

IGNEOUS ROCKS

A red school bus is partially submerged in a dark, jagged, and textured volcanic lava flow. The lava flow is composed of many sharp, angular fragments and has a rough, crystalline appearance. The bus is positioned in the lower center of the frame, with its front end and part of its side visible above the lava. The background is a vast expanse of the same dark, jagged lava flow, extending to the horizon. The overall scene is a dramatic illustration of the power of igneous rocks.

★ Where do igneous rocks form?

At ocean-ocean convergent boundaries, magmas originating from fluid-induced melting of the mantle give rise to volcanic island arcs erupting mostly basaltic lavas.

Magmas formed at ocean-continent convergent boundaries are mixtures of basalts from the mantle, remelted felsic continental crust, and materials melted off the top of the subducted plate. They give rise to volcanoes erupting andesitic lavas.

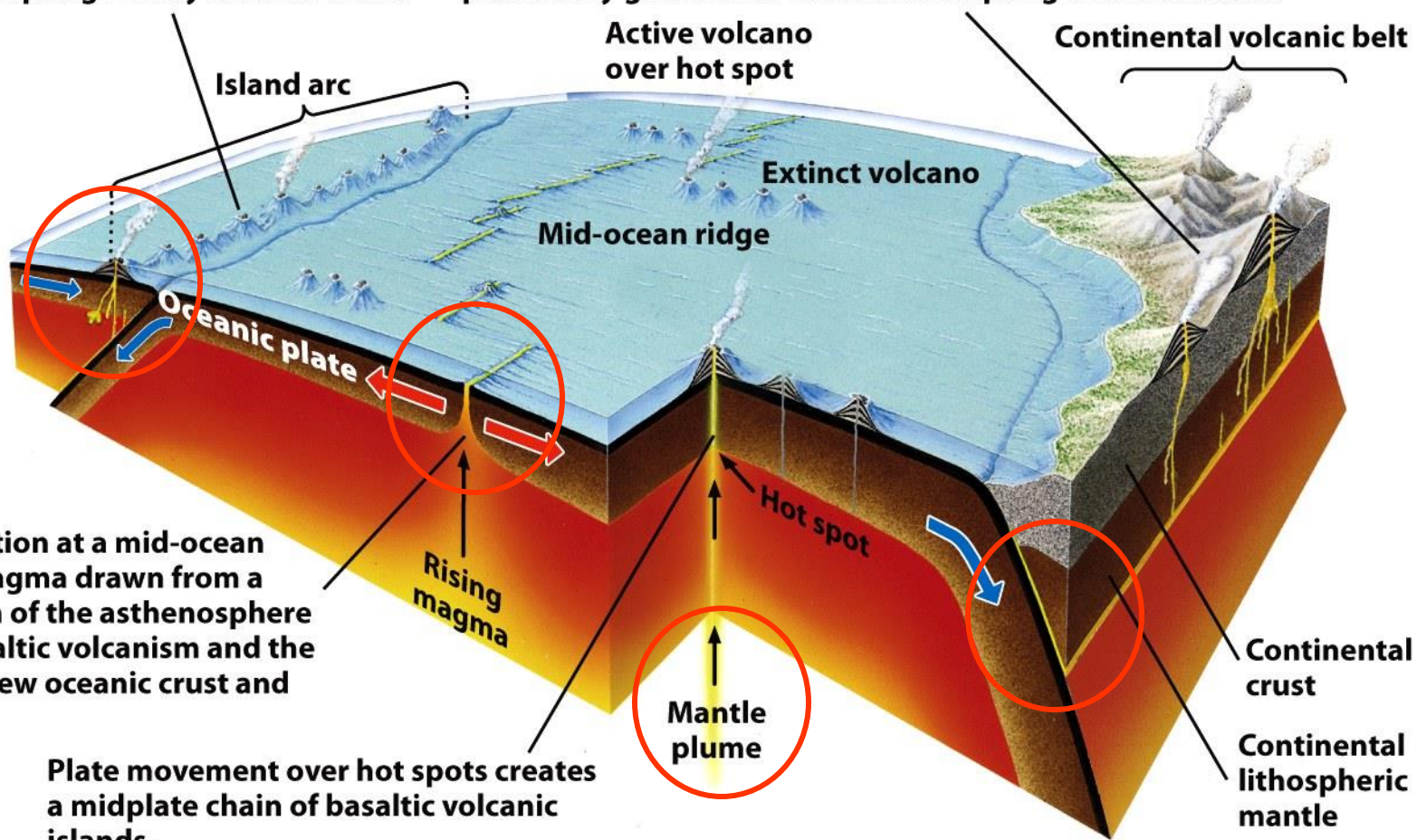


Plate separation at a mid-ocean ridge and magma drawn from a broad region of the asthenosphere result in basaltic volcanism and the creation of new oceanic crust and lithosphere.

Plate movement over hot spots creates a midplate chain of basaltic volcanic islands.

★ Classification of igneous rocks

1. TEXTURE

Cooling of magma/lava
Crystallization of minerals
Formation of an **igneous rock**

