

Economic Geology: Lecture Notes

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Orthomagmatic Ore Formation

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 1. Orthomagmatic Ore Formation
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I. Ore Formation Processes

For a long time in the past, processes associated with **differentiation and cooling of magmatic bodies** were thought to be the main agents of **ore deposit** formation. **Starting with metal-rich melts, ore minerals can form upon cooling or segregate from the silicate liquid.**

Because **mafic silicate minerals** crystallize at higher temperature, **intermediate and felsic residual melts** are formed with their own suite of ore deposits. **Late-stage magmatic fluids collect metals and produce hydrothermal mineralization.**

In addition, the role of **weathering, erosion and sedimentation** in concentrating metals is recognized. **Metamorphic processes** were seen to transform previously existing ore but without appreciable mass transfer.



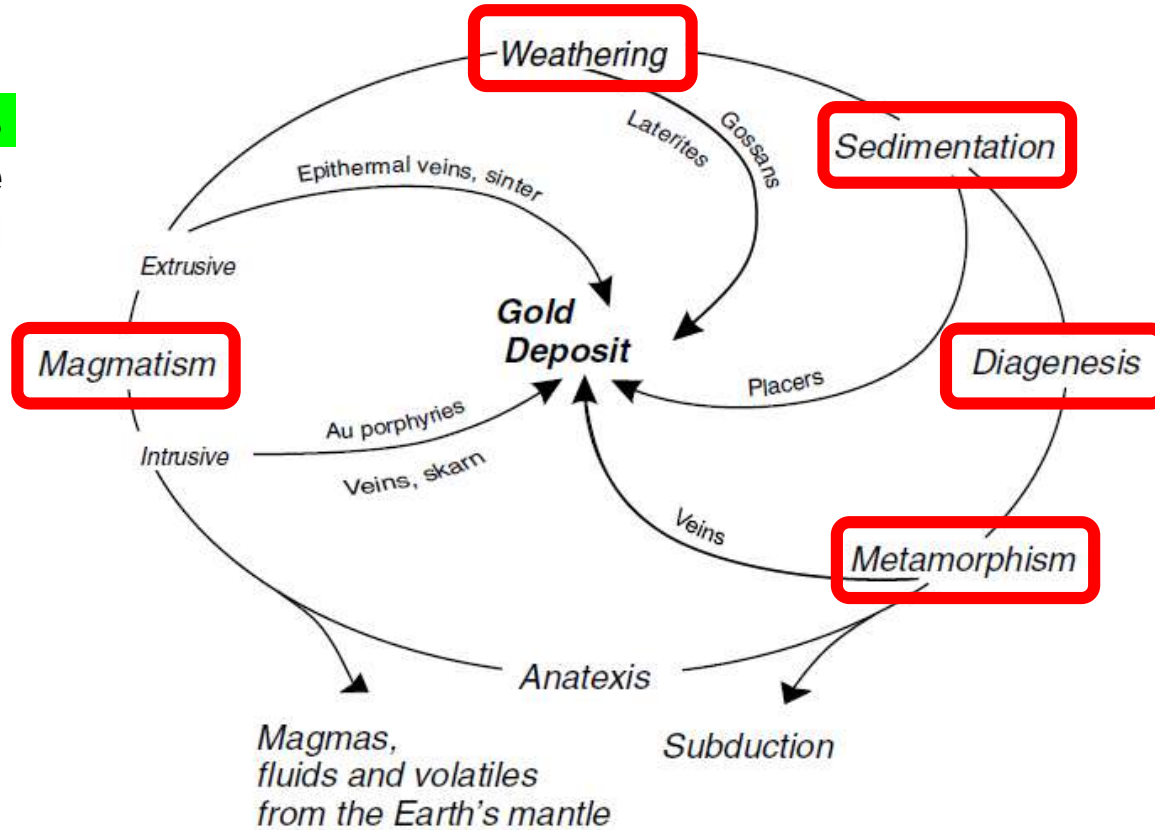
The classification of ore deposits by major earth process systems is quite simple. Complications arise mainly because of the extreme variability of individual deposits due to manifold combinations of different processes and factors.

In this course, **fundamental geological processes** and **ore-forming systems** are to interpret the ore metallogeny.

The **ore-forming processes** may be grouped into the following four broad categories:

- (a) **Orthomagmatic processes**
- (b) **Hydrothermal processes**
- (c) **Sedimentary processes**
- (d) **Metamorphic processes**

The formation of mineral deposits may involve a combination of processes.



The origin of gold deposits in relation to major geological process systems within the Earth's crust, demonstrating the variety of **ore forming systems**.

II. Mineral Deposit versus Orebody

A **mineral deposit/ore deposit** may be defined as a **rock body** that contains one or more elements (or minerals) **sufficiently above the average crustal abundance to have potential economic value.**

Mineral deposits can be classified into two broad categories:

(a) **metallic mineral deposits** (e.g., deposits of **copper, lead, zinc, iron, gold, etc.**), from which one or more metals can be extracted; and

(b) **nonmetallic (or industrial) mineral deposits** (e.g., deposits of **clay, mica, fluorite, asbestos, garnet, etc.**), which contain minerals useful on account of their specific physical or chemical properties.



- Iron
- Aluminum
- Copper
- Lead
- Zinc
- Nickel
- Cobalt
- Gold
- Silver
- Platinum



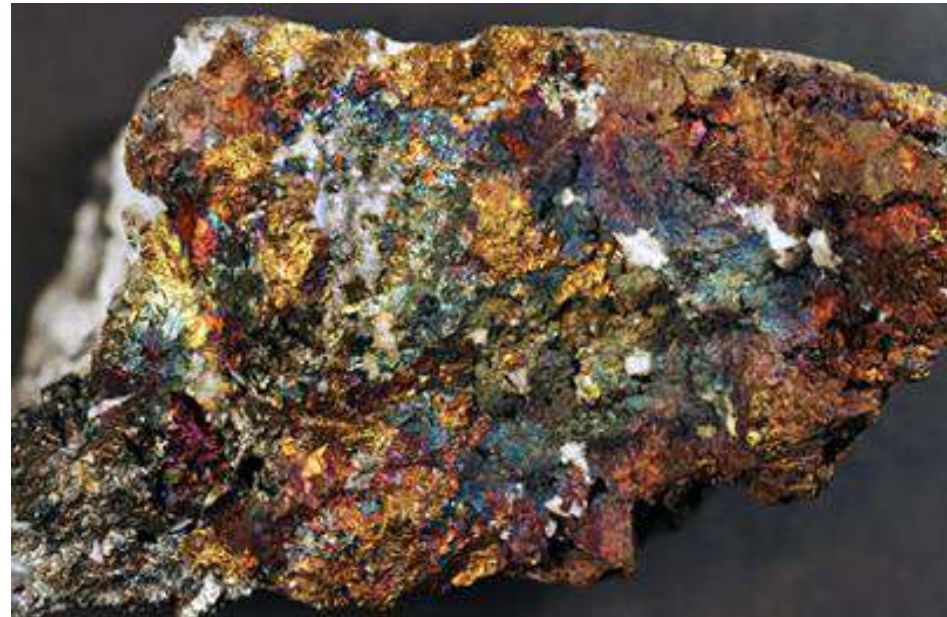
- Sulfides
- Lime
- Sulfur
- Halite
- Clay
- Gypsum
- Potash



The minerals of economic interest in a deposit are referred to as **ore minerals** and the waste material as **gangue**. Accessory sulfide-group and oxide-group minerals (e.g., pyrite and arsenopyrite), especially in metallic mineral deposits, however, are sometimes described as ore minerals.

