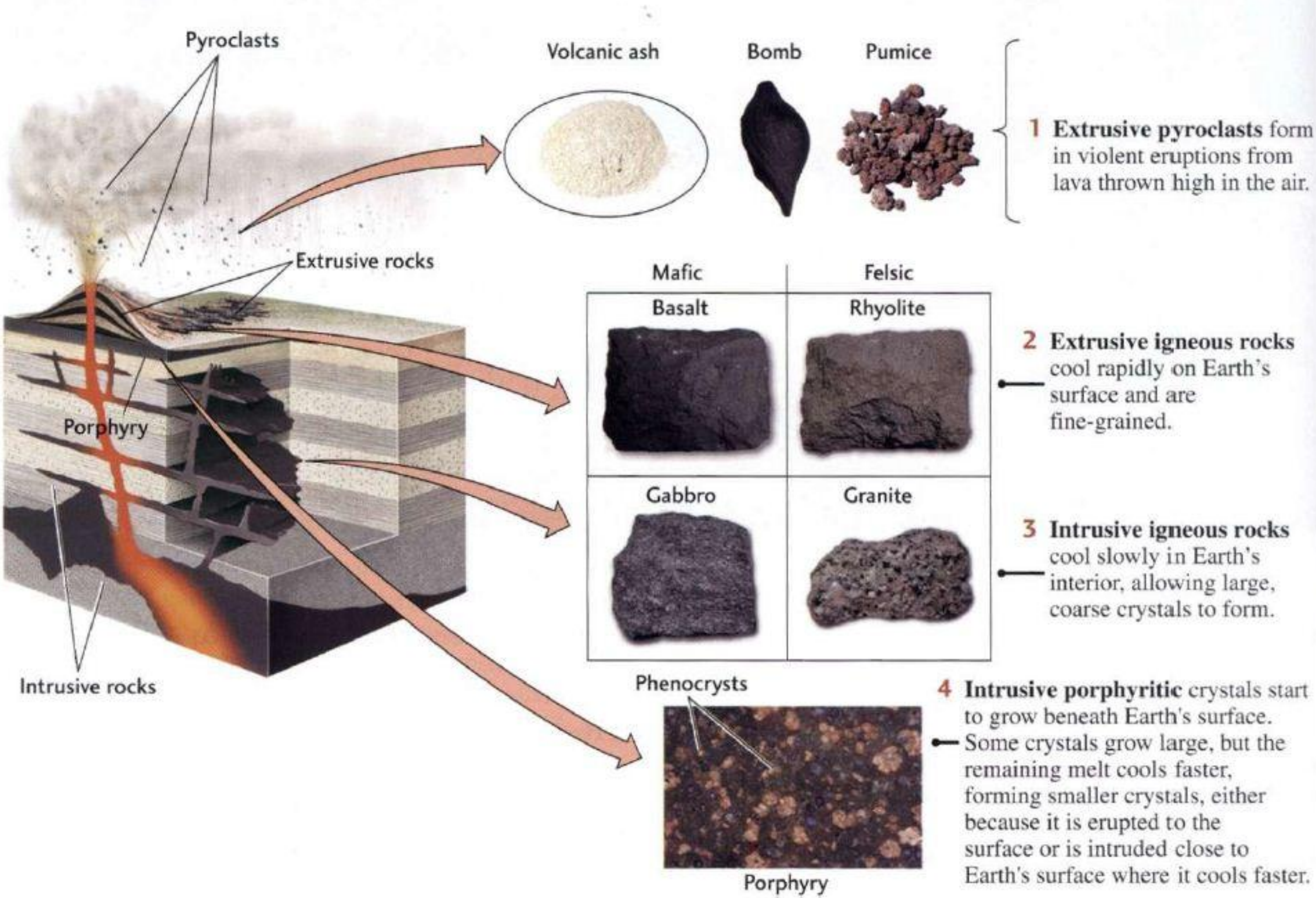
Rapid cooling at Earth's surface produces the finely grained texture or glassy appearance of the extrusive igneous rocks.

These rocks, form when lava or other material erupts from volcanoes. (volcanic rocks).

They fall into two major categories:

- Lavas
- Pyroclastic rocks
- Porphyry

Igneous Rocks



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Terminology:

Lavas: Are volcanic rocks formed from hot molten rock. They range in appearance from smooth and ropy to sharp, spiky, and jagged, depending on the conditions under which the rocks formed.

Pyroclastic rocks: *Are created from* violent eruptions.

- **Pyroclasts** form when broken pieces of lava are thrown high into the air.
- **Volcanic ashes** are the finest pyroclasts (extremely small fragments)
- **Bombs** are larger particles, hurled from the volcano
- **Tuffs** are all volcanic rocks lithified from these pyroclastic materials

Examples:

- **Pumice:** a mass of volcanic glass with high porosity.
- **Obsidian:** unlike pumice, it contains low porosity and so is solid and dense.

Porphyry: is an igneous rock with a mixed texture

- *large crystals* (phenocrysts) "float" in a predominantly fine crystalline (formed while magma was still below surface.
- Before crystals could grow, a volcanic eruption brought the magma to the surface, where it cooled quickly to a *finely crystalline mass*.

Igneous Rocks

B) Chemical and Mineral Composition:

Modern classifications now group igneous rocks according to their relative proportions of ***silicate minerals***

The silicate minerals (systematic series)

- Quartz,
- Feldspar (both orthoclase and plagioclase),
- Muscovite
- Biotite micas
- Amphibole
- Pyroxene
- Olivine

Felsic minerals are high in silica
Mafic minerals are low in silica.

Felsic = **Fel**dsbar + **Si**li**c**a
Mafic = **Ma**gnesium + **F**err**ic** "iron".

Mafic minerals: crystallize at higher temperatures (earlier in the cooling of a magma) than ***Felsic minerals***

Igneous Rocks

Classification of Igneous rocks:

A)identical in composition and differed only in texture.

Basalt: is an extrusive rock formed from lava.

Gabbro: has exactly the same mineral composition with basalt but forms deep in Earth's crust

Rhyolite and granite are identical in composition but differ in texture.

Intrusive + Extrusive Rocks

Form 2 chemically and mineralogically parallel sets of igneous rocks

Example:

From the classification model if we know:

The silica content of a rock sample,

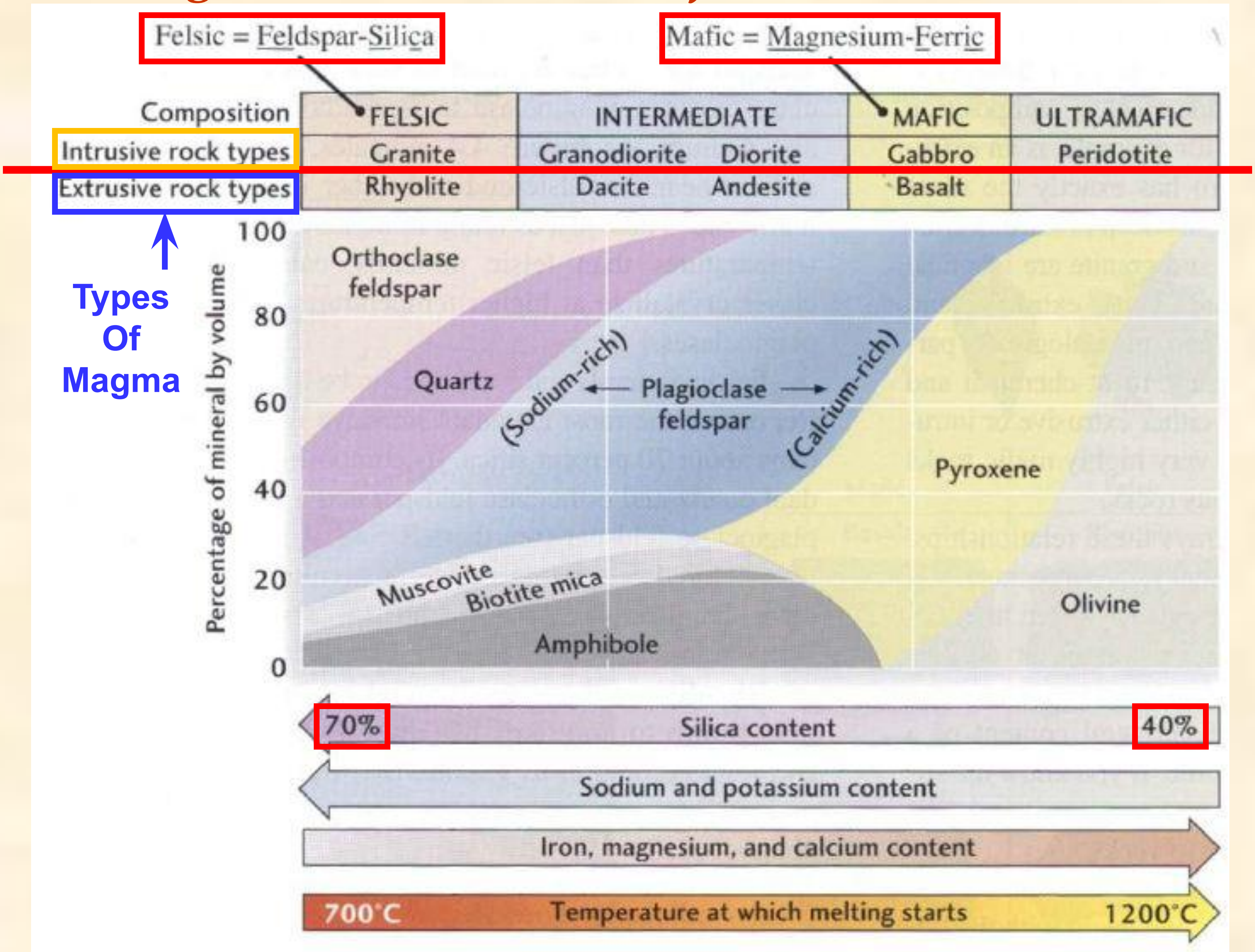
A)We can determine its mineral composition