Slow cooling
within the
lithosphere

Rapid
cooling
near or on **Earth's**
surface

INTRUSIVE IGNEOUS ROCKS

Coarser-grained texture

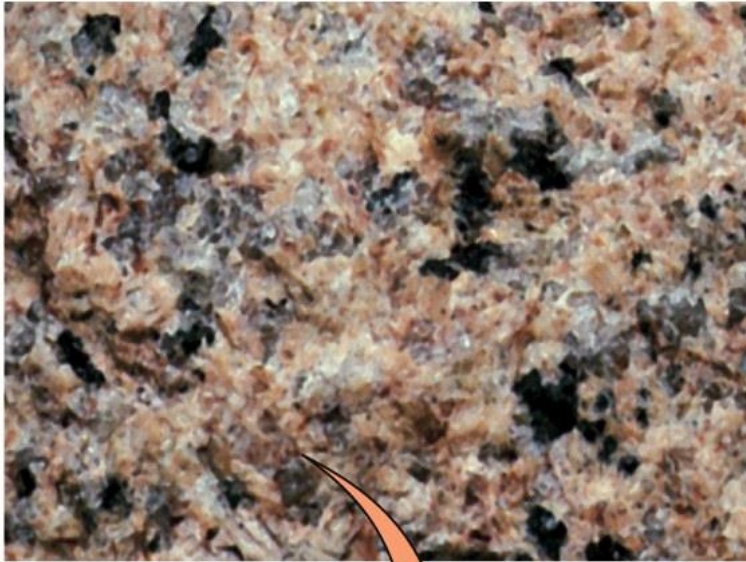
e.g. granite

EXTRUSIVE IGNEOUS ROCKS

Finer-grained texture

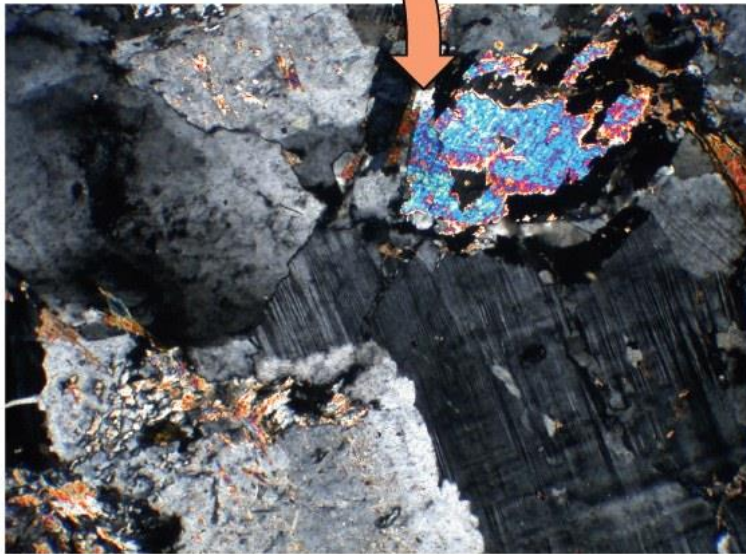
e.g. basalt

Granite



Seen
with a
magnifying
glass
1cm

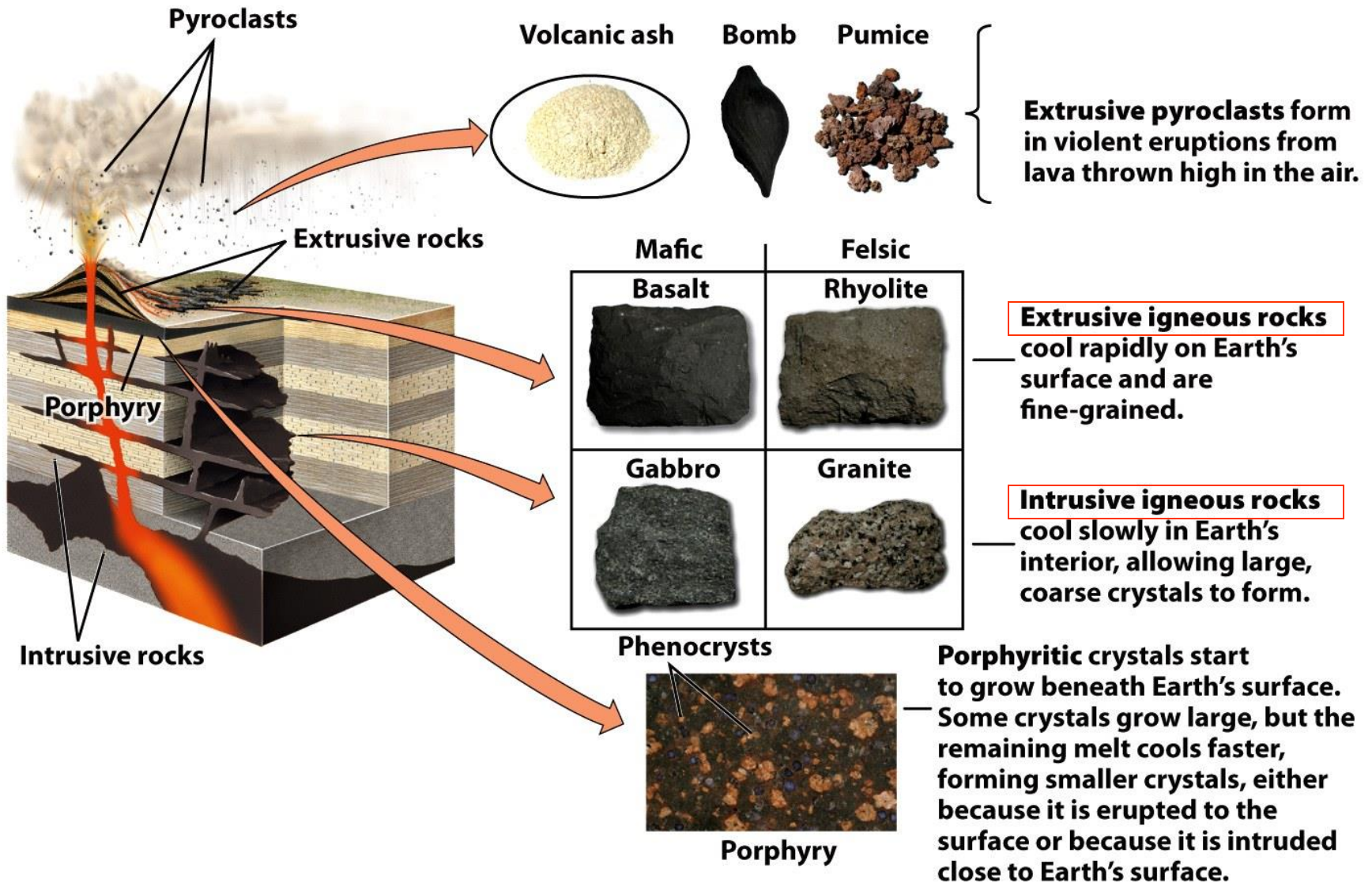
Basalt



Seen
through a
polarizing
microscope
1mm



Different types of igneous rocks identified based on the texture



2. CHEMICAL AND MINERALOGICAL COMPOSITION

Felsic vs. mafic compositions

Felsic : feldspar-silica

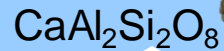
Mafic : magnesium-ferric

FELSIC	MAFIC
<p><i>Igneous rocks enriched in SiO₂ and silicates rich in Al, K, Na</i></p> <p><i>Quartz (SiO₂)</i></p> <p><i>Orthoclase (K-rich feldspar)</i></p> <p><i>Plagioclase (Na/Ca-rich feldspar)</i></p> <p><i>Muscovite (K-rich mica)</i></p> <p>Example: <i>granite (continental crust)</i></p> <p>Light color</p>	<p><i>Igneous rocks enriched in silicates rich in Fe, Mg</i></p> <p><i>Biotite (mica)</i></p> <p><i>Amphibole group</i></p> <p><i>Pyroxene group</i></p> <p><i>Olivine</i></p> <p>Example: <i>basalt (oceanic crust)</i></p> <p>Dark color</p>



CONTINUUM

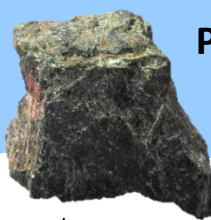
Anorthite:



Ca-rich plagioclase



Pyroxene



Quartz:

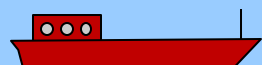


Orthoclase:
 KAlSi_3O_8

Granite



Basalt



Continental crust

0-7 km Oceanic crust Fe, Mg > 3.0 g/cm³

35-60 km Al, K, Na > 2.8 g/cm³

Fe, Mg >> 3.4 g/cm³

Mantle **Peridotite**

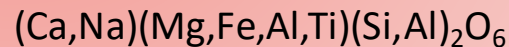


Olivine: $(\text{Mg, Fe})_2\text{SiO}_4$



Pyroxene: $\text{XY}(\text{Si,Al})_2\text{O}_6$
Enstatite (MgSiO_3) and
ferrosilite (FeSiO_3)

Augite



Felsic = Feldspar-Silica Mafic = Magnesium-Ferric

Composition	FELSIC	INTERMEDIATE	MAFIC	ULTRAMAFIC
Coarse-grained (intrusive)	Granite	Granodiorite Diorite	Gabbro	Peridotite
Fine-grained (extrusive)	Rhyolite	Dacite Andesite	Basalt	

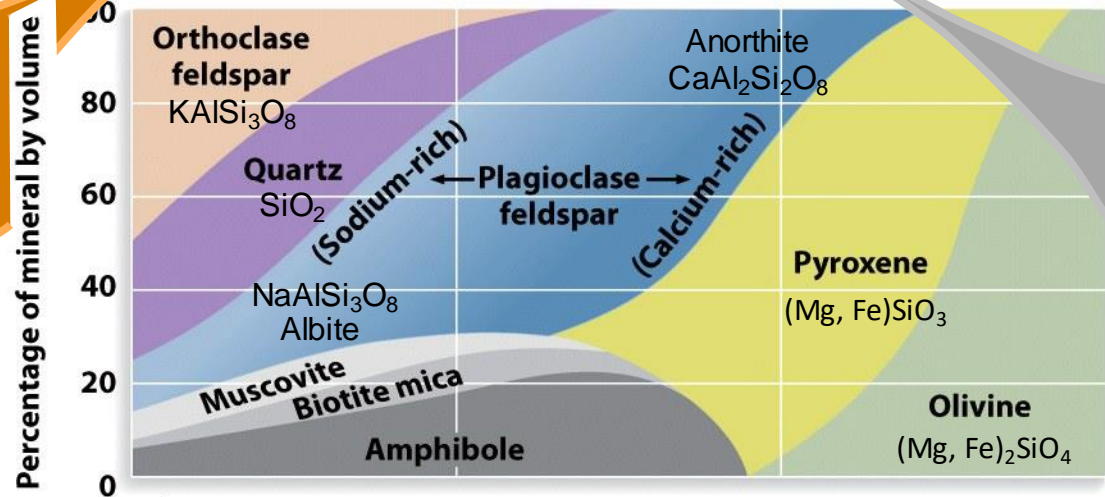
DOMINANT IN EARTH'S UPPER MANTLE

Intrusive

Extrusive

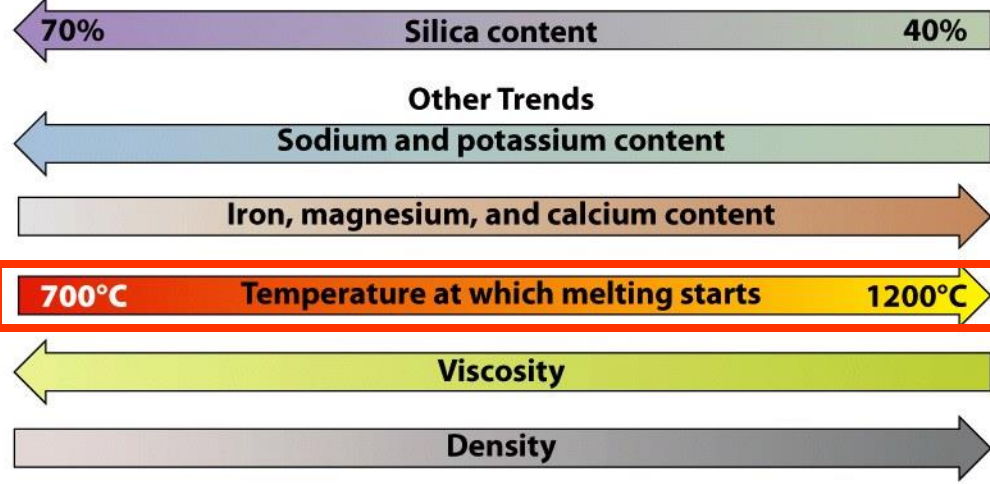
ABUNDANT IN THE CONTINENTAL CRUST

ABUNDANT IN THE OCEANIC CRUST (underlying ocean floor)



LIGHT color

DARK color

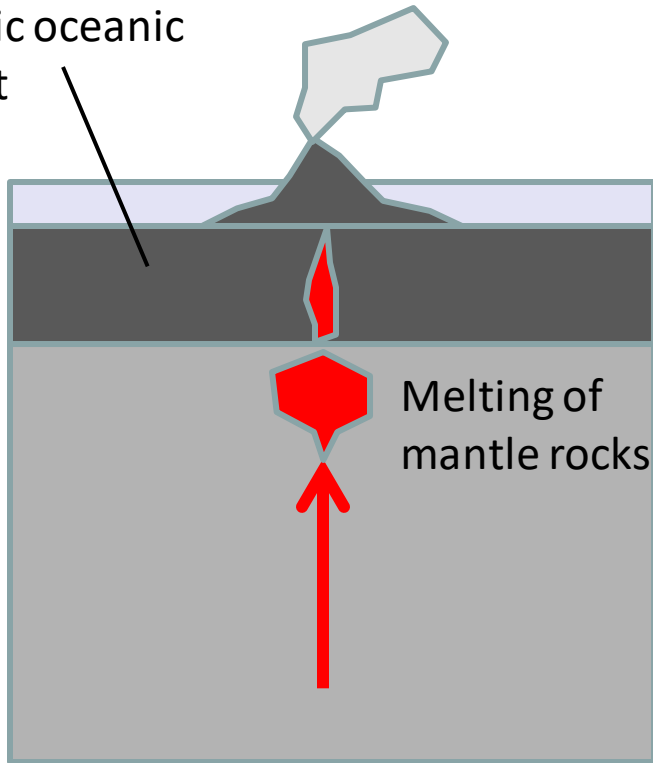


Crystallize and melt at different T !!!