An **ore body** refers to **a specific volume of material in a mineral deposit that can be mined and marketed at a reasonable profit**. Thus, many mineral deposits are not mined because they fail to pass the test of profitability.

Grade (or tenor) is the average concentration of a valuable substance in a mineral deposit, and **cut-off grade** the minimum concentration required to achieve the break-even point for a mine in terms of revenue and costs.



The reserves of an **ore body** are depending on the **degree of geologic certainty of existence**, commonly classified as **measured, indicated, or inferred**. Identified, sub-economic materials in a mineral deposit constitute potential resources **(materials that may be profitably mined in the future)**, which may be further subdivided into paramarginal and submarginal categories on the basis of economic feasibility.

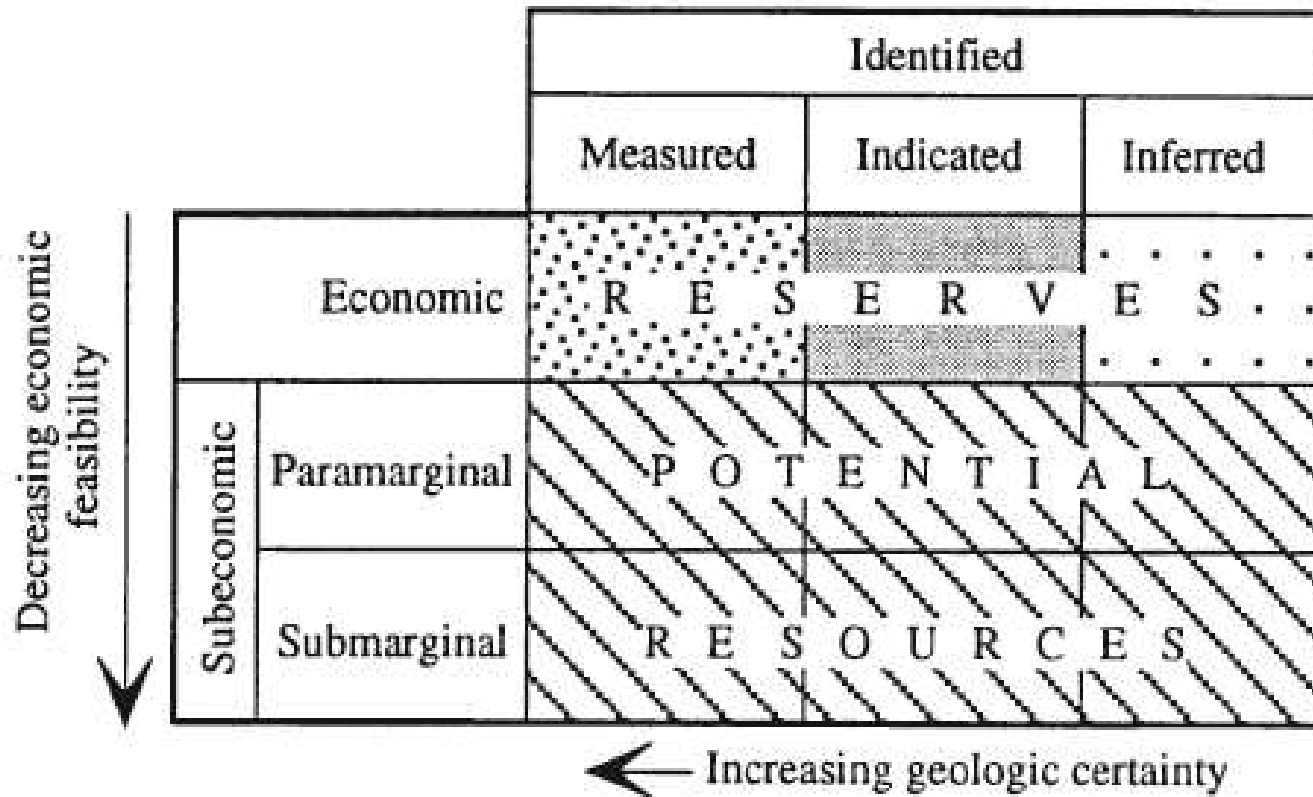


Figure 1.1. Classification of ore reserves based on degrees of geologic certainty and economic feasibility

III. Styles of Mineralization and Morphology of Mineral Deposits

The **style of mineralization** refers to the **pattern of distribution of ore minerals in a host rock**, and it varies from being very **subtle (even invisible to the naked eye as in some precious metal deposits)** to **quite pronounced (as in the case of massive sulfide deposits)**. The shapes of mineral deposits are also highly variable, from concordant tabular and stratiform to discordant veins and breccia bodies.

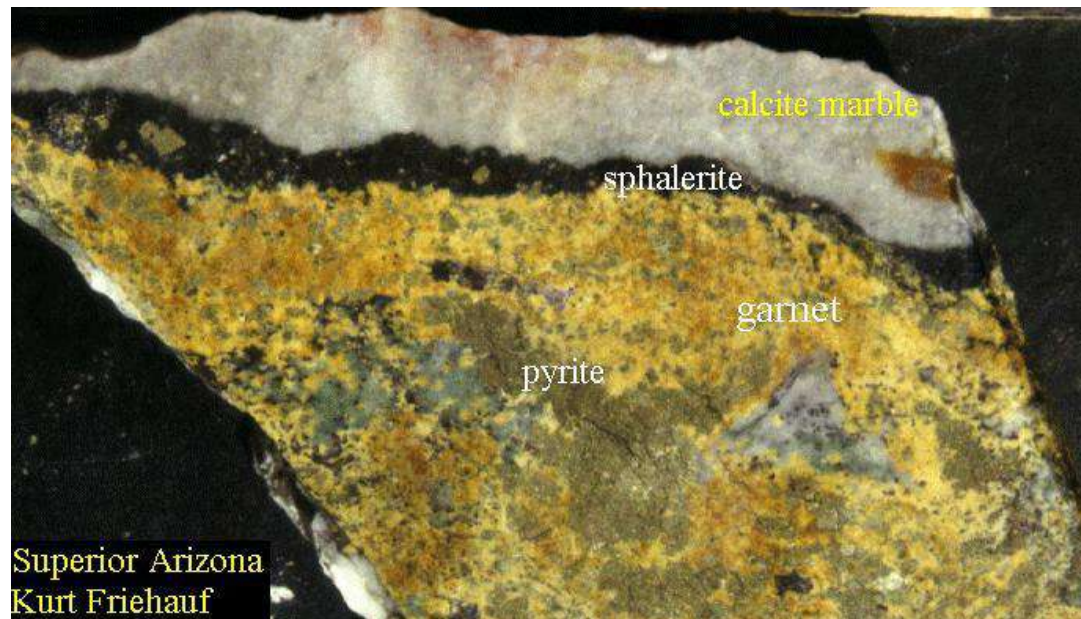
	Mode of occurrence	Typical examples
<i>Disseminated</i>	Ore minerals dispersed through the host rock	Diamond in kimberlite pipes
<i>Stockwork</i>	An interlacing network of small and narrow (commonly measured in centimeters), close-spaced ore-bearing veinlets traversing the host rock	Footwall alteration zone of volcanic-hosted massive sulfide deposits (see Figs. 10.1, 10.4)
<i>Massive</i>	Mineralization comprising >50% of the host rock	Volcanic-hosted massive sulfide lenses (see Fig. 10.4)
<i>Tabular</i>	An ore zone that is extensive in two dimensions, but has a restricted development in its third dimension	Sandstone-type uranium deposits (see Figs. 14.3, 14.7)
<i>Vein-type</i>	Mineralization in veins, commonly discordant to the host rock layering (depositional)	Base- and precious metal veins (see Figs. 2.28, 2.29)
<i>Stratiform</i>	Mineralization confined to a specific bed and, thus, broadly conformable to the host rock layering (depositional)	Kupferschiefer-type stratiform copper deposits (see Fig. 12.4)
<i>Strata-bound</i>	Mineralization discordant to host rock layering (depositional), but restricted to a particular stratigraphic interval	Mineralized breccia bodies in Mississippi Valley-type deposits (see Fig. 13.9)