B)From composition the type of rock

Rock sample: Granite

70% Silica / 6% Amphibole/ 3% Biotite / 5% Muscovite / 14% Plagioclase Feldspar / 22% Quartz / 50% Orthoclase Feldspar

Igneous Rocks (Classification model)



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Felsic Rocks Group

Are poor in **Fe** and **Mg** / rich in **Si** minerals.

Si rich minerals:

- Quartz,
- Orthoclase feldspar,
- Plagioclase feldspar.

Mafic minerals crystallize at higher temperatures than felsic

Felsic minerals and rocks tend to be light in color.

Granite: (intrusive igneous rock) contains 70% Si (pink/gray color).

Rhyolite: (extrusive igneous rock) equivalent to granite (brown to gray)

Difference = much more finely grained.

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Intermediate Igneous Rocks Group

Are the midway between the felsic and mafic igneous rocks.

These rocks are not:

- Rich in Si as the felsic rocks
- Poor as in the mafic rocks.

Intrusive

Granodiorite: Light-colored near felsic rock that looks something like granite. It is also similar to granite in having abundant quartz, but its predominant feldspar is plagioclase, not orthoclase.

Diorite: Dark-colored contains less Si and is dominated by plagioclase feldspar, with little / no quartz.

Extrusive

Dacite: (volcanic equivalent of Granodiorite)

Andesite: (the volcanic equivalent of Diorite)

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Mafic Igneous Rocks Group

Are high in pyroxenes and olivines.
Relatively poor in Si rich Mg/Fe, (dark colors).

Intrusive

Gabbro: (even less silica), is a coarsely grained with dark gray colour. It contains no quartz and only moderate amounts of calcium-rich plagioclase feldspar.

Extrusive

Basalt: (dark gray-black) is the fine-grained equivalent of gabbro. Is abundant igneous rock of the crust and underlies the entire seafloor.

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Ultramafic Igneous Rocks Group

Consist primarily of mafic minerals and contain less than 10% feldspar.

Peridotite: Very low Si of only about 45 %.

- Is a coarsely grained,
- Dark greenish gray rock
- Made up of olivine with smaller amounts of pyroxene.
- Dominant rocks of the mantle.
- Ultramafic rocks are rarely found as extrusives.
- Form at high temperatures (crystallyze at the bottom of a magma chamber)
- Rarely liquid and hence do not form typical lavas.

Cyprus is full of Peridotite (Ophiolites)

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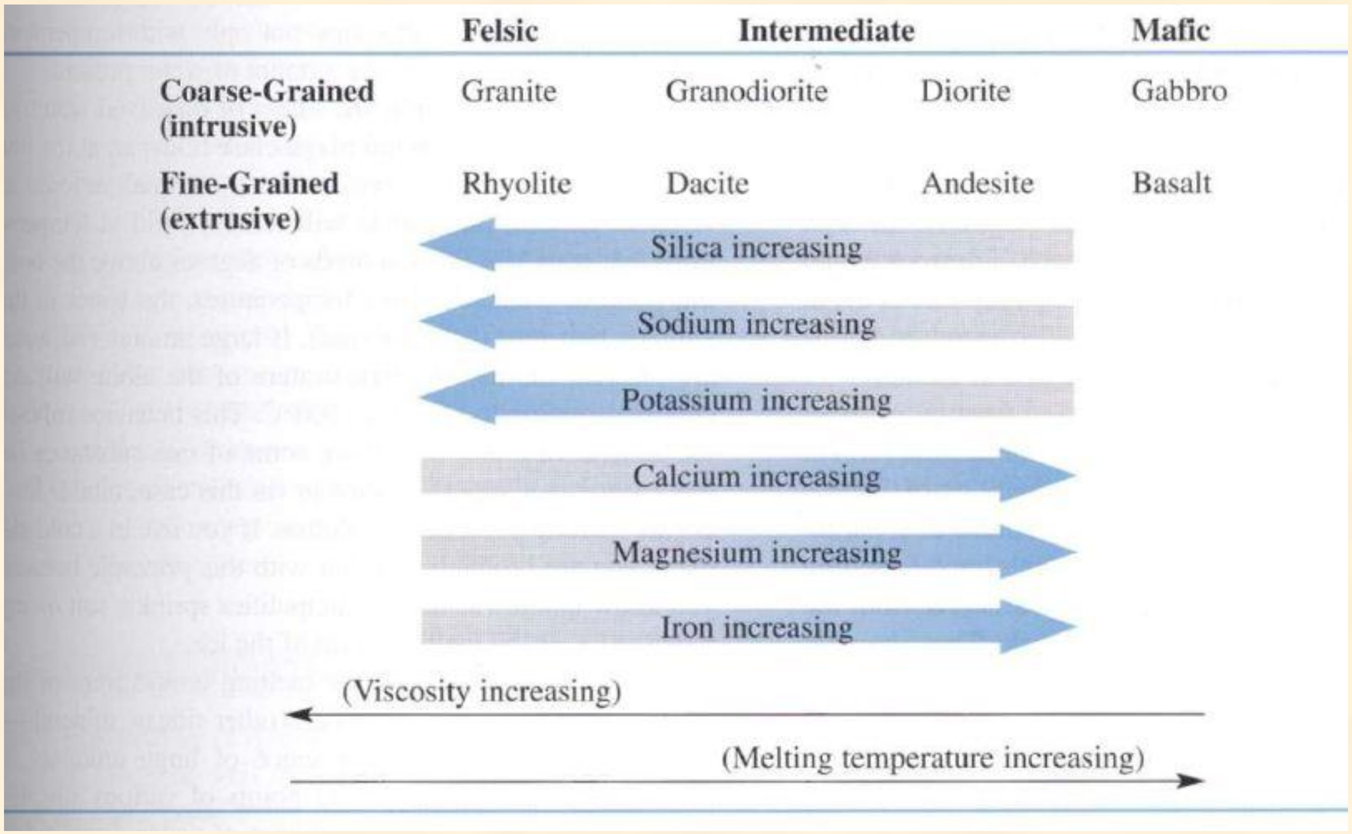
There is a strong correlation between:

- Mineralogy
- Temperatures

Crystallization or melting



Viscosity: The measure of a liquid's *resistance* to flow
Increases as silica content increases.

Igneous Rocks

How do Magmas Form?

Contradiction:

A) Earth transmits earthquake waves and the bulk of the planet is solid for thousands of km down to the core-mantle boundary.

B) The evidence of volcanic eruptions suggests that there must also be liquid regions where magmas originate.

How do we resolve this apparent contradiction?