Production of **basaltic magmas** at oceanic hot spots

Low-viscosity magmas

Mafic oceanic crust

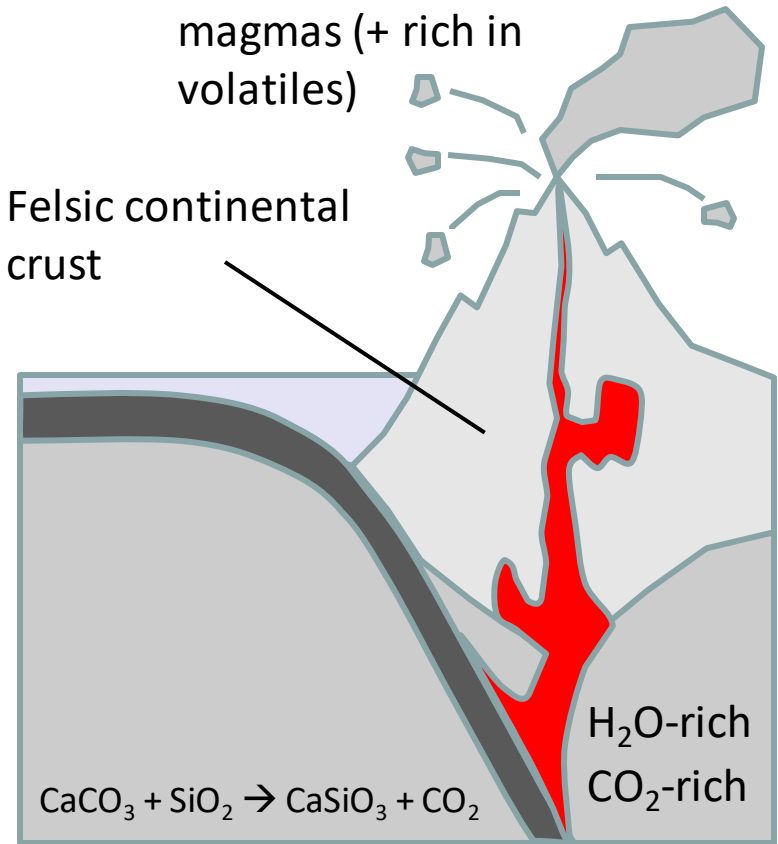


LOW RISK OF EXPLOSION

Production of more **felsic magmas** at ocean-continent subduction zones

High-viscosity magmas (+ rich in volatiles)

Felsic continental crust



HIGH RISK OF EXPLOSION

Basaltic volcanism (mafic composition)

Shield volcanoes

Hawaii hot spot

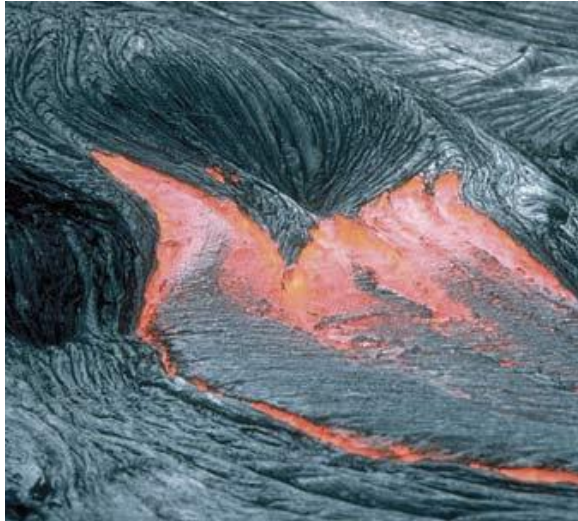
Understanding Earth 6th Ed.



“PAHOEHOE” LAVA



“AA” LAVA



www.britannica.com



www.britannica.com



“PILLOW” LAVA

Understanding Earth 6th Ed.

Rhyolitic volcanism (felsic composition)

Volcanic domes

MOUNT CHAITÉN (Chile)



Sam Beebe (Wikipedia)



RHYOLITIC LAVA DOME (Oregon, USA)



Understanding Earth 6th Ed.

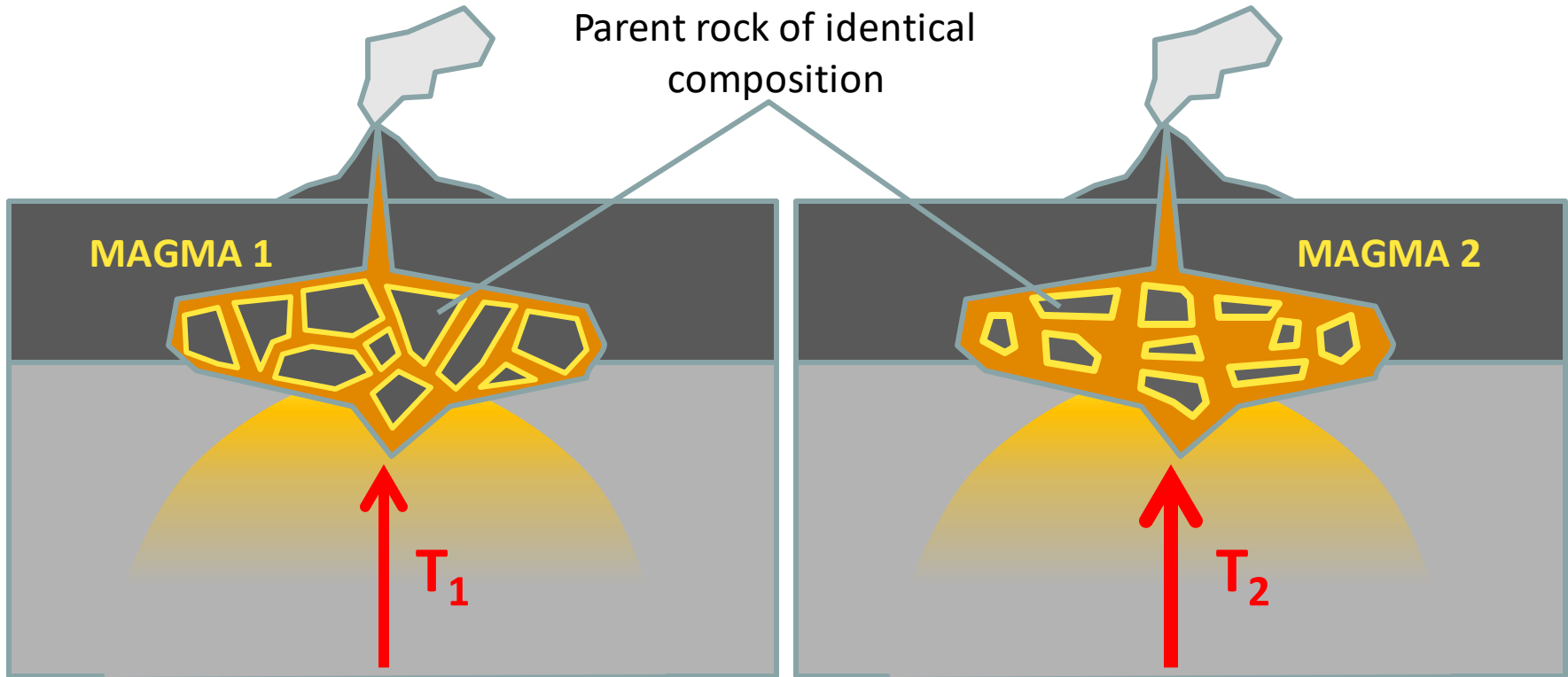
★ Processes of magma formation

Factors controlling magma production:

- 1. Temperature**
 - All minerals do not melt at the same temperature (felsic vs. mafic)
- 2. Pressure**
 - Lower pressures result in lower melting temperatures
→ Lowering the pressure facilitates melting!
- 3. Water content**
 - Increased water content results in lower melting temperatures
→ Adding water facilitates melting!

1. Role of temperature

Different minerals melt at different temperatures



Temperature 1 (T_1) < Temperature 2 (T_2)

% melting 1 < % melting 2

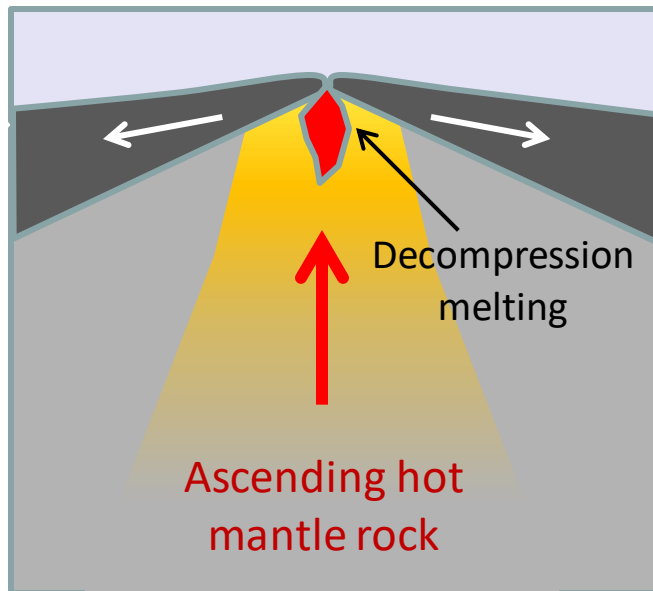
Composition of partial melt 1 (magma 1) \neq **composition** of partial melt 2 (magma 2)

2. Role of pressure

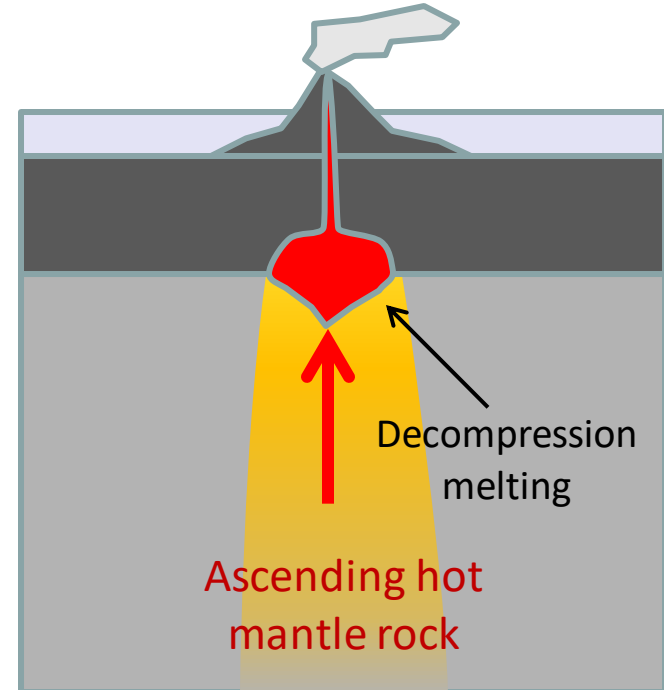
- **High pressures** deep in the Earth's interior prevent rocks from melting
- Hot mantle rock begins to melt when it rises beneath mid-ocean ridges and hotspots when the pressure drops =

Decompression melting

Mid Ocean Ridge
(MOR)