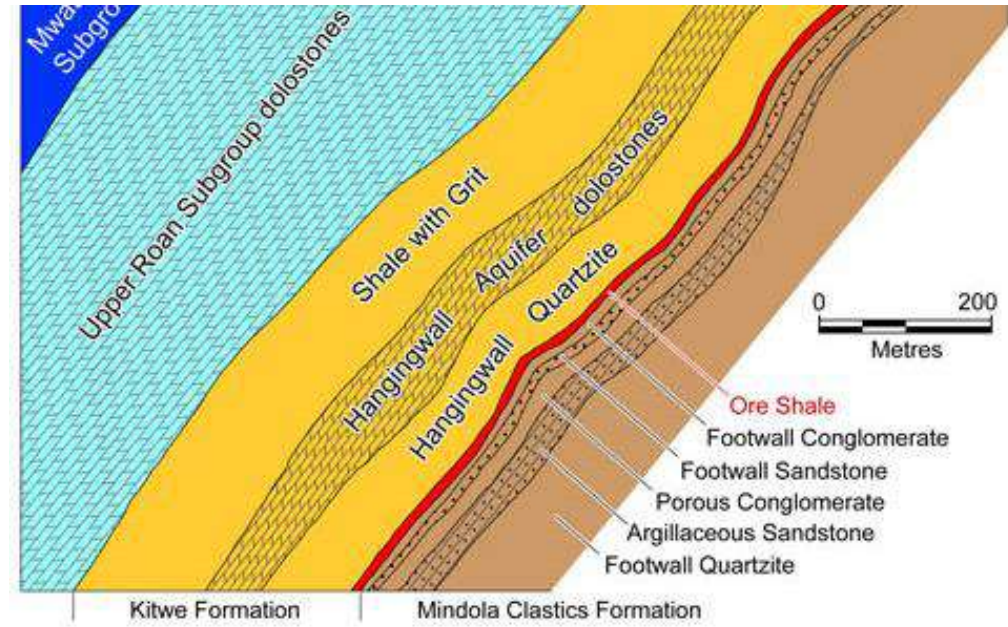
Disseminated



Stockwork



Massive



Stratiform



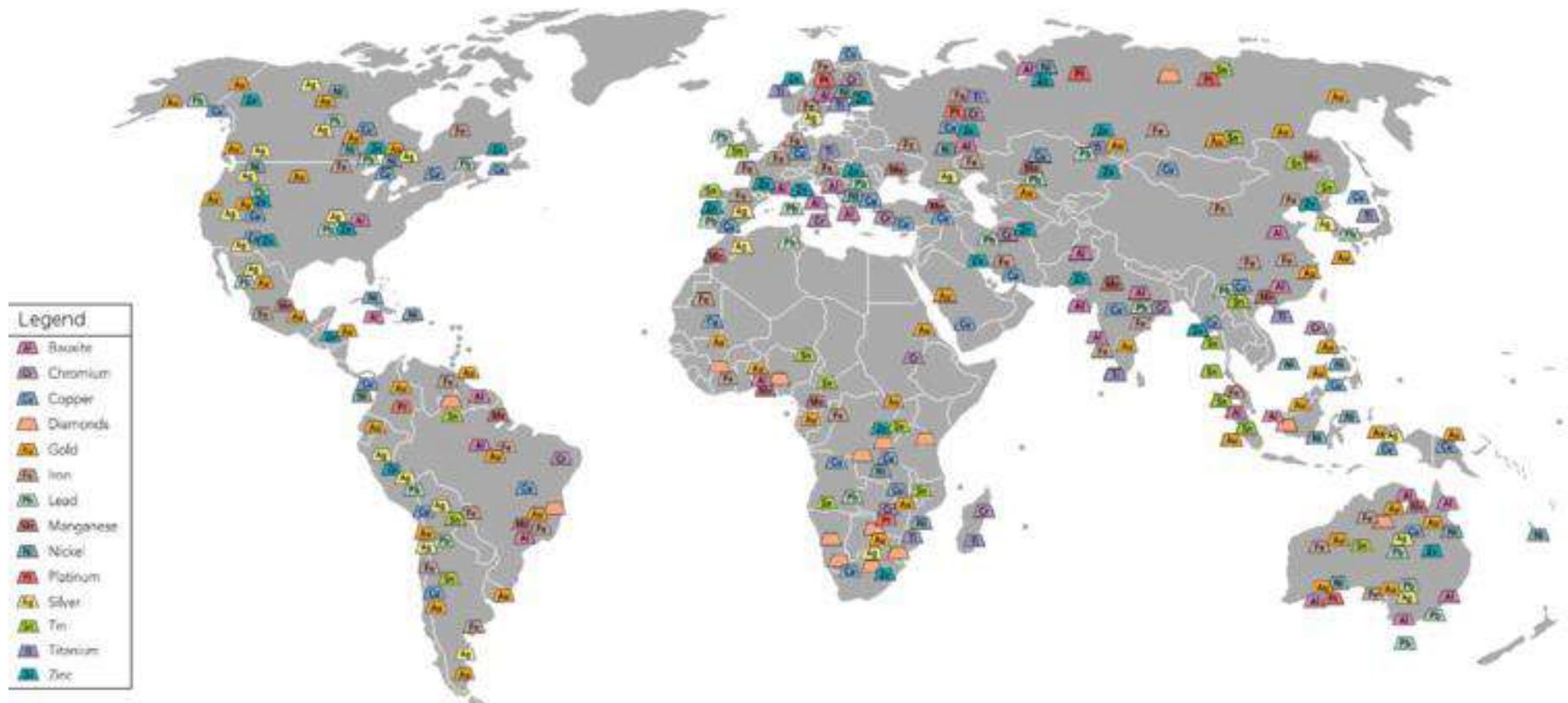
Tabular



Vein

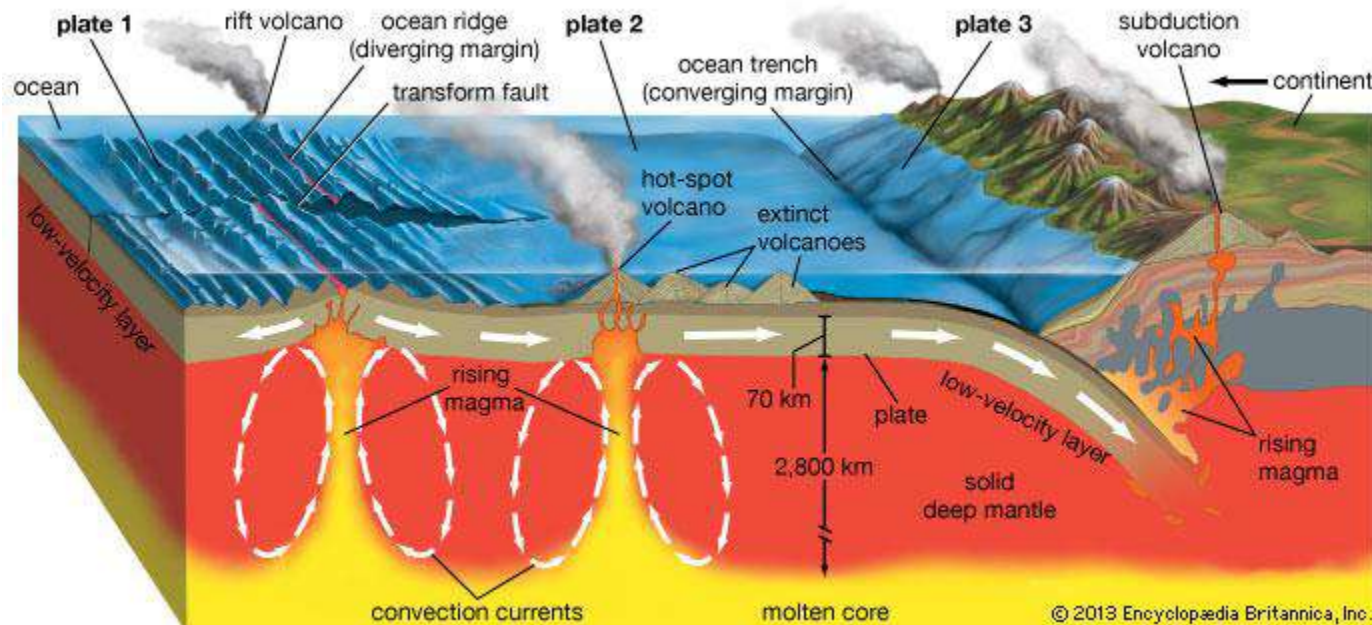
IV. Distribution of Mineral Deposits

A **metallogenic province** may be defined as **a mineralized area or region containing mineral deposits of a specific type** or a group of deposits that possess features (e.g., morphology, style of mineralization, composition, etc.) suggesting a genetic relationship. The size of **a metallogenic province** can be as large as the Superior Province (Canadian Shield) or as small as the Upper Michigan Peninsula native copper province.



A first-order control on the **localization of mineral deposits** is **tectonic setting** that, in turn, controls other factors favorable for the formation of mineral deposits. These factors – **controlled by the tectonic setting** - include:

1. the formation and composition of the associated igneous bodies,
2. the formation of sedimentary basins and the characteristics of sediments that fill the basins,
3. the development of faults and shear zones that provide conduits for mineralizing fluids or places for ore localization.



Porphyry copper deposits, volcanic-hosted massive sulfide (VMS), and podiform chromite deposits are **closely related to plate tectonics**. Other ores (Ni-sulfide deposits, sediment-hosted uranium deposits, Kupferschiefer copper deposits) **cannot yet be readily assigned to specific plate tectonic regimes or processes.**

All the common **ore-forming elements** are present in **magmas and ordinary rocks**, in amounts ranging from a few parts per billion to several thousands of parts per million. **Selective concentration of one or more ore constituents to form a mineral deposit** is achieved by some combination of the following:

- (a) **extraction** of the constituents from magmas, rocks, and oceans;
- (b) **transport** of the constituents in a fluid medium from the source region to the site of deposition; and
- (c) **localization** of the constituents at certain favorable sites.

For the present purpose, the ore-forming processes may be grouped into the following four broad categories:

- i. **Orthomagmatic ore-forming processes**
- ii. **Sedimentary ore-forming processes**
- iii. **Metamorphic ore-forming processes**
- iv. **Hydrothermal ore-forming processes**