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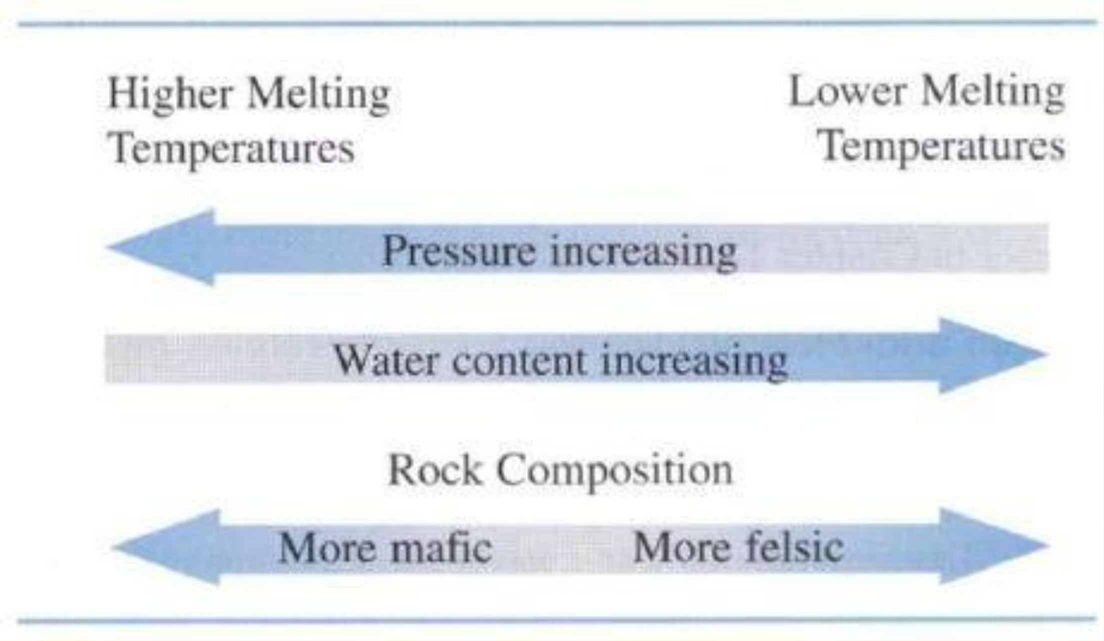
Rock melting (From laboratory experiments):

Rocks melting point depends on:

- Composition
- Conditions of temperature
- Conditions of pressure



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Rock melting (Temperature):

Observation

Discovered that a rock does not melt completely at any given temperature.

Understanding

Rocks undergo partial melting due to the minerals that compose them melt at different temperatures.

Process *of partial melting.*

- As temperatures rise, some minerals melt and others remain solid.
- If the same conditions are maintained at any given temperature,
- the same mixture of solid rock and melt is maintained.
- The fraction of rock that has melted at a given temperature is called a *partial melt.*

The *ratio of liquid to solid* in a partial melt depends

- Composition
- Melting temperatures of the minerals (make up the original rock)
- Temperature at the depth in the crust or mantle where melting takes place

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Rock melting (Temperature):

Partial melts (determines different kinds of magma)
Different temperatures
Different regions of Earth's interior.

Composition of a Partial Melt
Which only the minerals with the lowest melting points have melted may be significantly different from the composition of a completely melted rock.

Example
basaltic magmas that form in different regions of the mantle may have different compositions.

Explanation
Different magmas come from different proportions of partial melt

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Rock melting (Pressure):

Pressure increases with depth as a result of the increased weight of overlying rock.

Observation in laboratory

Melting rocks under various pressures, higher pressures led to higher melting temperatures.

Result

rocks that would melt at surface would remain solid at the same temperature in the interior.

The effect of pressure explains why rocks in most of the crust and mantle do not melt.

Rock can melt only

- Mineral composition
- Temperature
- Pressure conditions are right.

Decompression melting

As mantle material rises, the pressure decreases below a critical point and solid rocks melt spontaneously without any additional heat.

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Rock melting (Water content):

Observation

Water is present in some magmas. The compositions of ***partial*** and ***complete melts*** vary with:

- Temperature
- Pressure
- Water content.

General rule

- Dissolving one substance in another lowers the melting point of the solution
- Melting temperature of rocks drop considerably in the presence of large amounts of water.

Important knowledge of melting.

Water content is a significant factor in determining the *melting temperatures of mixtures of sedimentary* (large volume of water) and other rocks.

Igneous Rocks

Formation of Magma Chambers:

Physical understanding:
Substances are less dense in liquid form than in the solid form.

Density
Melted rock is lower than a solid rock of the same composition.

Understanding
Volume of melt would weigh less than the same volume of solid rock.

Formation (buoyancy driven flows)

- The less dense melt moves, in upward layers and rises to the surface.
- Being liquid, the partial melt moves slowly through pores and along the boundaries between overlying rocks.
- Hot drops of melted rock that move upward mix with other drops, gradually forming larger pools of molten rock within Earth's interior.

The ascent of magmas may be slow or rapid.
Rates of 0.3 – 50 m/year
Periods of 10.000 or even 100.000 of years

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Formation of Magma Chambers:

Magma chambers:

- Magma-filled cavities in the lithosphere that form as rising drops of melted rock push aside surrounding solid rock.
- Encompasses a volume as large as *several cubic kilometers*.
- Are *large, liquid-filled cavities* in solid rock, which expand as more of the surrounding rock melts or as liquid migrates through cracks and other small openings between crystals.
- Magma chambers *contract as they expel magma* to the surface in eruptions.
- Magma chambers exist because earthquake waves can show us the *depth, size, and general outlines of the chambers* underlying some active volcanoes

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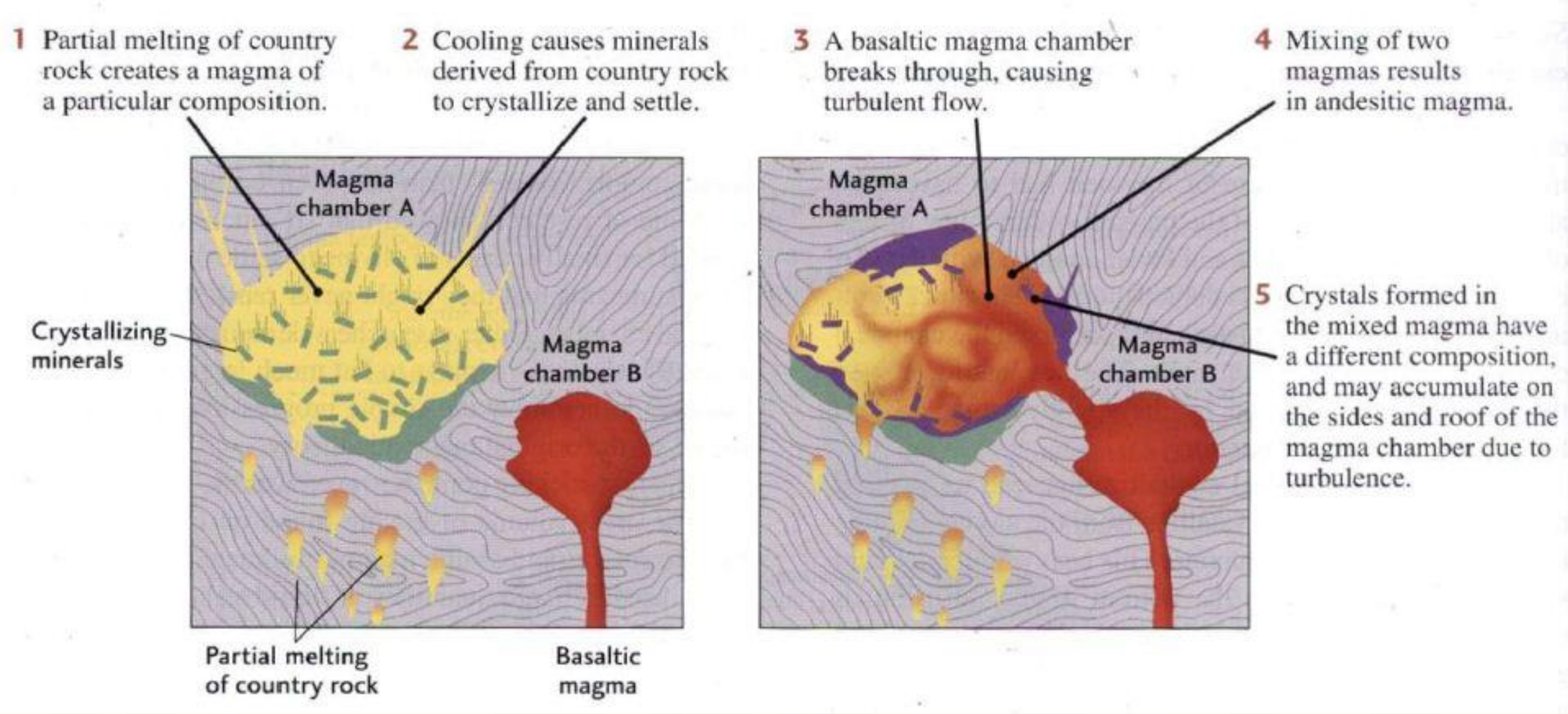
Magma chambers:



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Magma Formation:

Field +Laboratory observation

A) Volcanoes (land + under the sea) provide molten rocks. Give information about *where magmas are located*.