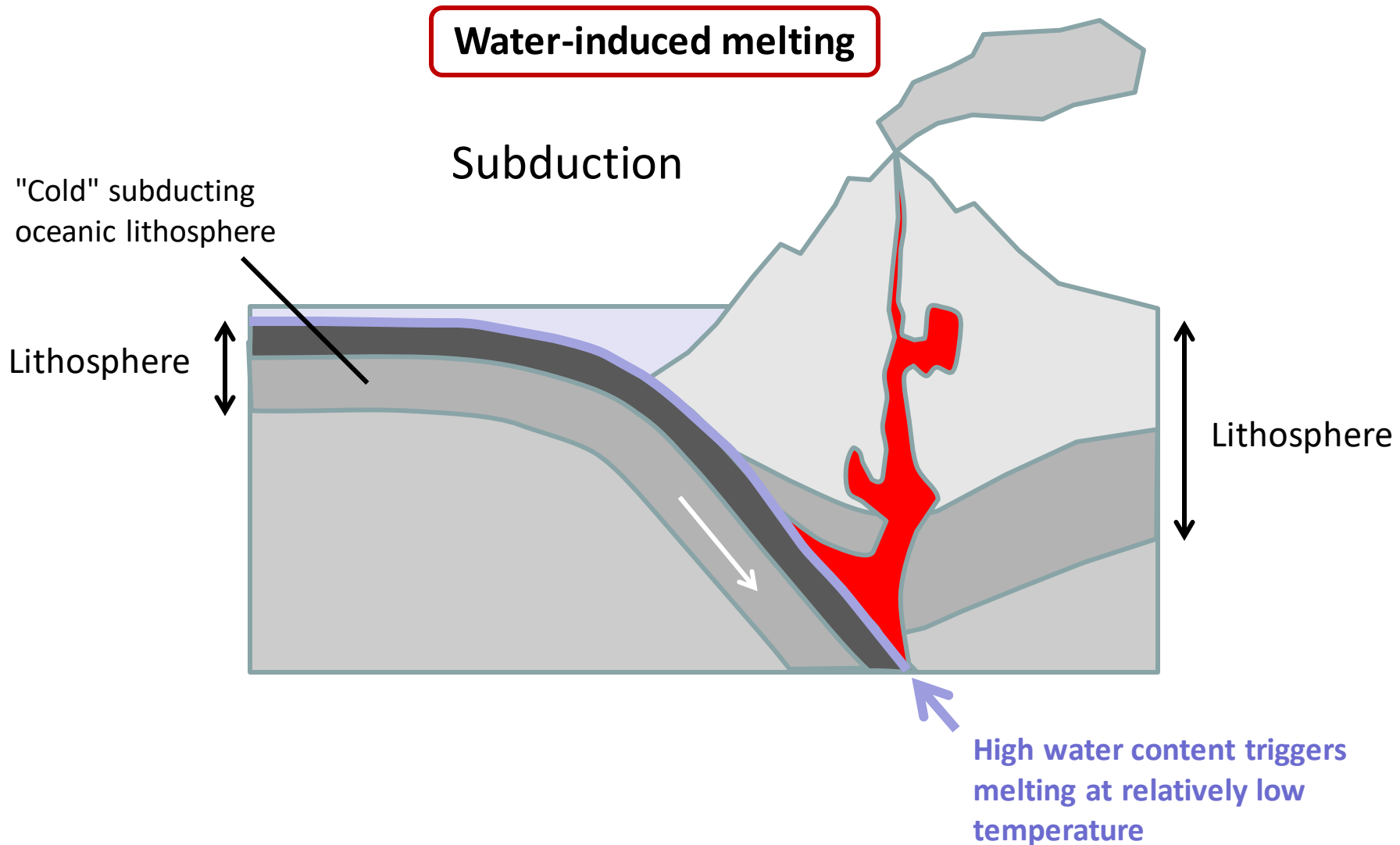


HOT SPOT

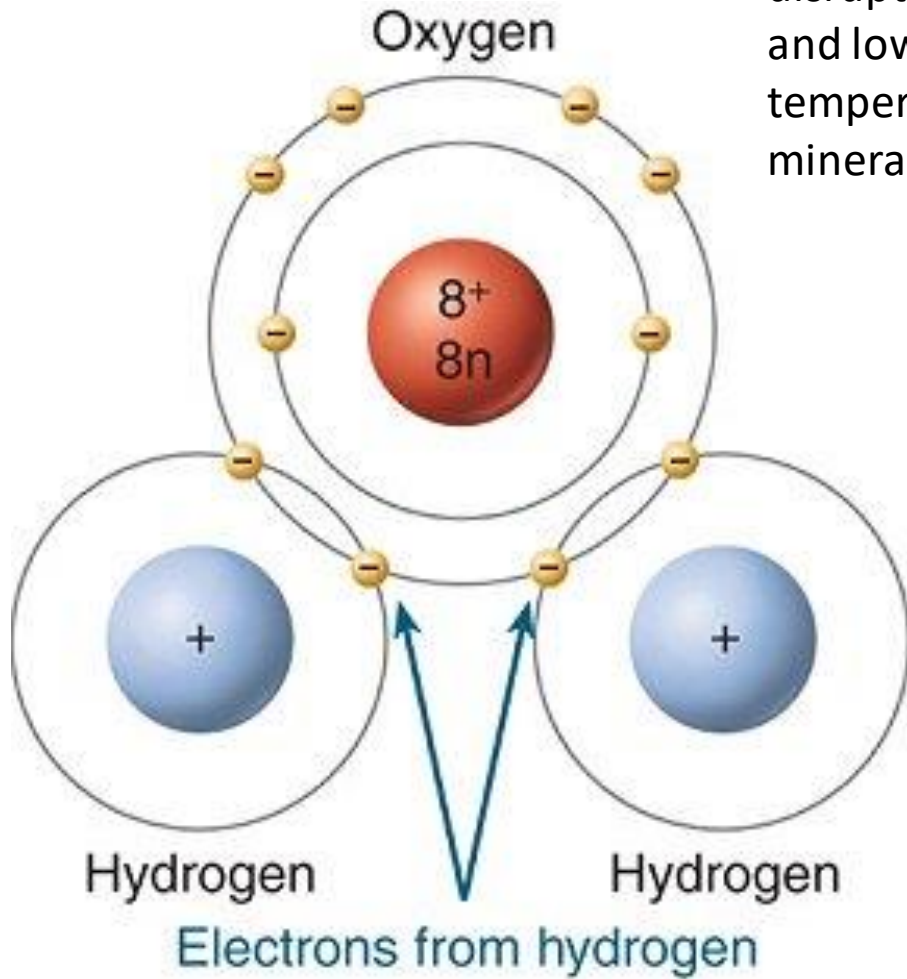


3. Role of water

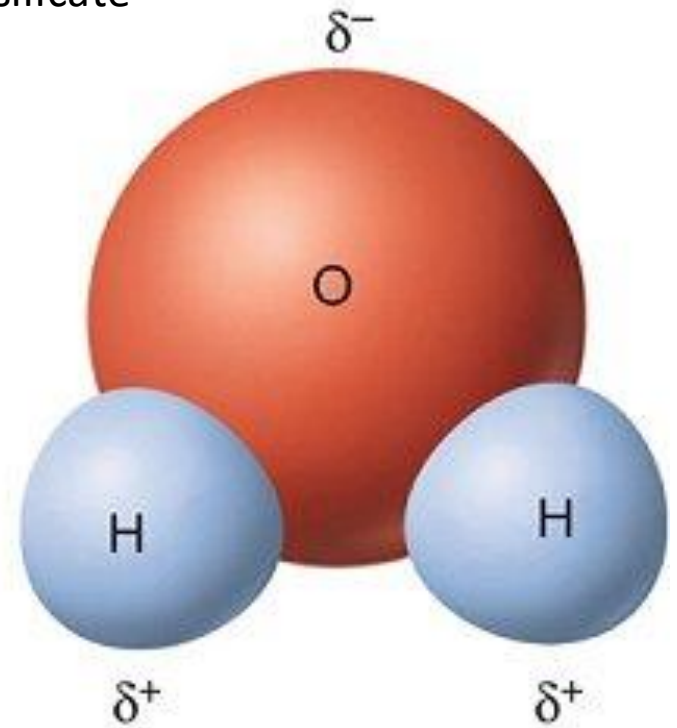
Sedimentary rocks carried by the subducting plate have a **high water content** in the **open space** between grains (pores) and in **clay minerals**.



Water molecules
disrupt chemical bonds
and lower the melting
temperature of silicate
minerals.



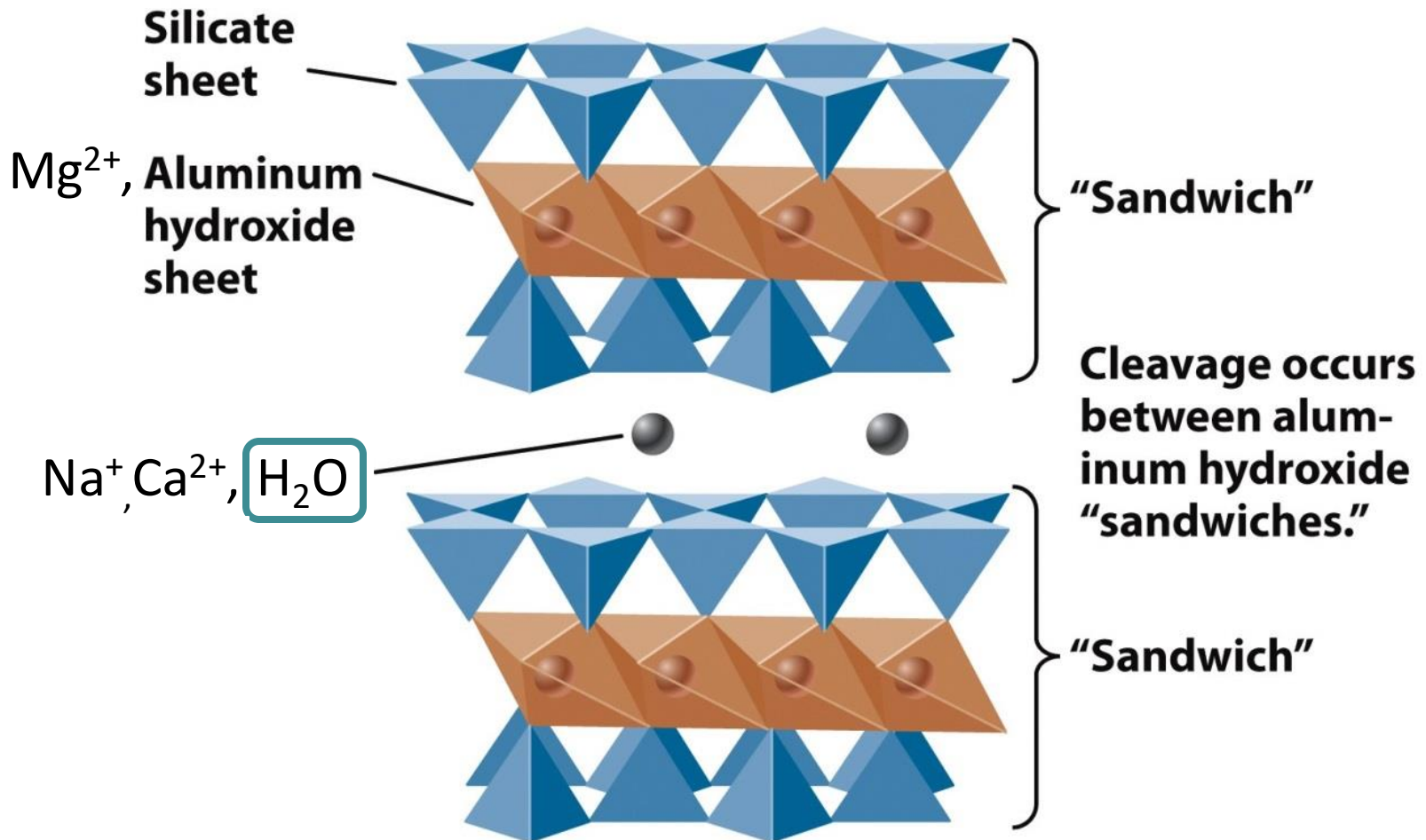
(a) Electron shells in a
water molecule



(b) Distribution of partial
charges in a water
molecule

Hydrous Aluminium Phyllosilicates (smectite group)