TABLE 2.1. Average abundances of selected ore-forming elements (in ppm) in the earth's continental crust, major rock types, and seawater (simplified from the compilation by Krauskopf and Bird 1995)

Element	Crust (a)	Granite (b)	Diabase (c) (Basalt)	Shale	Seawater (d)
Al	81,300	74,300	79,400	80,000	0.003
Fe	50,000	13,700	76,600	47,200	0.003
Ti	4,400	1,500	9,400	4,600	0.0001
Mn	950	195	1,280	850	0.0002
S	260	58	123	2,240	900
C	200	200	100	1,000	28
V	135	17	264	130	0.0022
Cr	100	20	114	90	0.0003
Ni	75	1	76	68	0.0005
Zn	70	45	86	95	0.0003
Cu	55	13	110	45	0.0002
Co	25	2.4	47	19	1 x 10 ⁻⁶
Pb	13	48	7.8	20	3 x 10 ⁻⁶
U	1.8	3.4	0.6	3.7	0.0032
Sn	2	3.5	3.2	6.0	6 x 10 ⁻⁷
Mo	1.5	6.5	0.6	2.6	0.01
W	1.5	0.4	0.5	1.8	0.0001
Hg	0.08	0.1	0.2	0.4	4 x 10 ⁻⁷
Ag	0.07	0.05	0.08	0.07	3 x 10 ⁻⁶

Concentrations of Au and Pt are <0.05 ppm in rocks and <0.00001 ppm in seawater.

(a) "Crust" means the continental crust only, a part of the crust that is assumed to be made up of roughly equal parts of granite and basalt. For the oceanic crust a composition similar to that of average basalt can be assumed.

(b) "Granite" includes silica-rich rocks ranging from alkali granite to granodiorite and their volcanic equivalents.

(c) "Diabase" includes the more common varieties of basaltic lava, diabase, and dolerite.

(d) "Seawater" is an average analysis of deep Atlantic and deep Pacific water.

V. Orthomagmatic Processes

Orthomagmatic ore-forming processes are related to the evolution of magmas emplaced at crustal levels. The two end members of this span continuum processes are:

- (a) orthomagmatic processes – resulting in concentration of ore minerals as a direct consequence of silicate melt magmatic crystallization; and
- (b) (magmatic) hydrothermal processes – leading to concentration of ore minerals from magmatic hydrothermal fluids by crystallization dominated by crystal volatile equilibria.

Deposits of iron, copper, nickel, chromium, titanium, and platinum, are restricted to mafic and ultramafic rocks. In addition, deposits of some of these metals characteristically occur in particular kinds of mafic and ultramafic rocks - e.g.,

1. chromium in dunite and peridotite;
2. nickel in peridotite and norite, and;
3. titanium in gabbro and anorthosite,



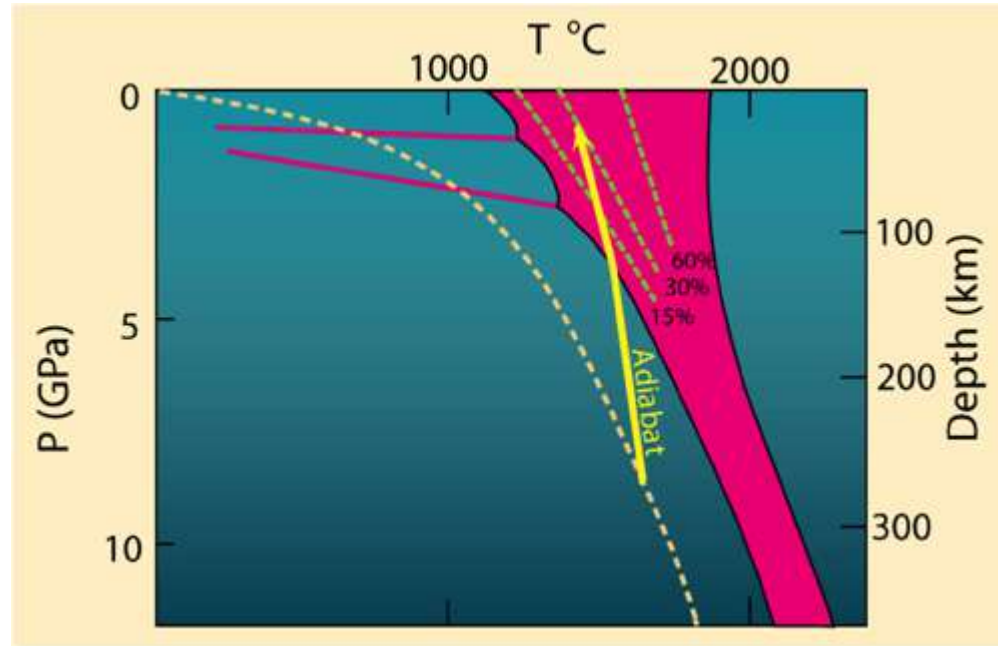
Because of the small quantity of dissolved water, crystallization of mafic and ultramafic magmas seldom leads to the generation of large amounts of ore-forming hydrothermal fluids, except perhaps when substantial assimilation of water-bearing crustal rocks is involved.