B) Deep drill records of temperatures from holes and mine shafts. This shows that the *temperature* of Earth's interior *increases with depth*.

Result

Estimation of the rate at which temperature rises as depth increases.

Example

A) Temperatures recorded at a given depth in some locations are much higher than other locations.

B) These indicates that some parts of Earth's (mantle + crust) are hotter than other parts

Realization

A) Various kinds of rocks can solidify from magmas formed by partial melting.

B) Increasing temperatures in the Earth's interior could create magmas

Continue

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Magmatic Differentiation:
Discussion about rock melting

Questions?

- What accounts for the variety of igneous rocks?
- Are magmas of different chemical compositions made by the melting of different kinds of rocks?
- Do some processes produce a variety of rocks from an originally uniform parent material?

Answer = Laboratory **<< *Birth of Magmatic Differentiation* >>**

1) Production of mixture of chemical elements in proportions that simulate compositions of natural igneous rocks
2) Melt these mixtures in high-temperature furnaces.
3) As the melts cool and solidify, we carefully observe and record

- The temperatures at which crystals form
- The chemical compositions of those crystals

***Magmatic Differentiation* =** process that rocks of varying composition can arise from a uniform parent magma.

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Magmatic Differentiation:
Occurs because different minerals crystallize at different temperatures.

Crystallization process:

- The *composition of the magma changes* as it is depleted of the chemical elements that form the crystallized minerals.
- First *minerals to crystallize* are the ones that were *the last to melt* from partial melting.
- This initial crystallization withdraws chemical elements from the melt and *changes* the magma's *composition*.
- Repeated crystallization of minerals that had melted at the next lower temperature range during the partial melting *changes further* the chemical *composition* until complete solidification.
- This is how the *same parent magma can give different igneous rocks*.

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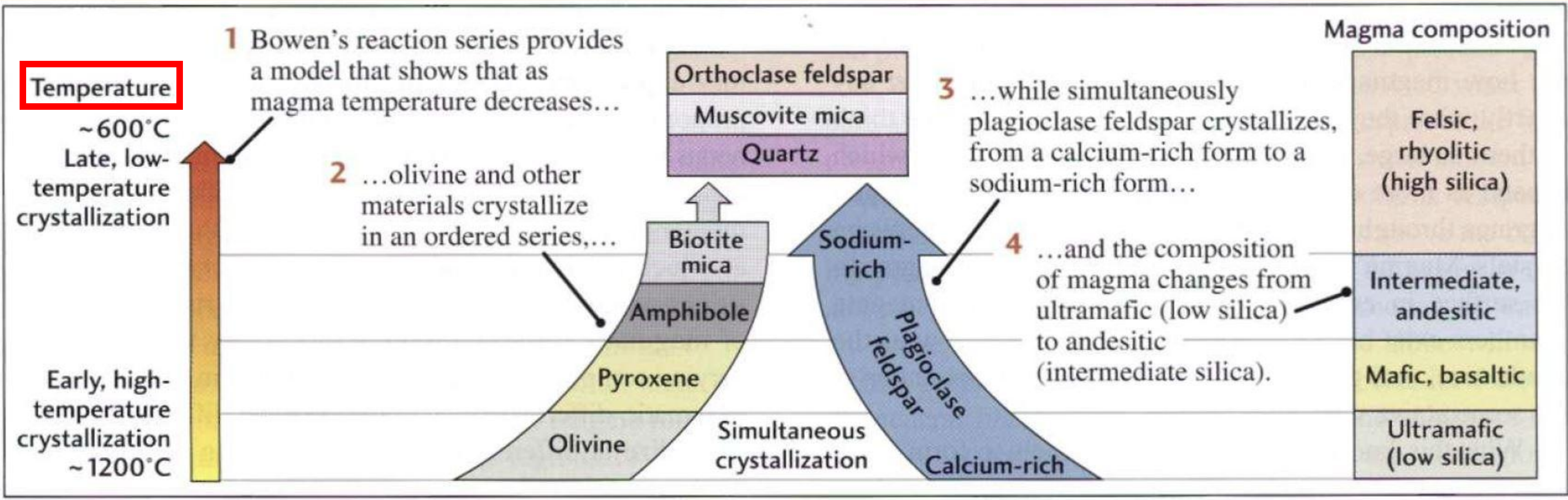
Fractional Crystallization:

Process by which the crystals formed in a cooling magma are segregated from the remaining liquid.

Scenario

- Crystals formed in a magma chamber settle to the chamber's floor and are thus removed from further reaction with the remaining liquid.
- The magma then migrates to new locations, forming new chambers.
- Crystals that had formed early segregate from the remaining magma, which continues to crystallize as it cools.

Bowen crystallization model



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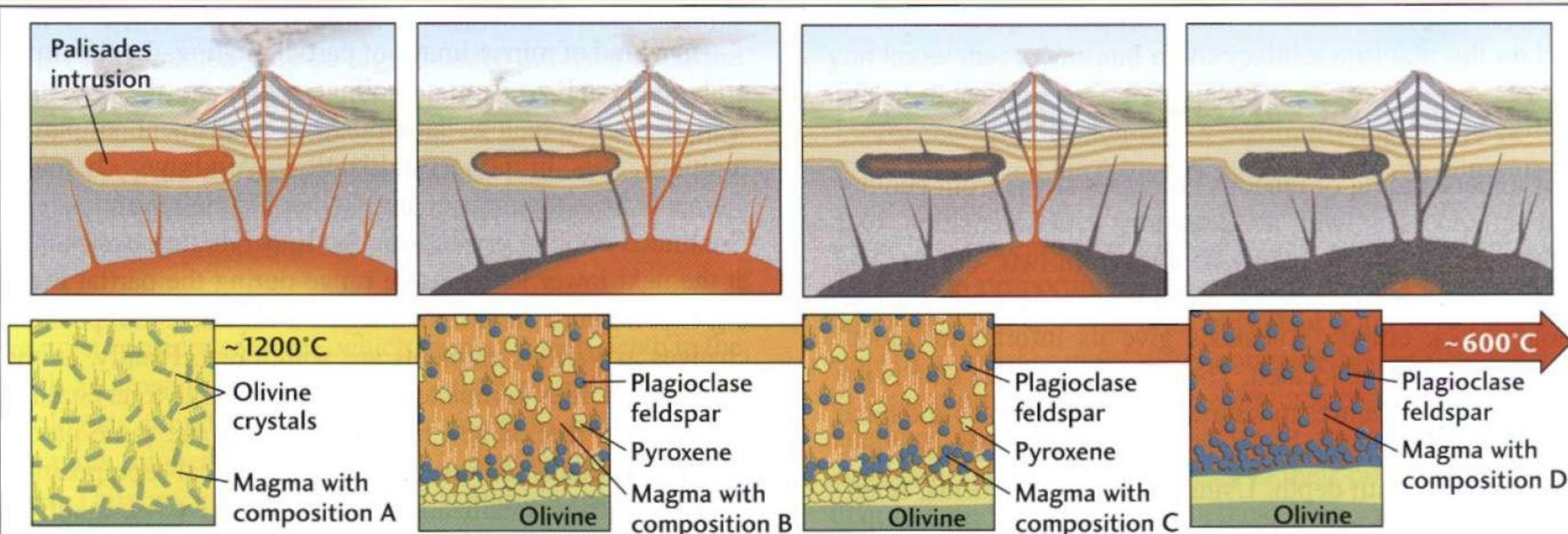
Example of Fractional Crystallization : ***Palisades Intrusion***



5 Olivine crystallizes first, leaving magma with composition A.

6 Pyroxene and plagioclase feldspar then crystallize, again changing the magma composition…

7 …and because the pyroxene settles out first, a gradient of pyroxene and feldspar is established, leaving a magma with composition C.