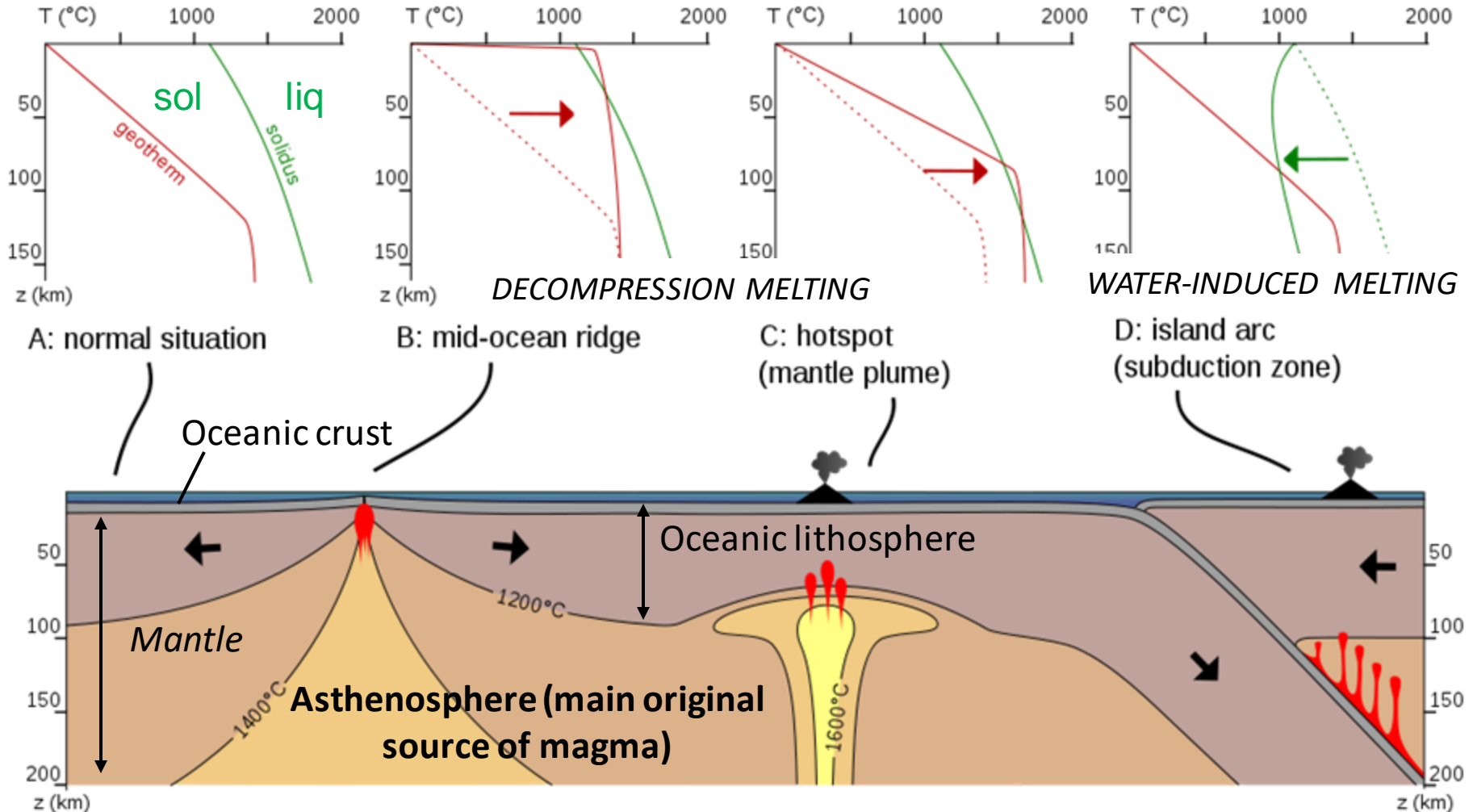
e.g. montmorillonite $\rightarrow (\text{Na}, \text{Ca})_{0.33}(\text{Al}, \text{Mg})_2\text{Si}_4\text{O}_{10}(\text{HO})_2 \cdot n\text{H}_2\text{O}$



How magma forms: Geothermal gradient & rock solidus

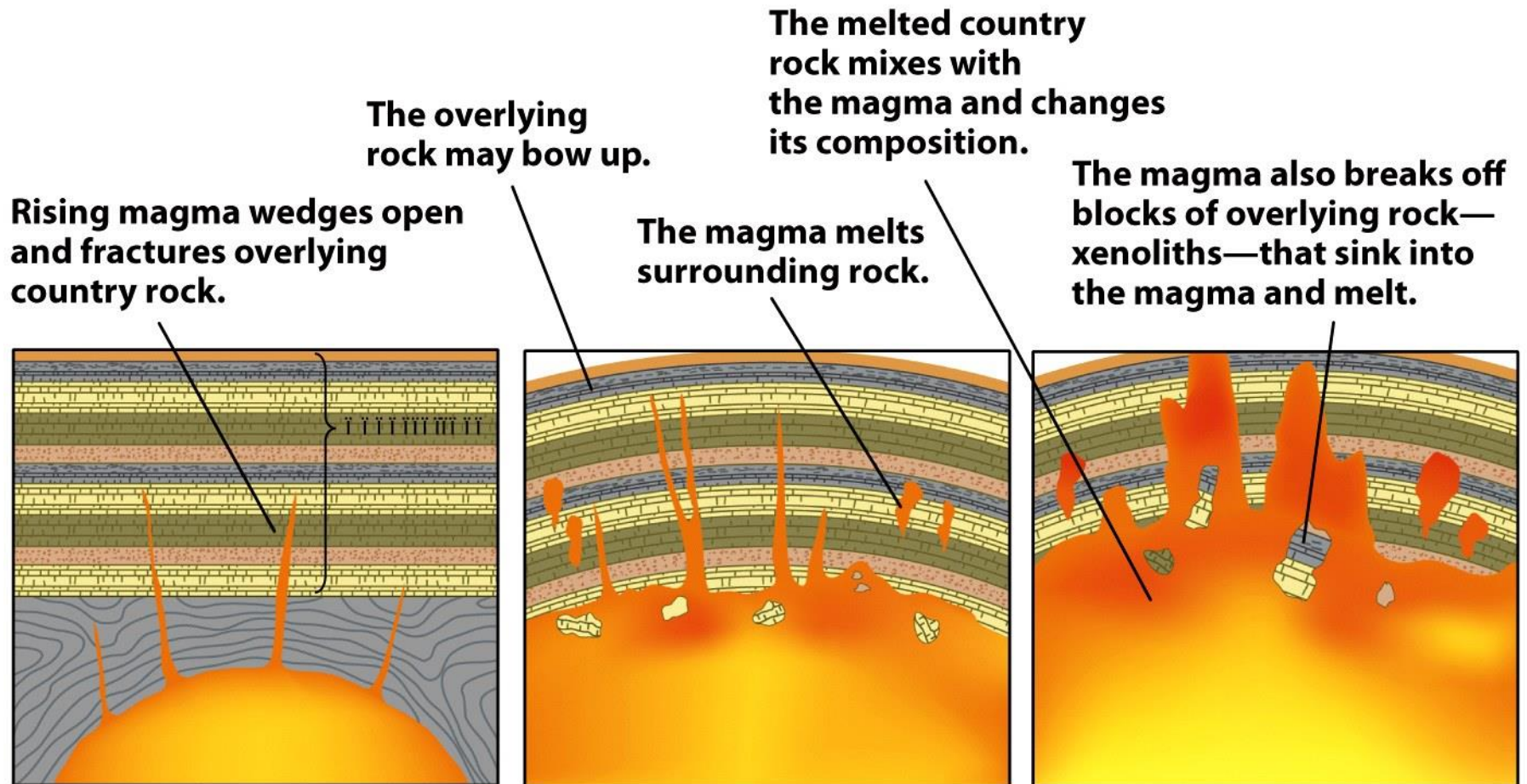
Red line (geotherm): Rock temperature vs. depth (T increases with depth)