VI. Magmas as sources of Ore Constituents

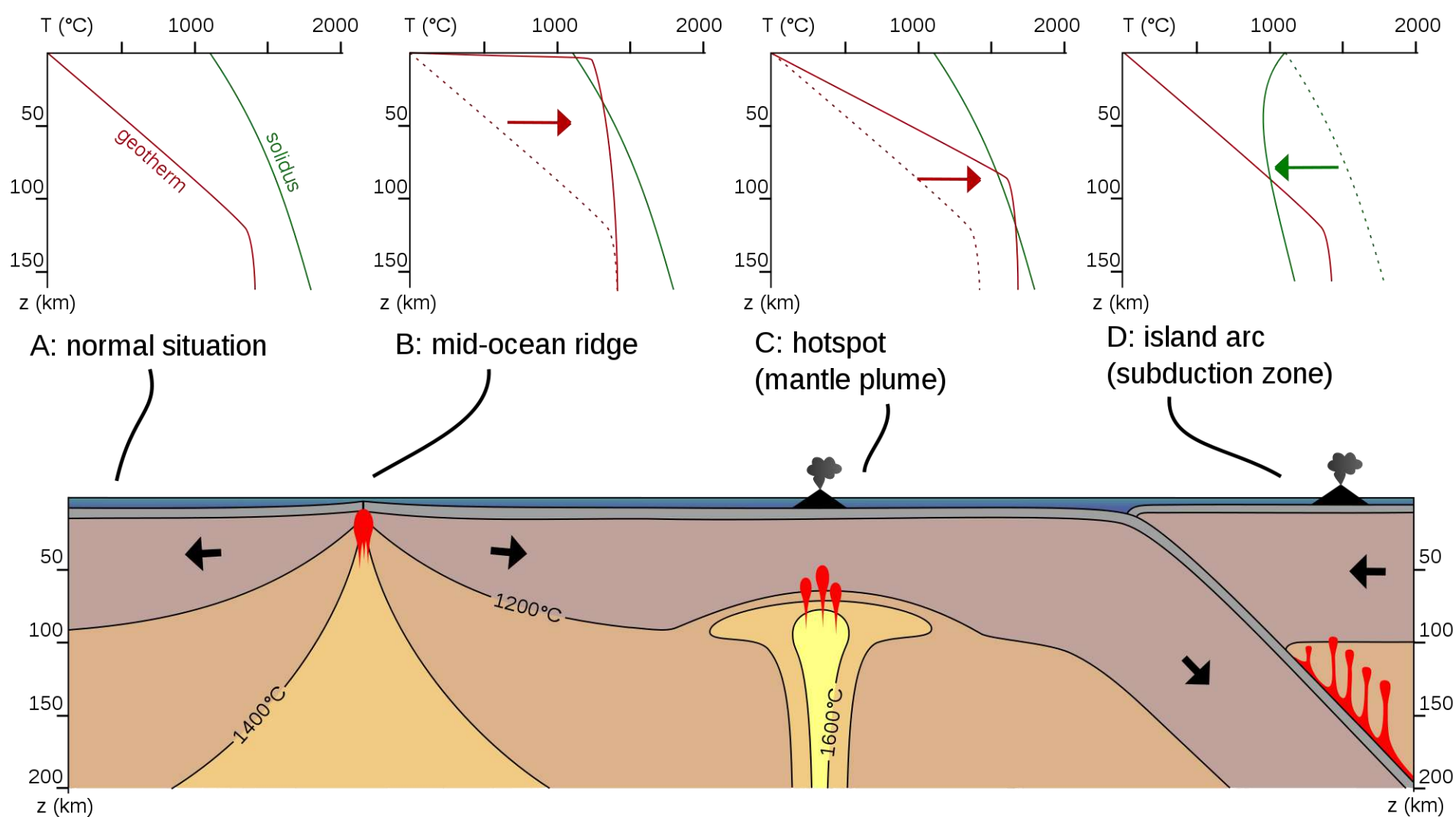
Magmas - essentially silicate melts with variable amounts of ore metals and other elements, water, and relatively minor amounts of other volatile constituents (e.g., CO_2 , H_2S , SO_2 , HCl , HF , H_2) - are generated by partial melting of lower crustal or upper mantle material.

Partial melting of the top 100-200 km of the upper mantle by **adiabatic decompression** (pressure-release melting) produces **primary magmas** of mafic (basaltic or picritic) or ultramafic (komatiitic) composition in most tectonic settings.

The wide compositional spectrum of terrestrial igneous rocks is attributable to parental magmas formed by subsequent differentiation and/or assimilation.



When a rapid decrease in pressure occurs the mantle begins to melt. This is called *adiabatic melting* – or, more commonly, *decompression melting*. *Adiabatic melting* commonly occurs at divergent plate boundaries, where two tectonic plates are moving away from each other. Mid-ocean ridges are the classic example, but *adiabatic melting* also occurs during continental lithospheric extension and in some mantle plumes.



Schematic diagram showing the physical processes within the Earth's upper mantle that lead to the generation of magma. A to D are different [plate tectonic](#) settings. The graphs show the [geotherm](#) (temperature curve inside the Earth, red) and the [solidus](#) (temperature where rock starts to melt, green). When the two curves cross each other, magma is generated by [partial melting](#).

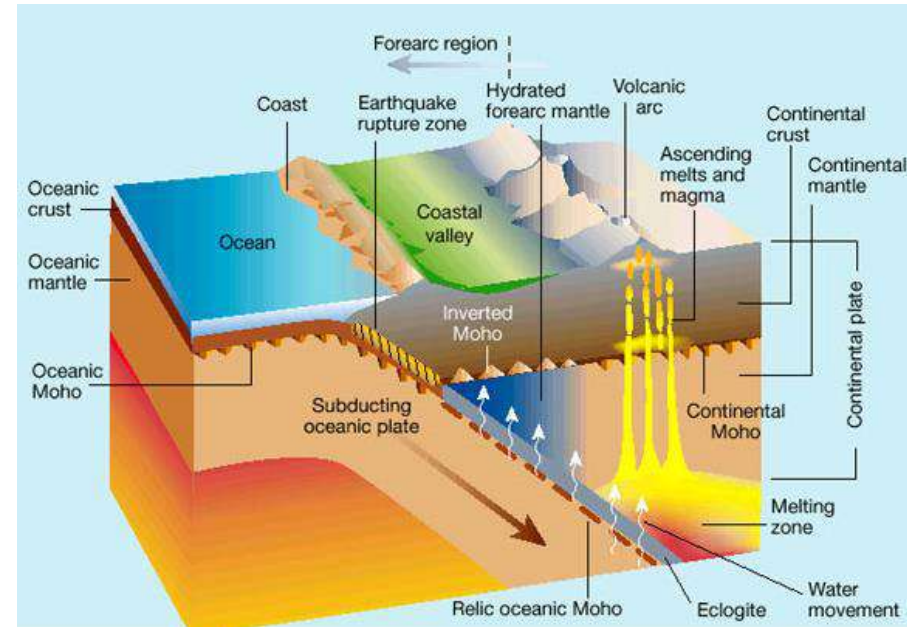
- A) the curves do not cross - no magma is generated**
- B) at mid-ocean ridges magma generation occurs at quite shallow depths due to high temperatures and very thin lithosphere**
- C) over mantle plumes magma generation occurs at larger depths due to even higher temperatures but thicker lithosphere**
- D) over subducting slabs magma generation occurs at larger depths due to lowering of melting temperature of the rock by fluids released from the slab**