8 Finally, pyroxene is entirely crystallized and plagioclase feldspar continues to crystallize from magma with composition D.

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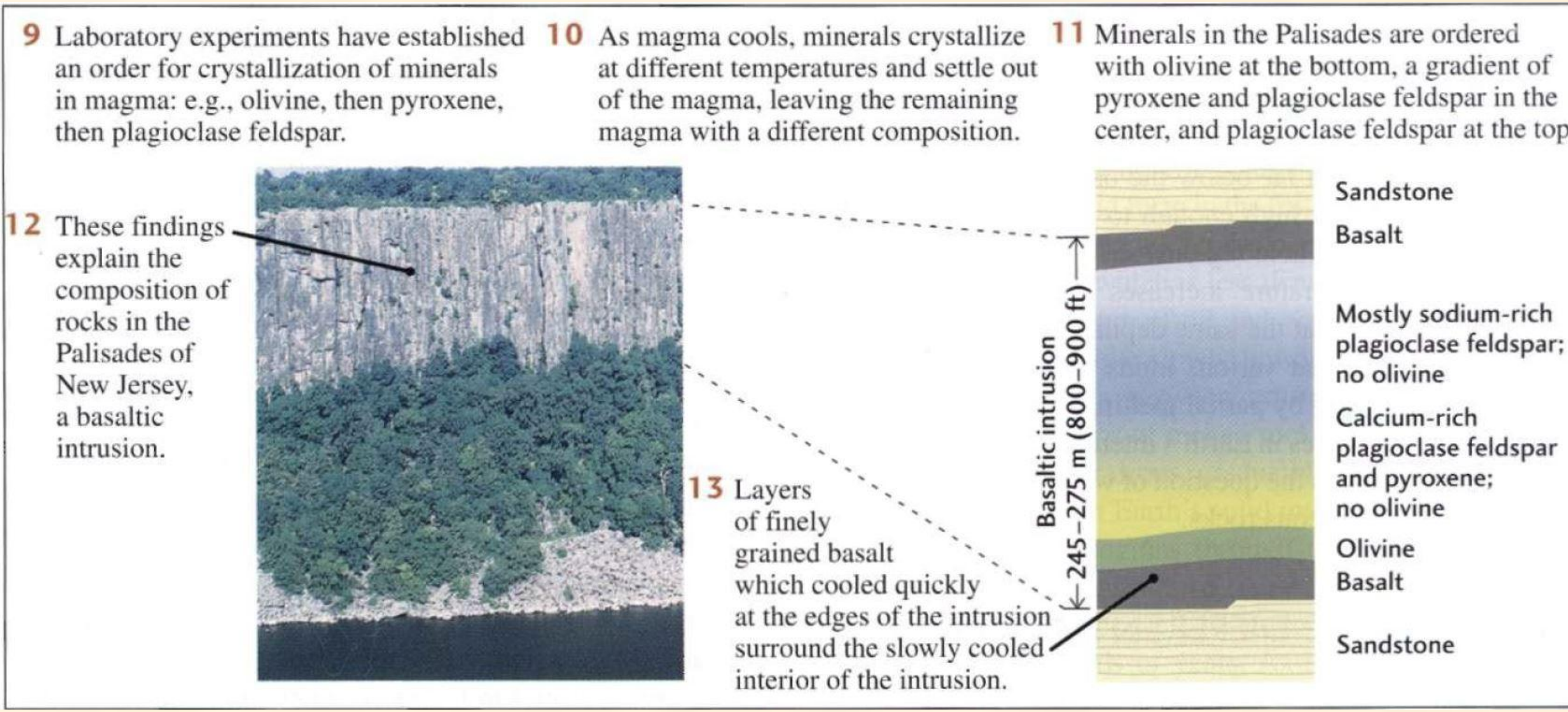
Evidence of Fractional Crystallization : ***Palisades Intrusion***



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Magmatic Differentiation and Types of Magma

Magma types:

A) Basaltic (Mafic)
B) Andesitic/Dacitic (Intermediate)
C) Rhyolitic (Felsic)

Idea of magmatic differentiation:

- ***Basaltic magma*** would gradually cool and differentiate into a cooler, more silicic melt by fractional crystallization.
- The ***early stages*** of this differentiation would produce ***Andesitic*** magma, a) Erupt to form andesitic lavas or
  b) Solidify by slow crystallization to form Diorite intrusives.
- Intermediate stages would make magmas of ***granodiorite composition***.
- Process continues, the ***late stages*** would form ***Rhyolitic lavas*** and Granite intrusions


Felsic = Feldspar-Silica
Mafic = Magnesium-Ferric

Composition	FELSIC	INTERMEDIATE		MAFIC	ULTRAMAFIC
Intrusive rock types	Granite	Granodiorite	Diorite	Gabbro	Peridotite
Extrusive rock types	Rhyolite	Dacite	Andesite	Basalt	

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Dispute

Magmatic differentiation is a more complex process (Still under divelopment)

Open questions:

A) Much time is needed for small crystals of olivine to settle through viscous magma that they might never reach the bottom of a magma chamber.

B) The source of granite (great volume on Earth) not formed from basaltic magmas and by magmatic differentiation.

Reason:

Large quantities of liquid volume are lost by differentiation. To produce the existing amount of granite, a volume of basaltic magma 10 times the size of a granitic intrusion would be required

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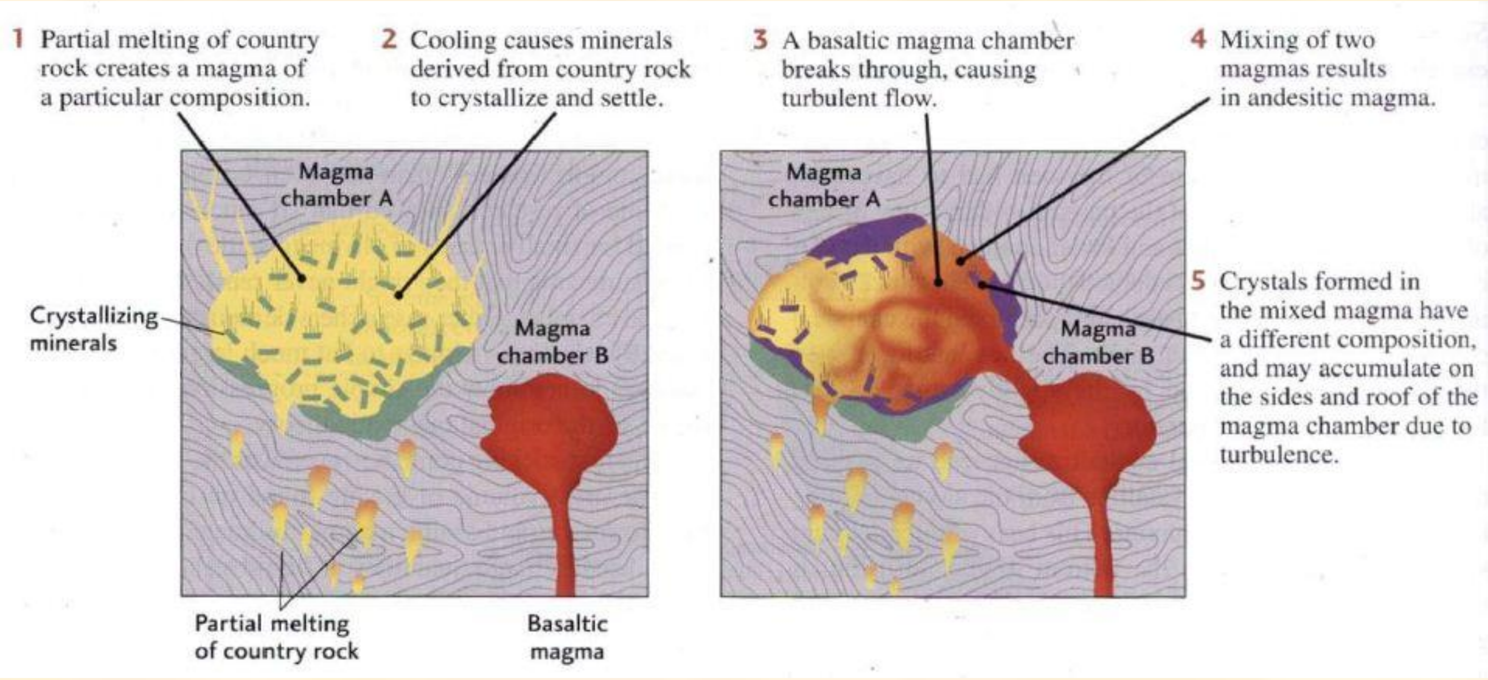
Granitic Magma