Green line (solidus): Temperature at which the rock starts to melt

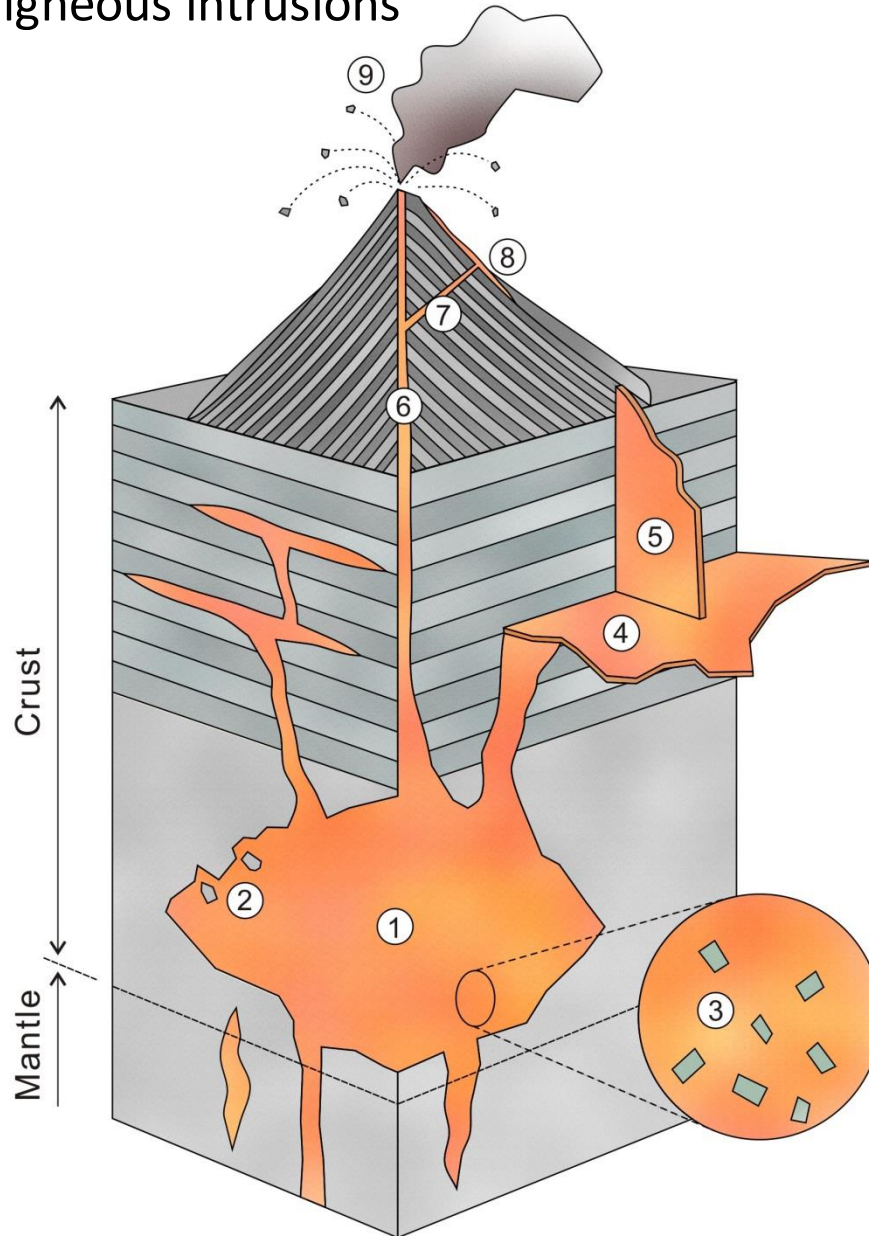


Magma is less dense than surrounding solid rocks and rises through fissures in the rock or by melting its way up.

Magma accumulates in large **magma chambers** in the crust.



Forms of igneous intrusions



1. Magma chamber (pluton)
2. Surrounding rocks melt and influence magma composition
3. Different minerals crystallize at different temperatures which influence the composition of the remaining melt
4. Sill (horizontal sheet-like intrusion)
5. Dyke (vertical sheet-like intrusion)
6. Central vent
7. Side vent
8. Lava flow
9. Pyroclasts

★ Magma crystallization and formation of igneous rocks

How can we explain the diversity of igneous rocks?

1. Crystal fractionation

- Minerals crystallize at different temperatures. Minerals that crystallize first in the magma chamber tend to settle down first. This is called **crystal fractionation**. This process results in the formation of igneous rocks of different compositions. One single parent magma can therefore produce different igneous rocks. Change in magma composition during crystallization is called **magmatic differentiation**.

2. Crustal contamination

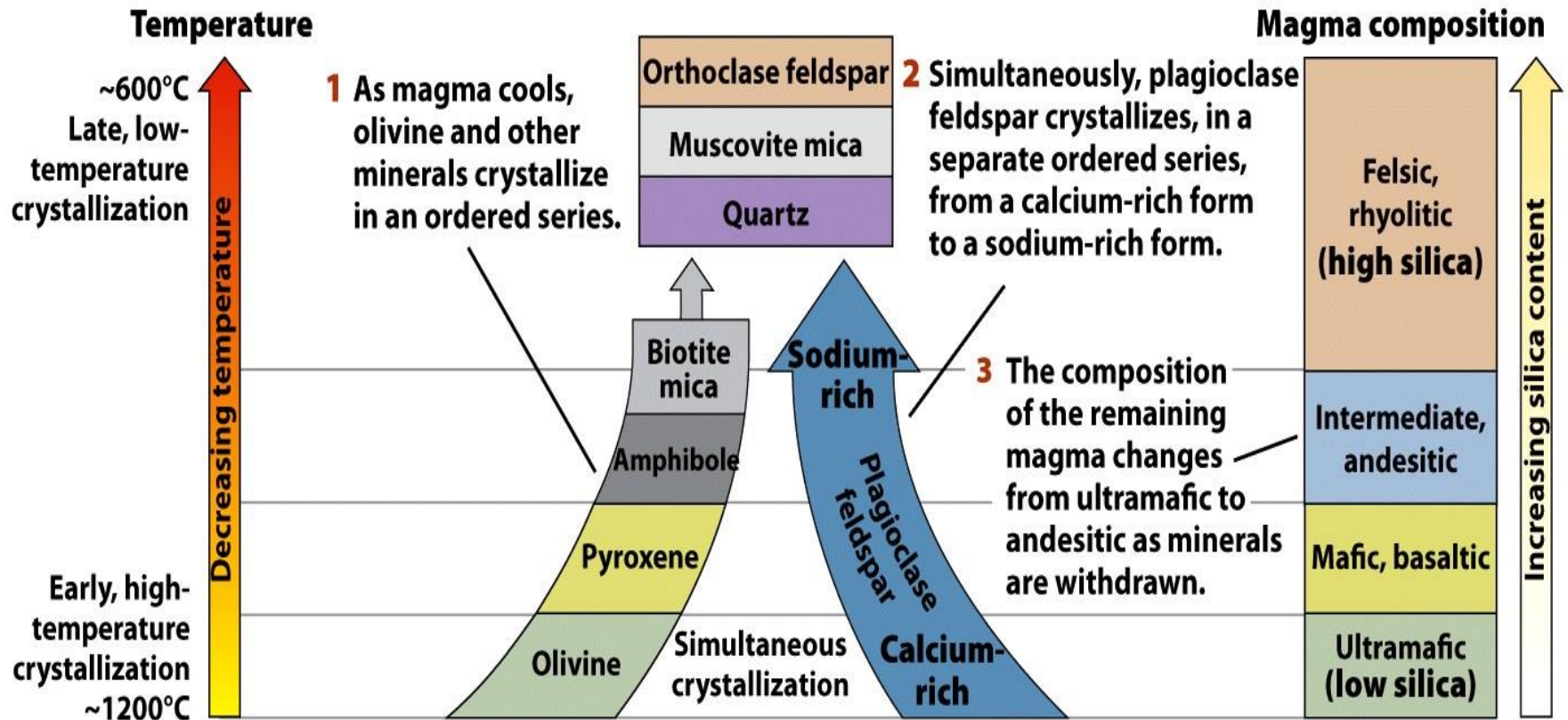
- Changes in magma composition as the magma travels in the crust and incorporate pieces of the surrounding crustal rocks.

3. Magma mixing

- The mixing of magmas with different chemical compositions may lead to the formation of igneous rocks whose compositions differ from the rocks that would have been produced if the two magmas had crystallized separately without mixing.

1. Crystal fractionation

The **Bowen's reaction series** (established experimentally)

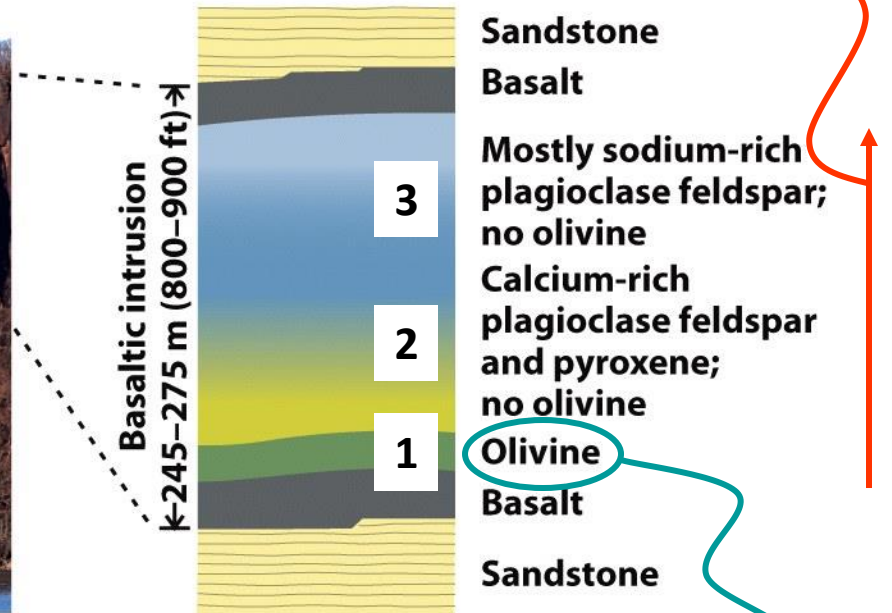


Minerals crystallizing first tend to settle down first in magmatic intrusions which means that layers of igneous rocks of different compositions can form.

Crystal settling rate also depends on density and size of crystals and the viscosity of the remaining magma (+ turbulences in magma chamber)

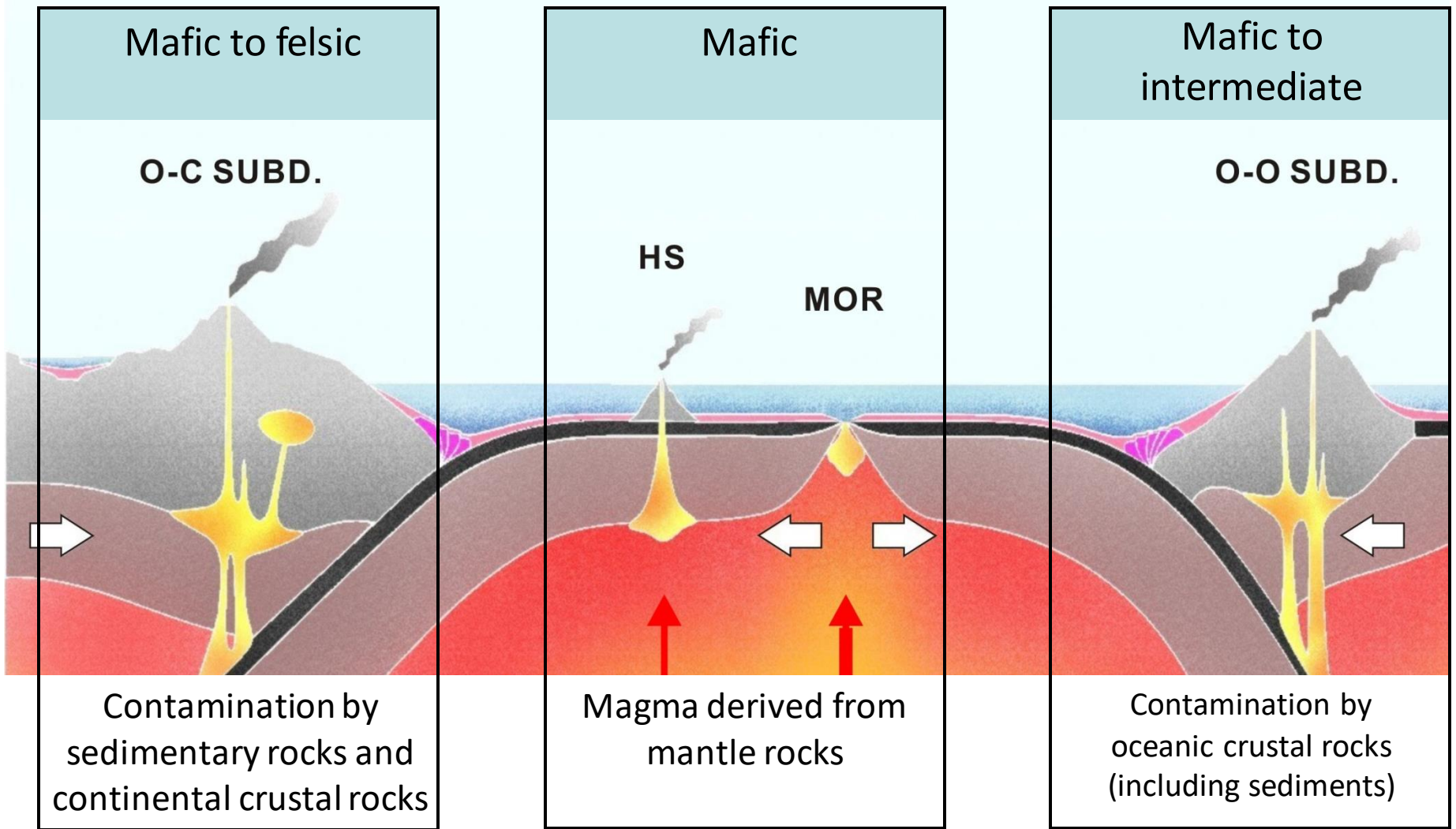
As magma cools, minerals crystallize at different temperatures and settle out of the magma in a particular order.