The generation of significant amounts of **water-saturated magmas** or **hydrous fluids** is **unlikely in the upper mantle** because of **its low water content**. On the other hand, **dioritic and granitic magmas** generated **by partial melting** of **lower crustal rocks** are likely to be more hydrous and capable of generating an aqueous fluid phase with progressive crystallization (magmatic hydrothermal solutions).

The two main end-member **models of partial melting** are (two types of melting):

(a) **equilibrium or batch melting** that involves **continuous reaction and equilibration** of the partial melt with the **crystalline residue** - the **melted rock** - until mechanical conditions allow the melt to escape (or segregate) as a single "batch" of magma; and

(b) **fractional melting** in which the partial melt is continuously removed from the system as soon as it is formed, thereby preventing further reaction between the melt and the solid residue.



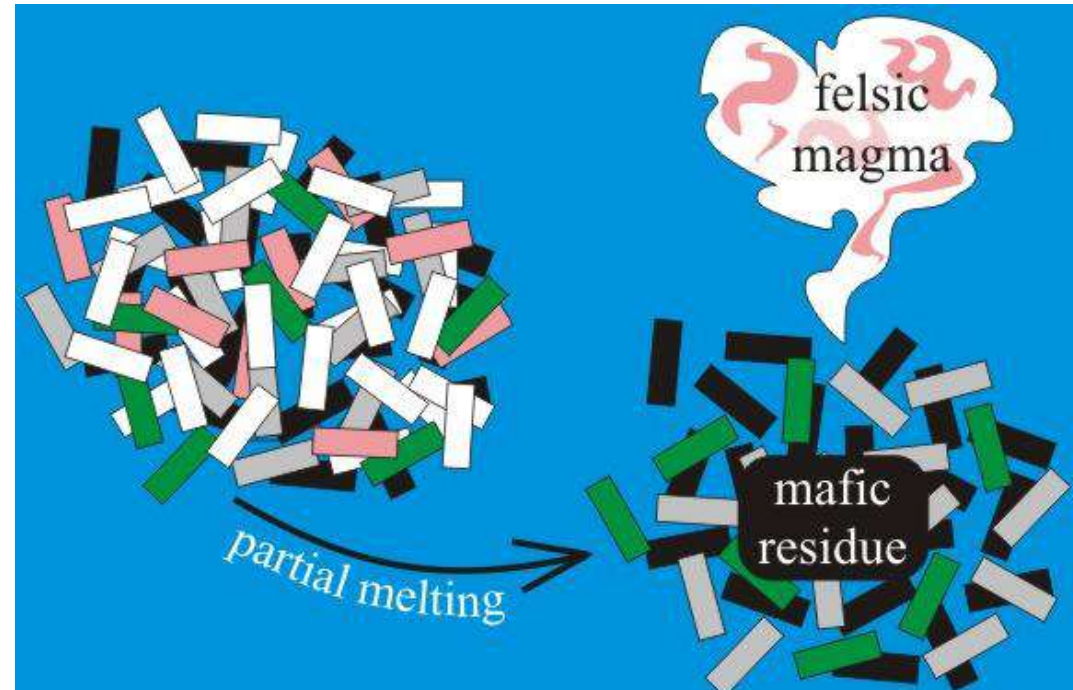
The mantle, with an estimated **sulfur concentration** in the range of 300-1,000 ppm, is believed to be the **dominant source of sulfur carried in basaltic magmas**. During **partial melting of the mantle the available iron sulfide would melt well before the beginning of silicate melting**.

Estimates of sulfur concentration in oceanic basalts is from 600 ± 150 ppm to as high as 1,600 ppm.

It is, however, difficult to predict the sulfur contents of silicate melts, because **the solubility of sulfur** is controlled by a number of interdependent variables, such as **temperature, pressure, O_2 , S_2 and, especially, the activities of FeO and SiO_2 in the melt**.

The sulfur solubility in silicate melts decreases with:

- Decreasing temperature,
- Increasing activity of FeO or increasing activity of SiO_2 , and
- decreasing S_2 or increasing O_2 .



The actual amount of juvenile sulfur (liquid sulfur) carried by a basaltic magma might be significantly higher than its saturation limit at the source, if some of the sulfide melt in a given volume of mantle material was incorporated into the partial melt as an immiscible phase. The sulfur content might also be enhanced by assimilation of sulfur from the country rocks. I-type granitoid-magmas have a greater potential for bulk assimilation of country-rock sulfur than S-type magmas.