Source rocks of the upper mantle and crust is responsible for the variation in magma composition:

1. Rocks in the ***upper mantle*** might partially melt to produce ***basaltic*** magma.
2. A ***mixture of sedimentary*** rocks and ***basaltic*** oceanic rocks (subduction zones) might melt to ***form andesitic magma***.
3. A melt of ***sedimentary, igneous, and metamorphic*** continental crustal rocks might produce ***granitic magma***



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Forms of Magmatic Intrusions

Limitations:

- Cannot directly observe the shapes of intrusive igneous rocks formed when magmas intrude the crust.
- We deduce their shapes and distributions only by observing them after they have been uplifted and exposed by erosion
- Indirect evidence of current magmatic activity from earthquake waves.
- Cannot reveal the detailed shapes or sizes of intrusions arising from those magma chambers.
- Measurements of temperatures in deep drill holes reveal a crust much hotter than normal, which may be evidence of an intrusion at depth.

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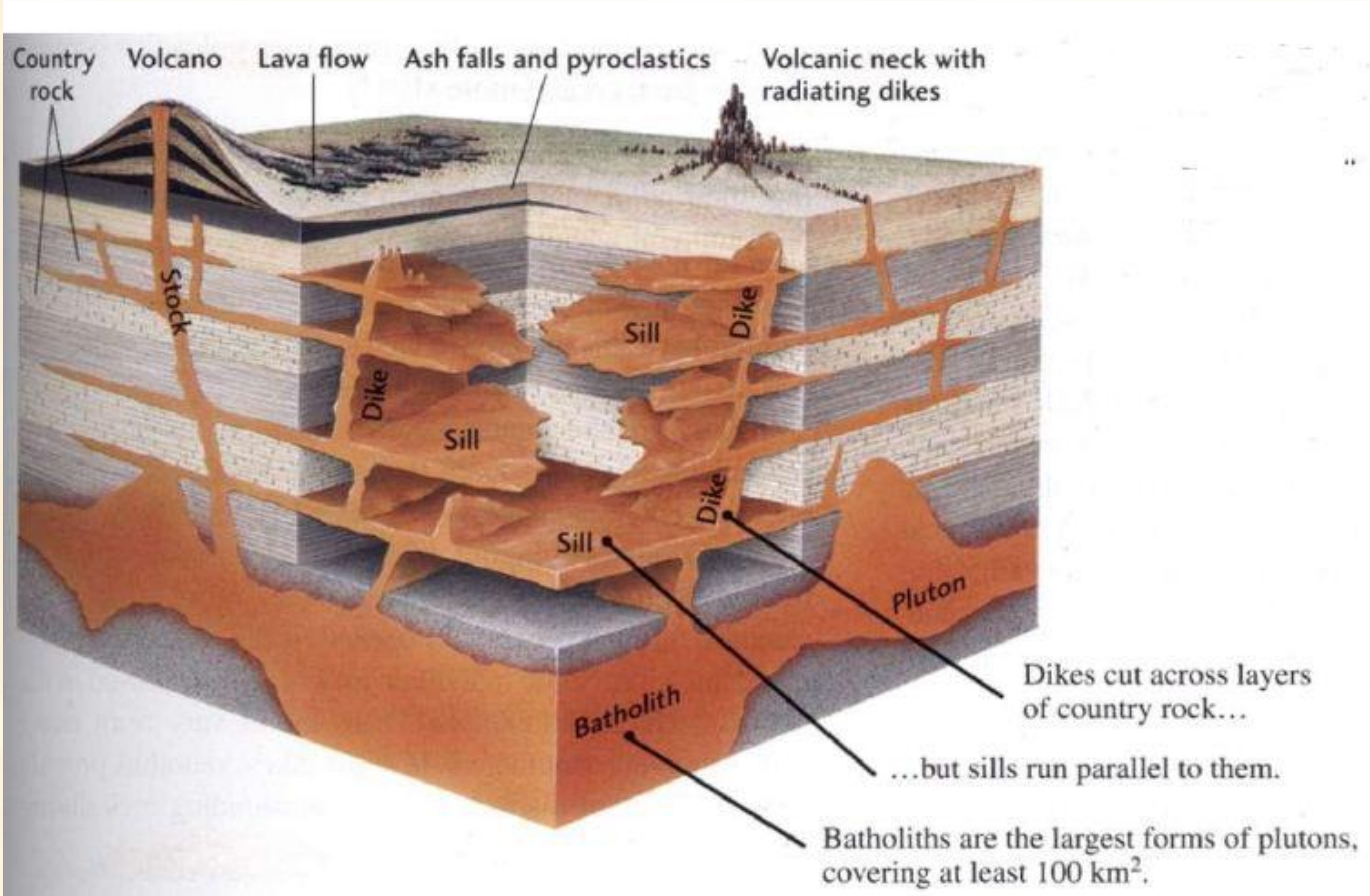
Types of representative Igneous Rocks

A)Volcanic (Extrusive rocks)

B)Plutons (Intrusive rocks)

Types of Rocks :

Plutons, Sills, dikes, veins



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Plutons

- Are large igneous bodies formed at depth in the crust.
- They range in *size 1km^3* to *100 km3*.
- Study these large rock bodies when *uplift and erosion* uncover them Plutons are highly *variable, in size and shape* (different ***ways magma makes space*** for itself).

Observations

- Most magmas intrude at depths greater than 8 to 10 km.
- At these depths, few holes or openings exist. (great pressure would close them).
- upwelling magma overcomes that pressure

Physical process

Magma rising makes space for itself in three ways (*magmatic sloping):*

1. Wedging open the overlying rock. As magma lifts great weight, it fractures the rock, penetrates the cracks, and flows into the rock. Overlying rocks bow up during this process.

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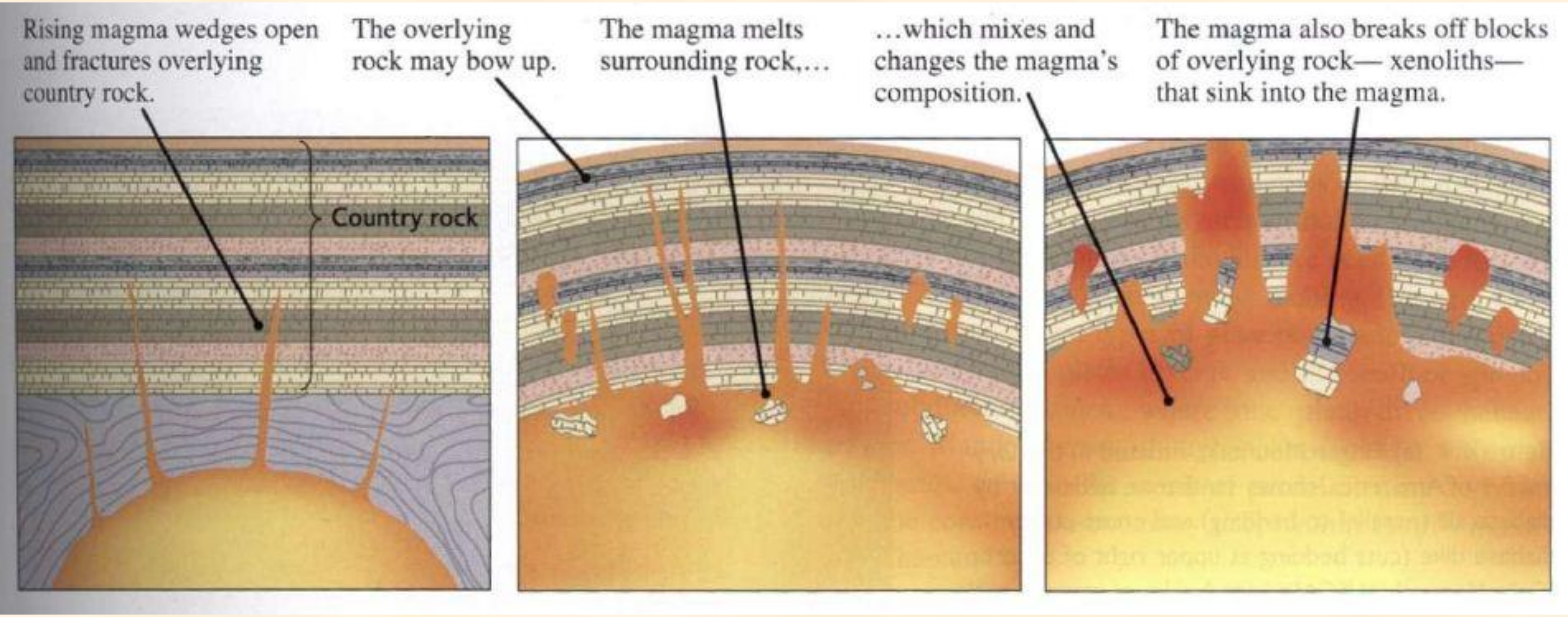
2. Breaking off large blocks of rock. Magma pushes its way upward by breaking off blocks of the invaded crust (*xenoliths),* sink into the magma, melt, and blend into the liquid, in some places changing the composition of the magma.