Order that follows Bowen's reaction series



Olivine crystallized first and settled down at bottom

2. Crustal contamination



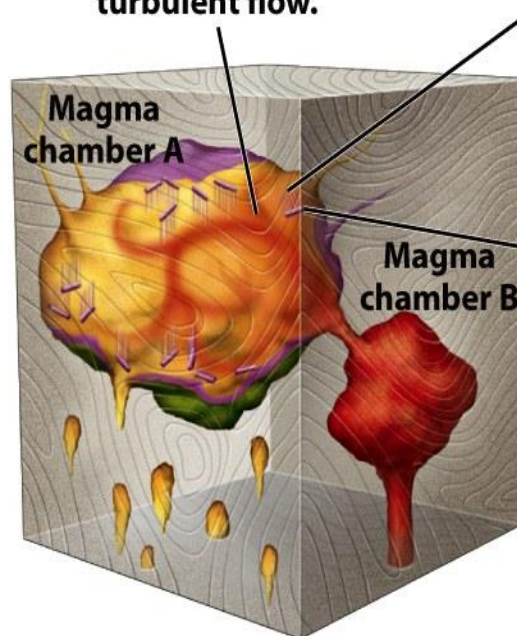
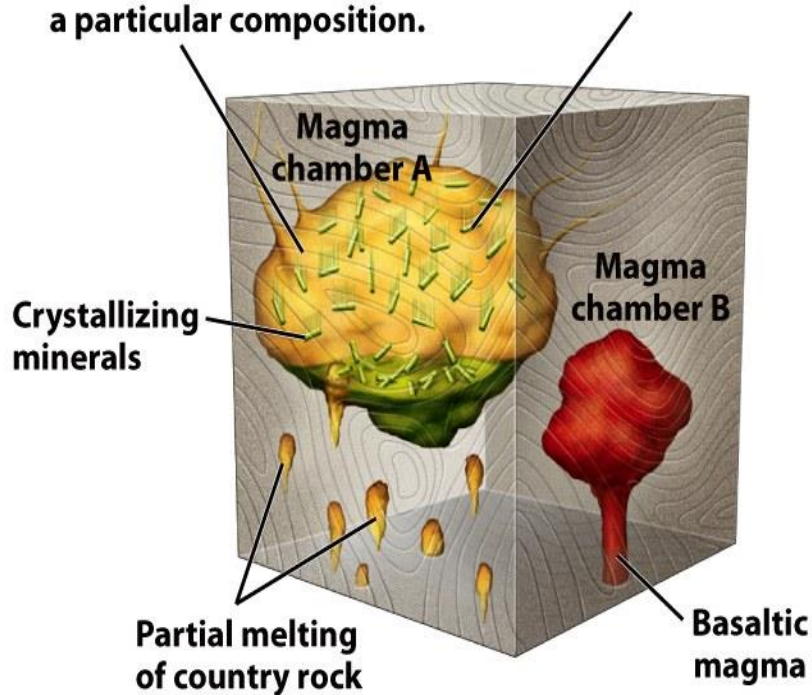
3. Magma mixing

1 Partial melting of country rock creates a magma of a particular composition.

2 Cooling causes minerals to crystallize and settle.

3 A basaltic magma chamber breaks through, causing turbulent flow.

4 Mixing of two magmas results in andesitic magma.



5 Crystals formed in the mixed magma have a different composition, and may accumulate on the sides and roof of the magma chamber due to turbulence.

NB: Some magmas are immiscible, which means they cannot mix (like oil and water)

Igneous differentiation can lead to the segregation of valuable minerals in layered intrusions.

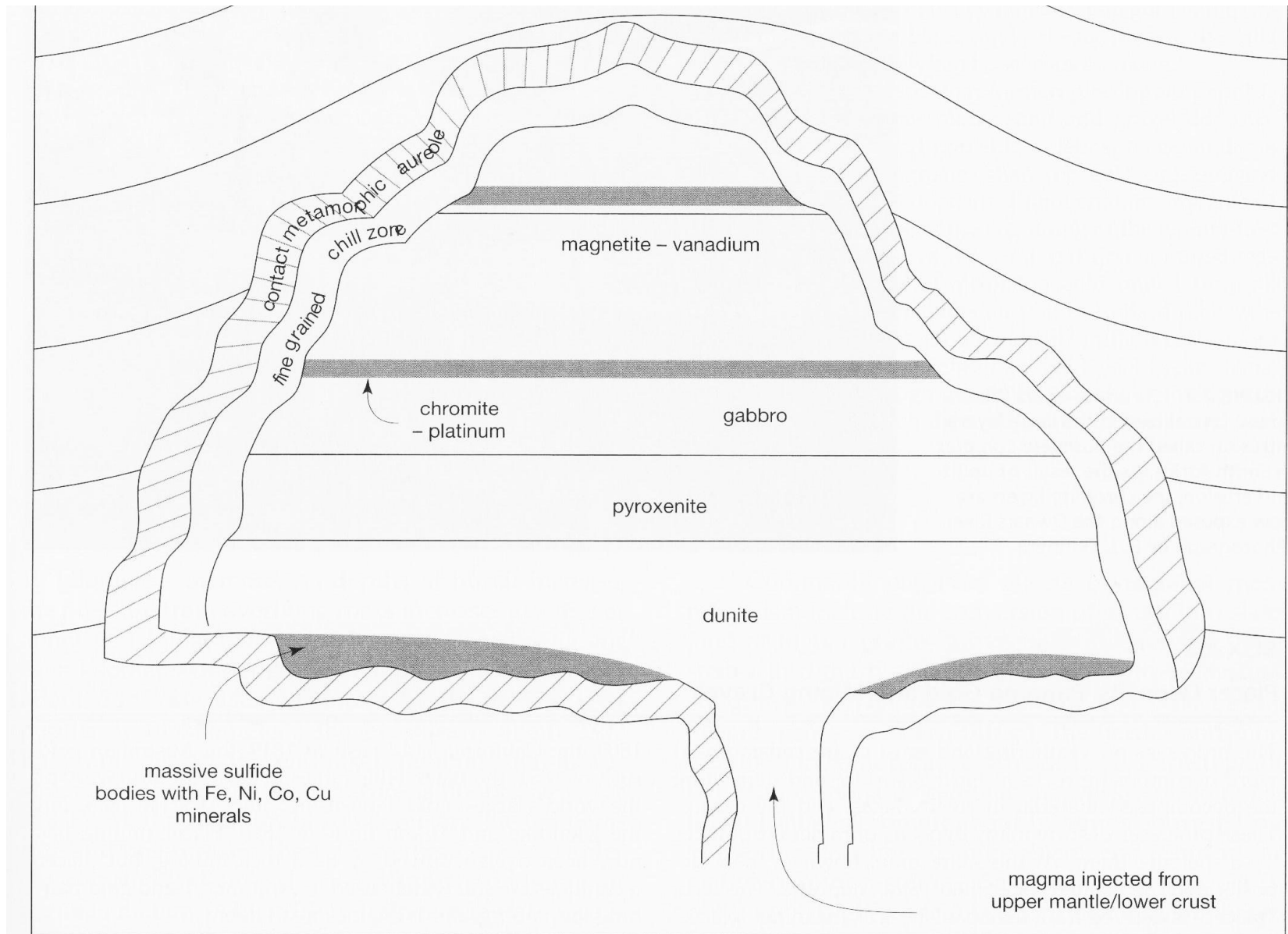


FIGURE 2.6 After large masses of silica-poor magmas are emplaced or melt their way into Earth's crust, they may take tens of thousands to millions of years to crystallize. During crystallization, these intrusions acquire a distinctly layered structure, with some zones being rich in minerals useful as mineral resources.