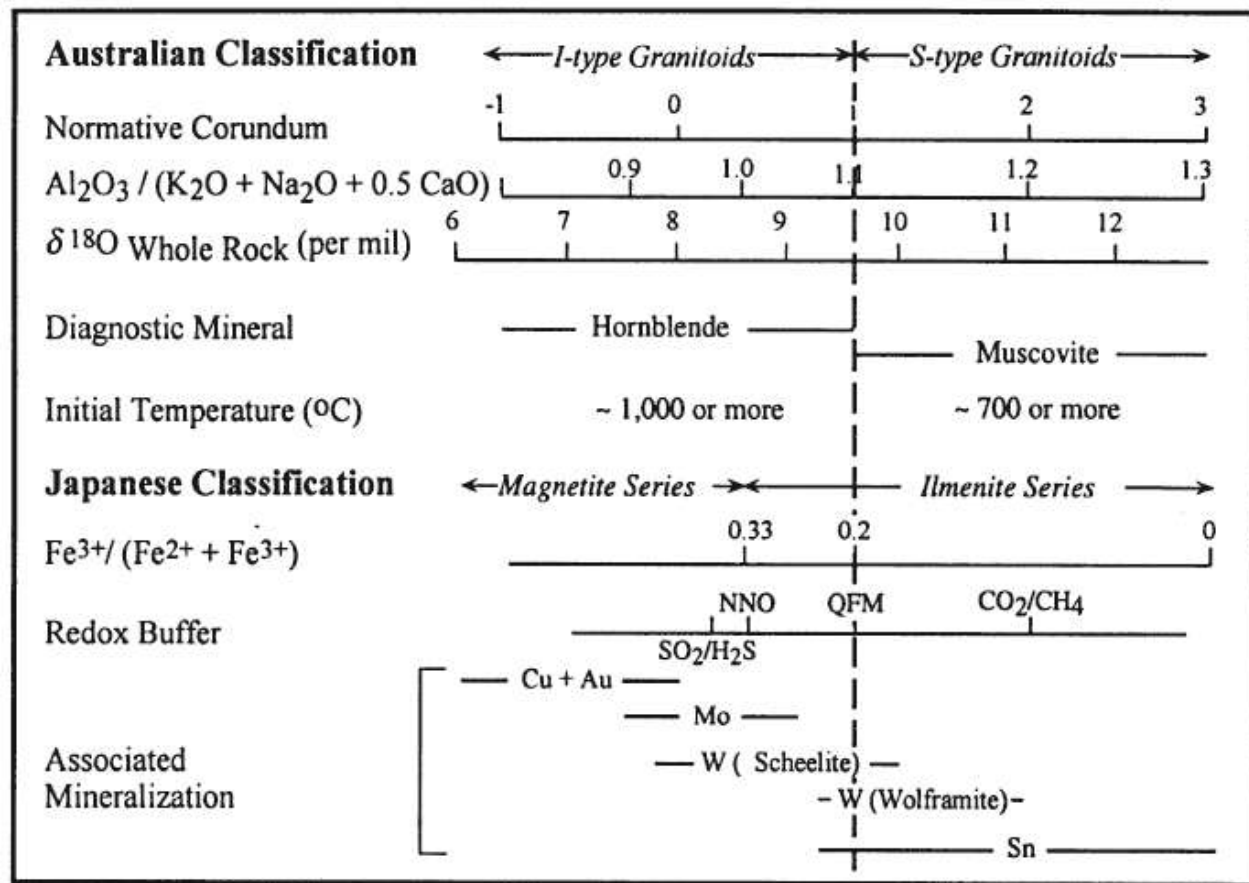
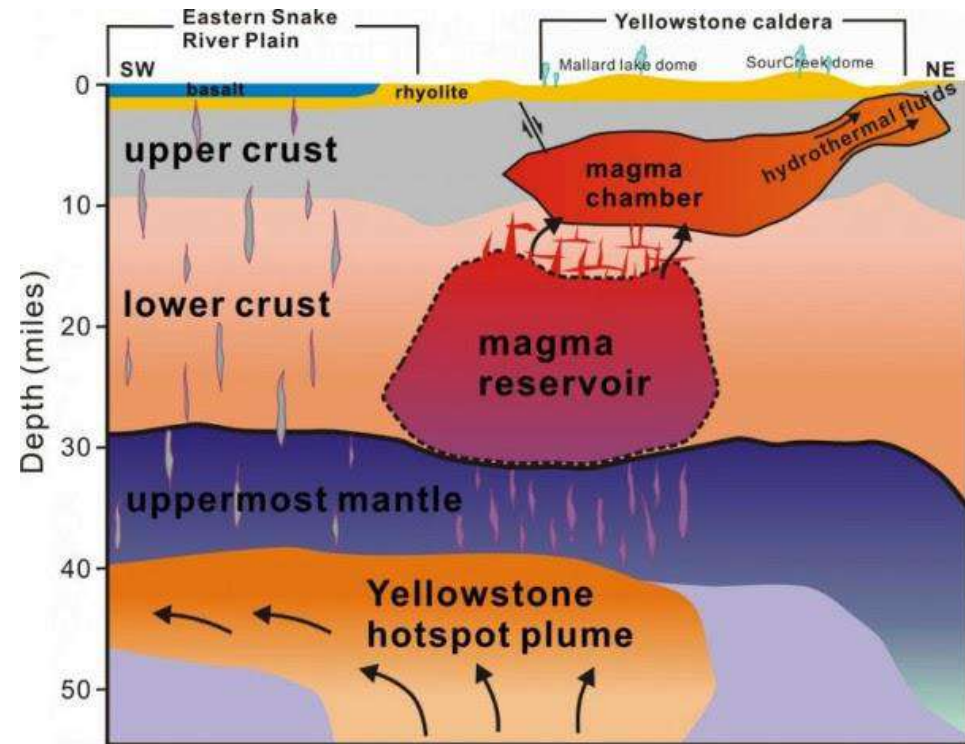


Figure 2.2. Generalized characteristics of I-type and S-type granitoids (after Ohmoto 1986). Note that magnetite-series and ilmenite-series granitoids, as defined by Ishihara (1977) on the basis of modal compositions (relative abundance of magnetite vs. ilmenite) and bulk $Fe_2O_3:FeO$ ratios, correspond only roughly to I-type and S-type granitoids.

The separation of **liquid phase/hydrothermal fluid** (aqueous/vapor) from a magma, is controlled mainly by **the solubility of H₂O in the melt**, which is very strongly pressure-dependent but, however, only weakly temperature dependent .

The amount of **hydrothermal fluid** that will be **exsolved** from a magma depends on its **initial H₂O content**, its **depth of emplacement**, and its **crystallization history**. The **initial H₂O contents** of magmas ranges from “2.5 to 6.5 wt%”, with a median value close to 3.0 wt% (in basaltic magma). For **dioritic and granitic magmas**, the initial melt would contain in excess of 3.3 wt% H₂O.

When an ascending **water-bearing magma** begins to crystallize, the volume of the residual magma becomes smaller and smaller, and H₂O (with other volatiles) gets concentrated in this decreasing volume of residual magma. The exsolved aqueous **hydrothermal fluid** phase can be highly saline.

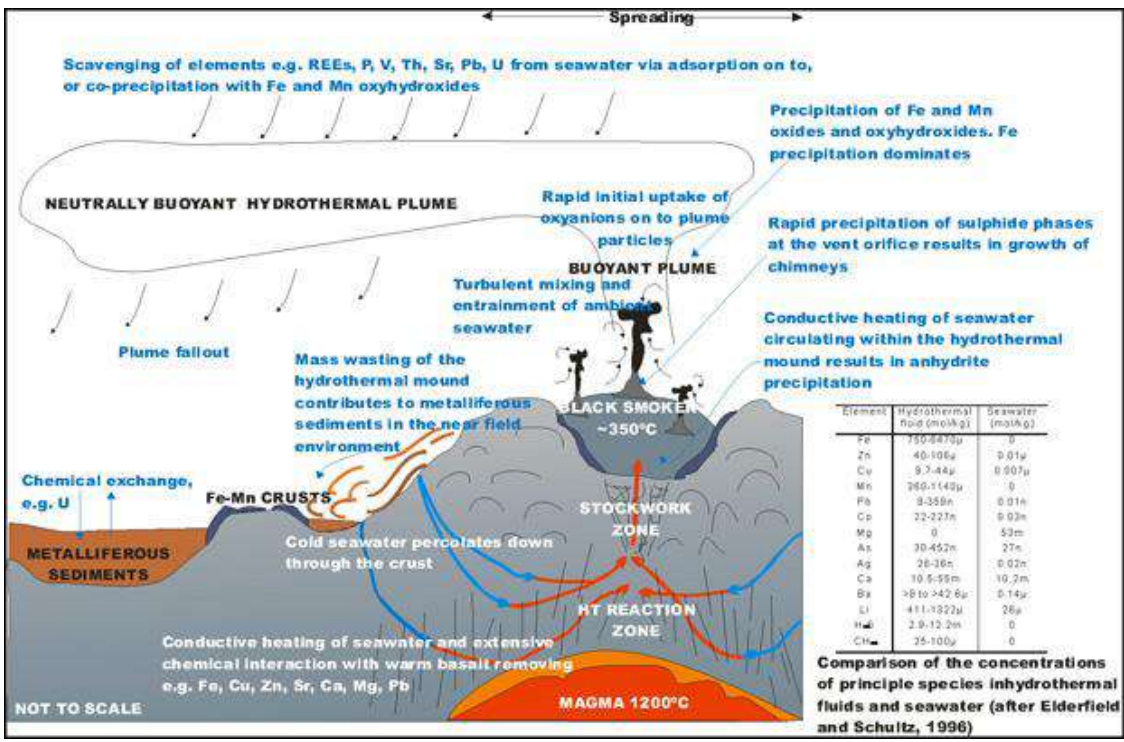


The **sulfur content** of the **hydrothermal solution** is determined by its $\text{SO}_2/\text{H}_2\text{S}$ ratio that increases with increasing O_2 of the parent magma.