3. Melting surrounding rock. Magma also makes its way by melting walls of country rock.



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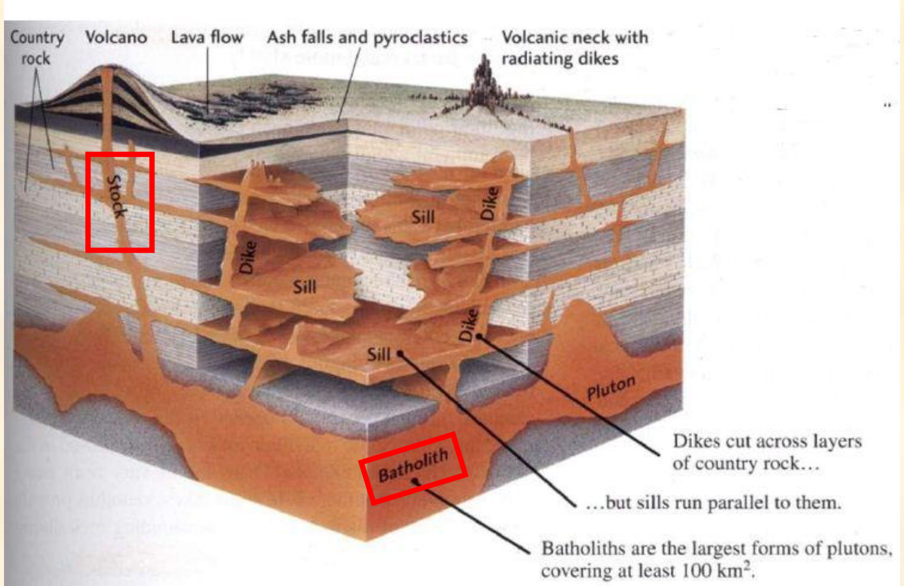
Plutons: Batholiths

- The largest plutons
- Great irregular masses of coarse-grained igneous rock that by definition cover at least 100 km^2.
- Are found in the cores of tectonically deformed mountain belts.
- are thick, horizontal, sheetlike or lobe-shaped bodies
- Their bottoms may extend 10 to 15 km deep.
- The coarse grains of batholiths result from slow cooling at great depths.

Plutons: Stocks

Are the rest of the plutons, similar but smaller.

Discordant intrusions: rocks that cut across the layers of the country rock that they intrude. (batholiths / stocks)



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Sills and Dikes:

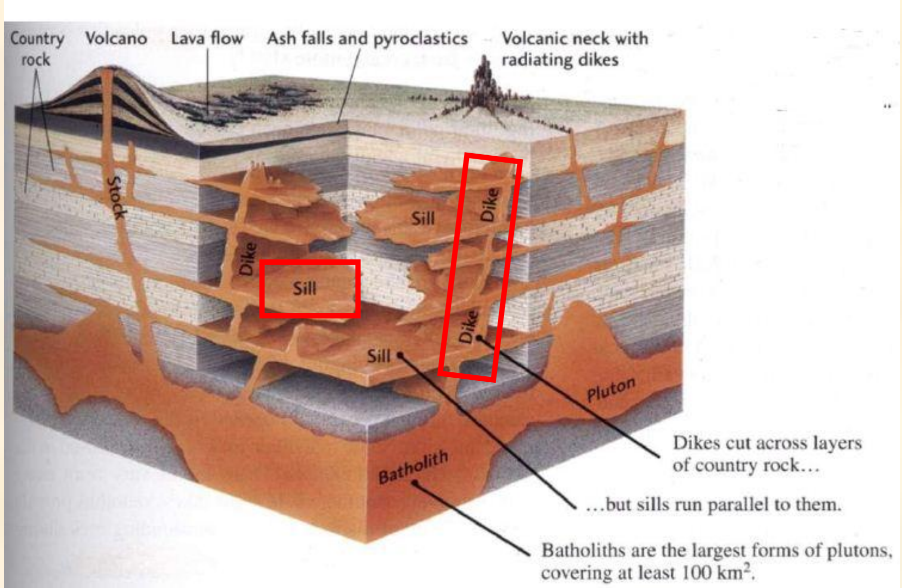
Are similar to plutons (smaller) and have a different relationship to the layering of the surrounding intruded rock.

Sill: is a sheet like body formed by the injection of magma between parallel layers of pre-existing bedded rock**.**

Sills range in thickness from cm to 100m and they can extend over considerable areas.

The 300-m-thick Palisades intrusion is a large sill.

Concordant intrusions: rocks that their boundaries lie parallel to these layers, whether or not the layers are horizontal (Sills).



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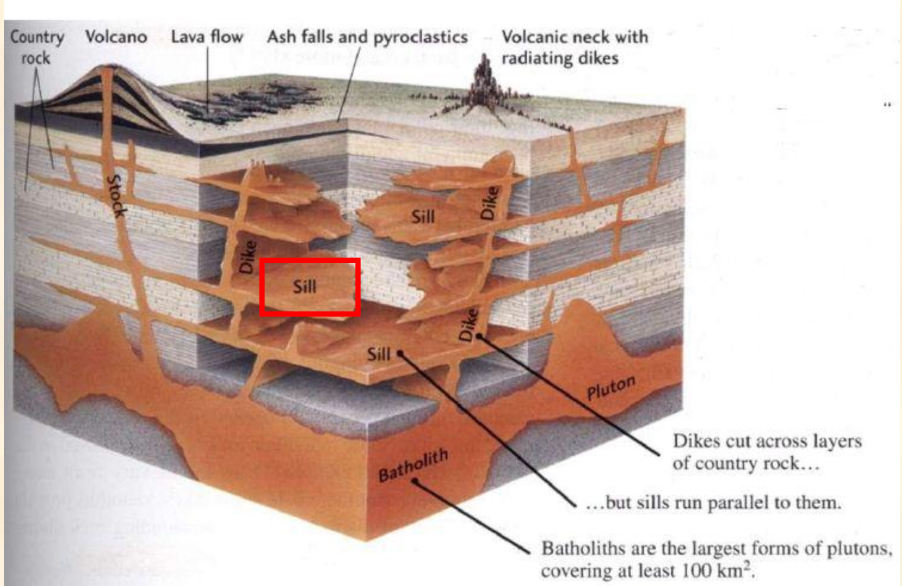
Dikes:

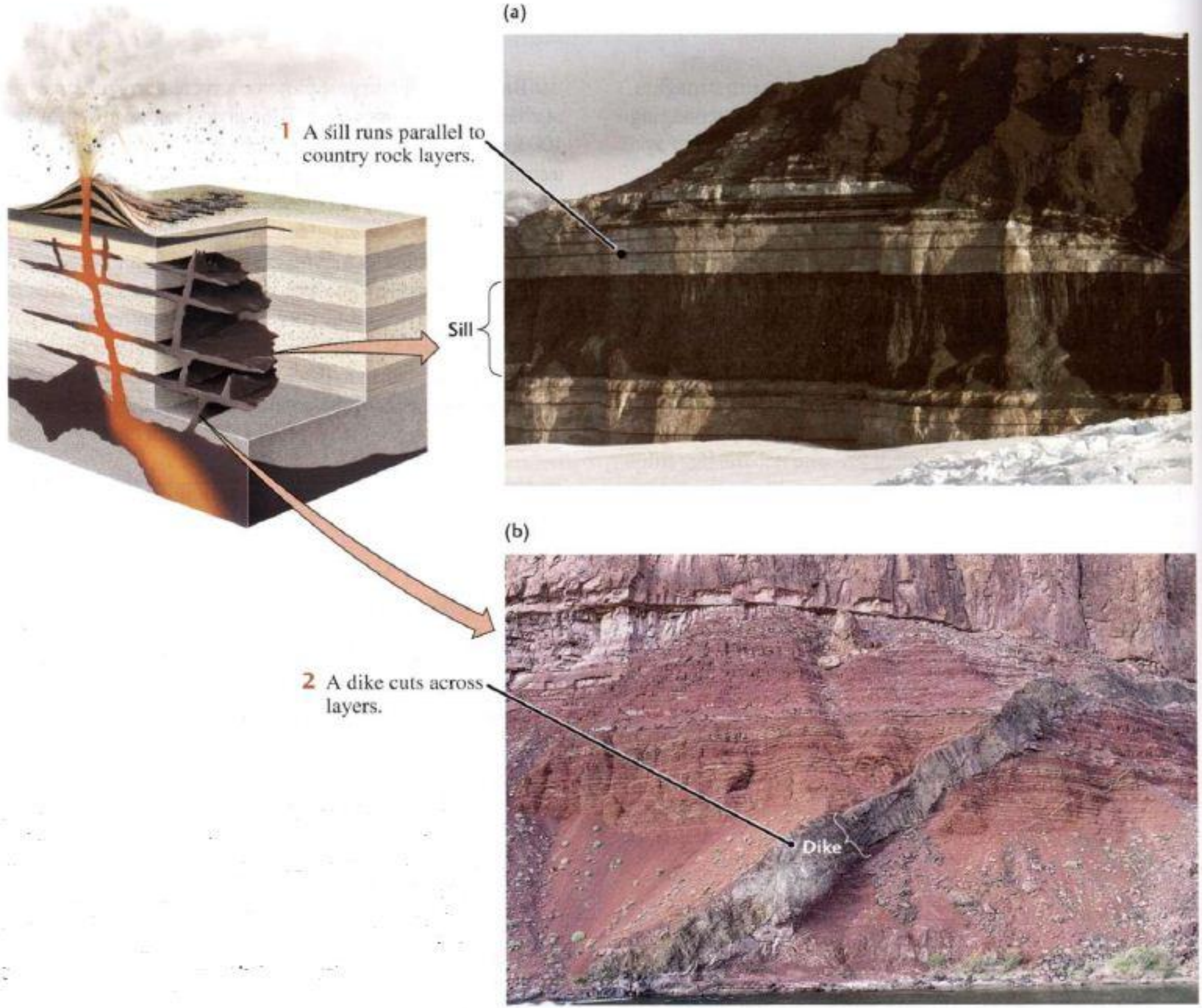
Are the major route of magma transport in the crust. They are like sills (sheet like igneous bodies) but cut across layers of bedding in country rock and so are discordant.

Some dikes can be followed in the field for 10 km’s.
Widths vary from m-cm.
Dikes rarely exist alone, hundreds or thousands of dikes are found in a region that has been deformed by a large igneous intrusion.
The texture of dikes and sills varies.

A) Many are coarsely crystalline, with an appearance typical of intrusive rocks.

B) Many others are finely grained and look much more like volcanic rocks. (texture = rate of cooling).




(a)
1 A sill runs parallel to country rock layers.
Sill
(b)
2 A dike cuts across layers.
Dike

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Veins (Pegmatites):

- Are deposits of minerals found within a rock fracture that are foreign to the host rock.
- They may be a few mm to several m across, and they tend to be 10m to km long or wide.
- Veins of extremely coarse-grained granite cutting across a much finer grained country rock are called **Pegmatites.**
- They crystallized from water-rich magma in the late stages of solidification.
- Pegmatites provide ores of many rare elements, such as lithium and beryllium.

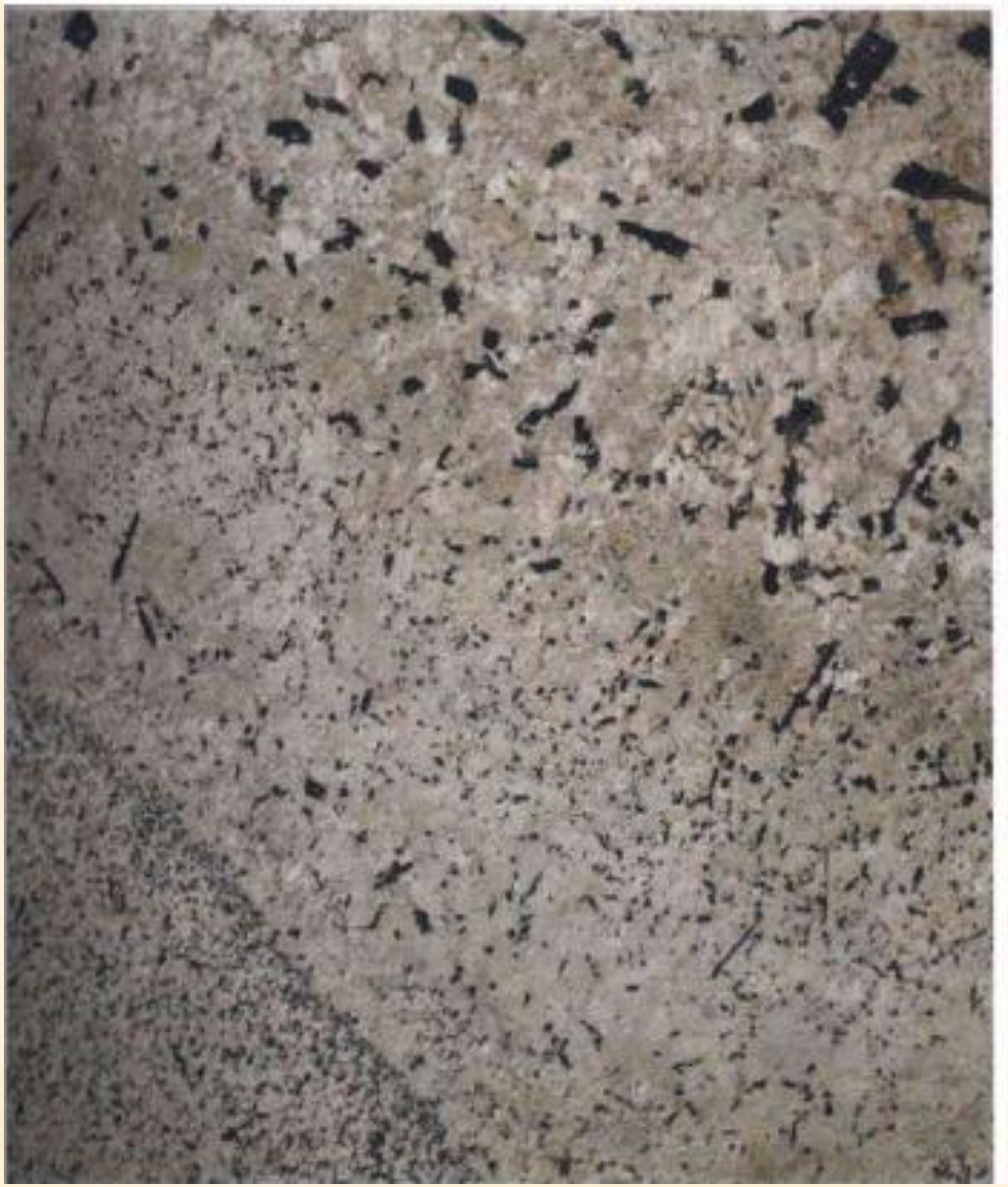
Hydrothermal veins

Filled with minerals that contain large amounts of chemically bound water and are known to crystallize from hot-water solutions.

Groundwaters: originate as rainwater seeps into the soil and surface rocks. Hydrothermal veins are abundant along mid-ocean ridges. seawater infiltrates cracks in basalt and circulates down into hotter regions, emerging at hot vents on the seafloor

Igneous Rocks

Veins (Pegmatites):



Thanks
For
Your Attention

Questions?