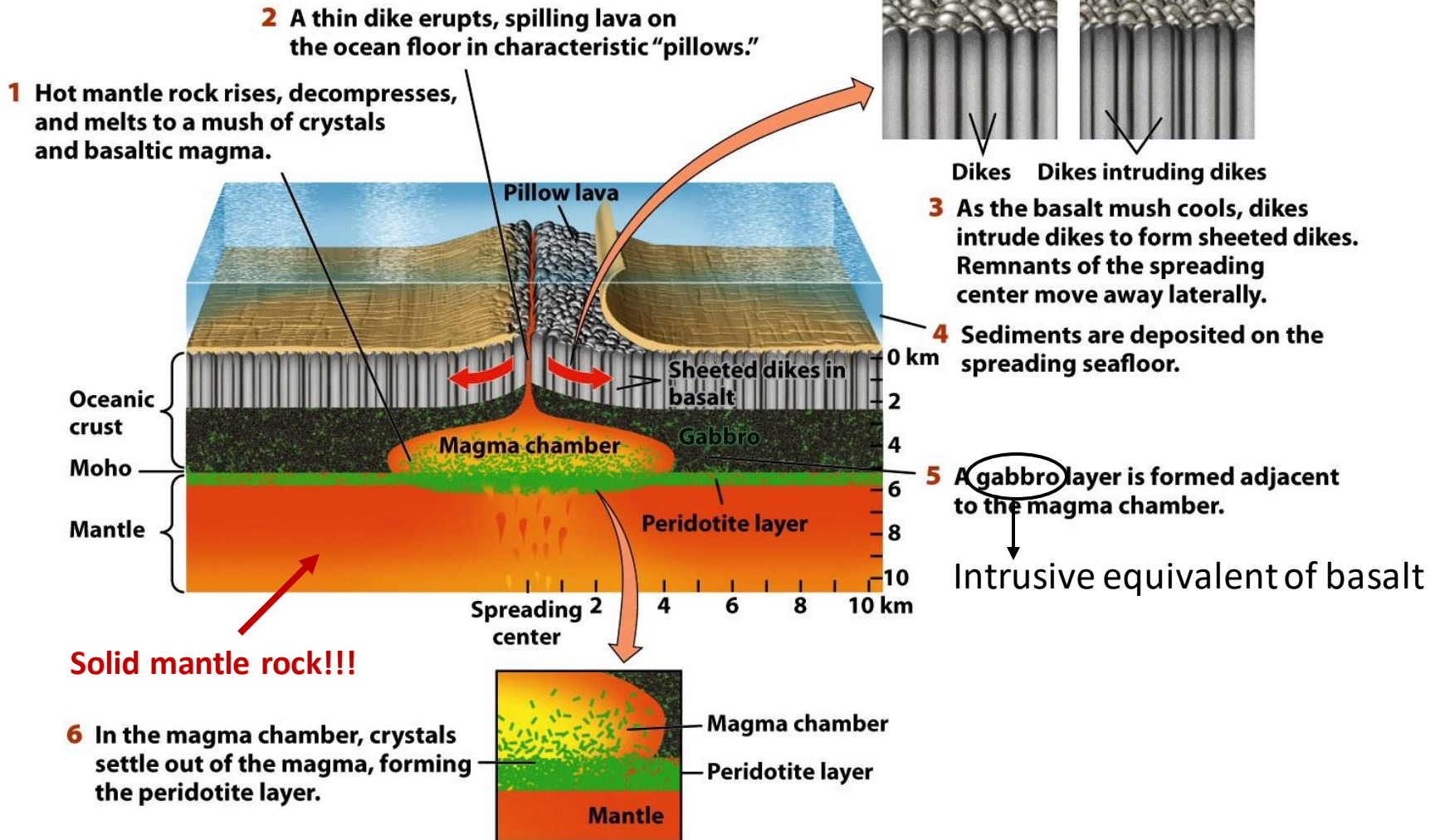


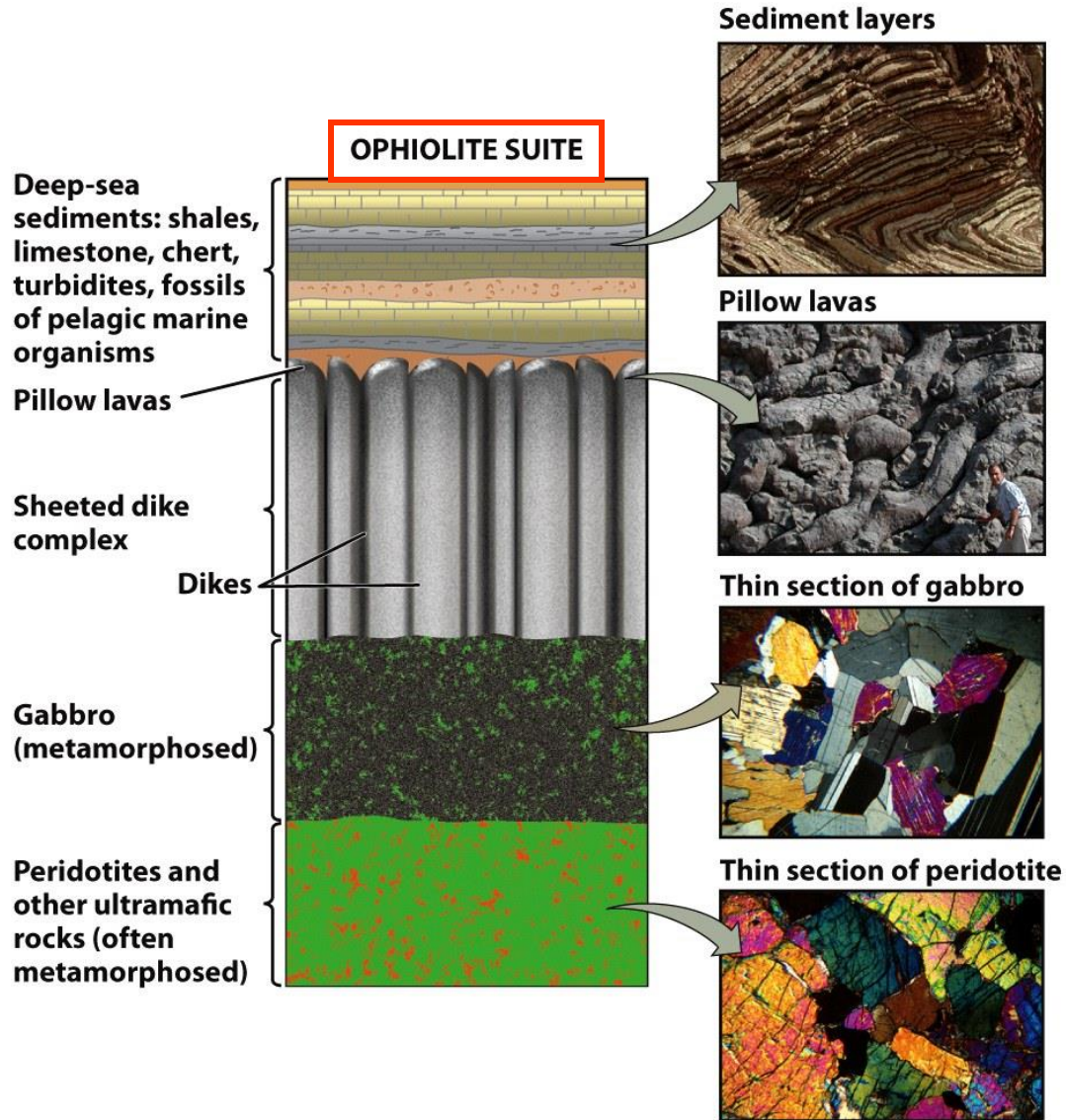
Layers of chromite (black), Bushveld (*photo: Jackie Gauntlett, blogs.agu.org*)



Iron-titanium oxide (ilmenite) mining in Norway (*wikipedia*)

★ Formation of oceanic crust at mid-ocean ridges



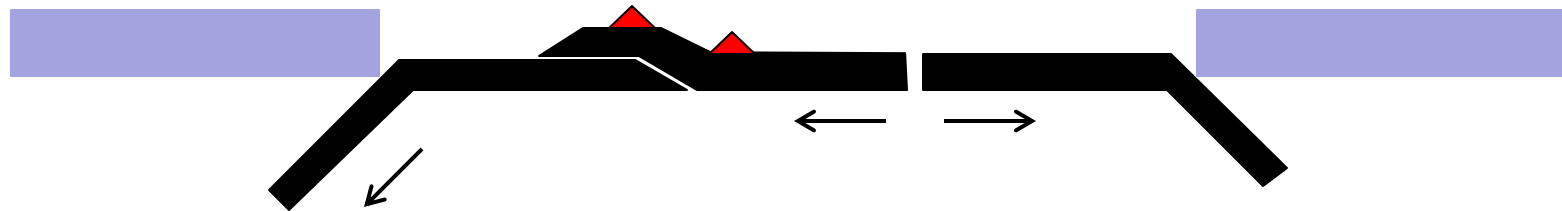
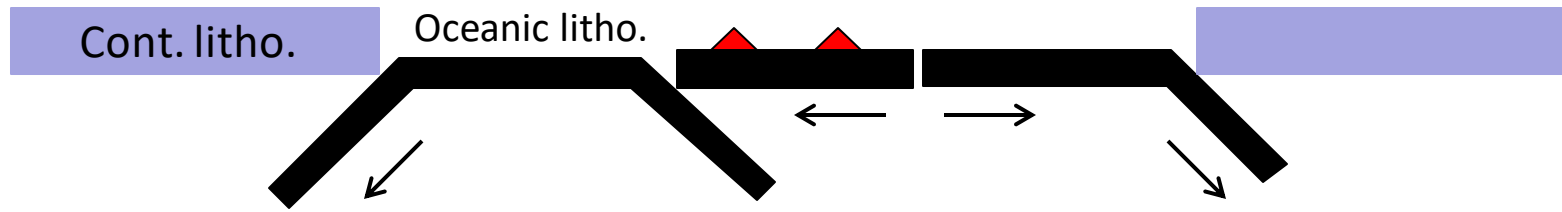


Large ophiolite outcrops
occur in Oman



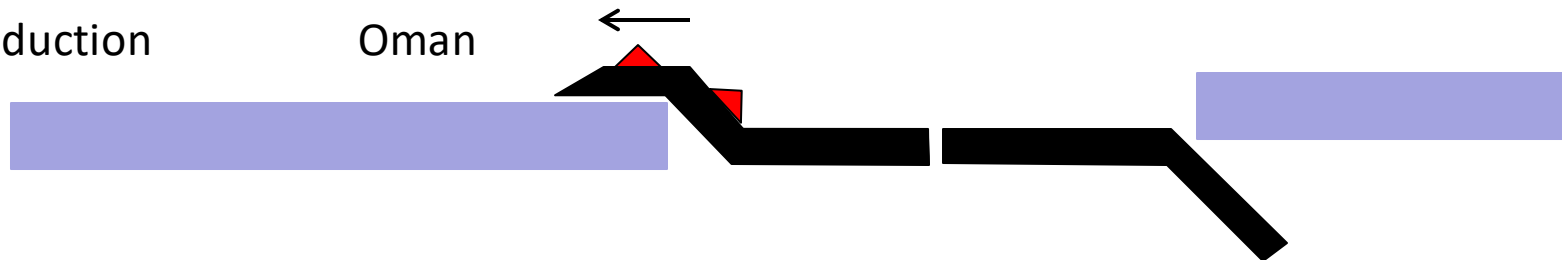
100-80 x 10⁶ yr ago

Subduction



Obduction

Oman



▲ Copper sulfide deposits
related to black smokers