Hydrothermal solutions derived from **I-type magmas** (with high O_2) may contain large quantities of SO_2 as well as H_2S . (How?)

At lower temperatures both:

- the hydrolysis of SO_2 ($4\text{SO}_2 + 4\text{H}_2\text{O} = \text{H}_2\text{S} + 3\text{H}_2\text{SO}_4$) and,
 - the reaction of SO_2 with Fe^{2+} -bearing minerals of the wall-rock ($\text{SO}_2 + 6\text{FeO} + \text{H}_2\text{O} = \text{H}_2\text{S} + 3\text{Fe}_2\text{O}_3$)
- increase the activity of H_2S causing precipitation of sulfide ore minerals from the highly saline (metal chloride complexes) the hydrothermal solution.



In contrast, **hydrothermal solutions** derived from **S-type magmas (with low O₂)** may contain as much H₂S as those derived from I-type magmas, but because of lower O₂ they contain much smaller amounts of SO₂ and, therefore, **low total sulfur**.

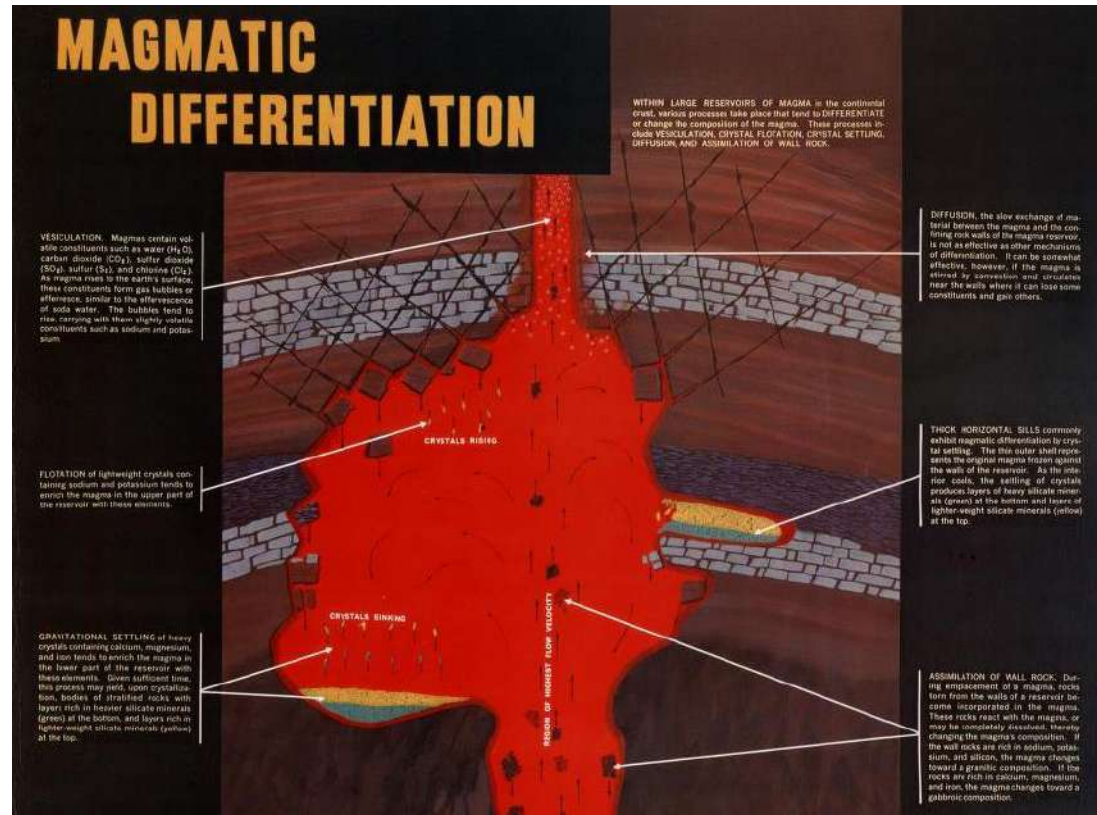
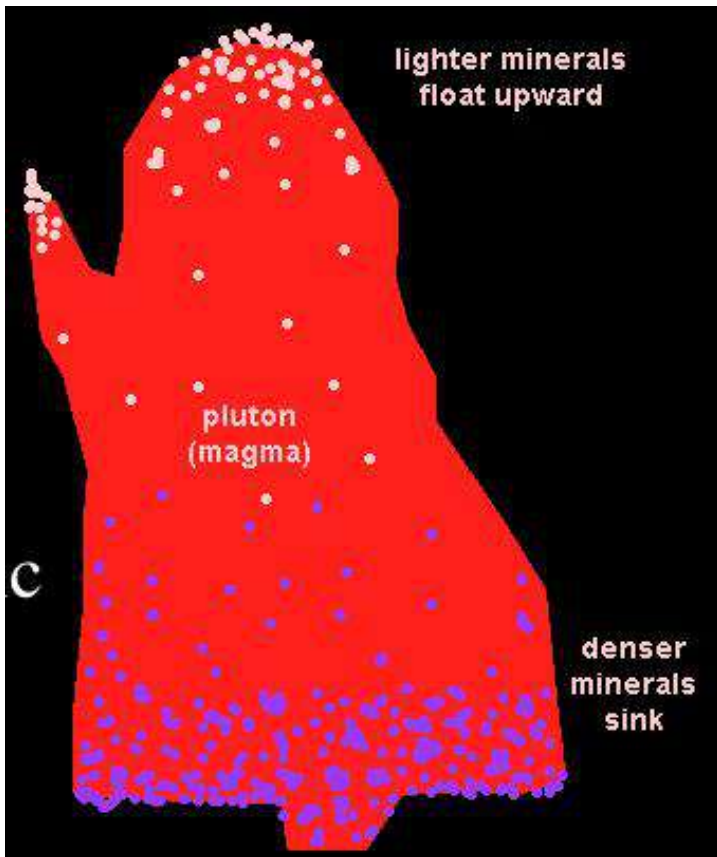
Thus, **hydrothermal solutions that separate from I-type magmas tend to produce Cu-Mo-Zn-Fe sulfide deposits**, whereas hydrothermal solutions from S-type magmas generally precipitate smaller quantities of sulfides, mainly pyrrhotite, and correspondingly larger quantities of oxides, such as cassiterite.

Sulfur is one of the most abundant volatiles in magmas. Sulfur has significant effects on the partitioning of a wide variety of elements between silicate melts, liquid metals, gases, and solids, and consequently magmatic sulfur species exert major controls on the genesis of a large variety of ore deposits. The behavior of sulfur in silicate melts/hydrothermal solutions is much more complex than that of other volatiles, such as water and carbon dioxide, because of its different oxidation states. At low oxygen fugacities, sulfide (S²⁻) is the predominant sulfur species whereas at higher oxygen fugacities sulfate (SO₄²⁻) is dominant. Other species such as sulfite (S⁴⁺) may exist as well at specific conditions. It is often difficult to predict the behavior of sulfur in natural and industrial processes.

VII. How would ore-minerals concentrated by magmatic crystallization?

Ore constituents present in a magma may be concentrated further during the course of crystallization. Three **magmatic differentiation processes** have been considered particularly important for the formation of **orthomagmatic ore deposits**:

1. Liquid immiscibility;
2. Gravitational settling;
3. Filter pressing.



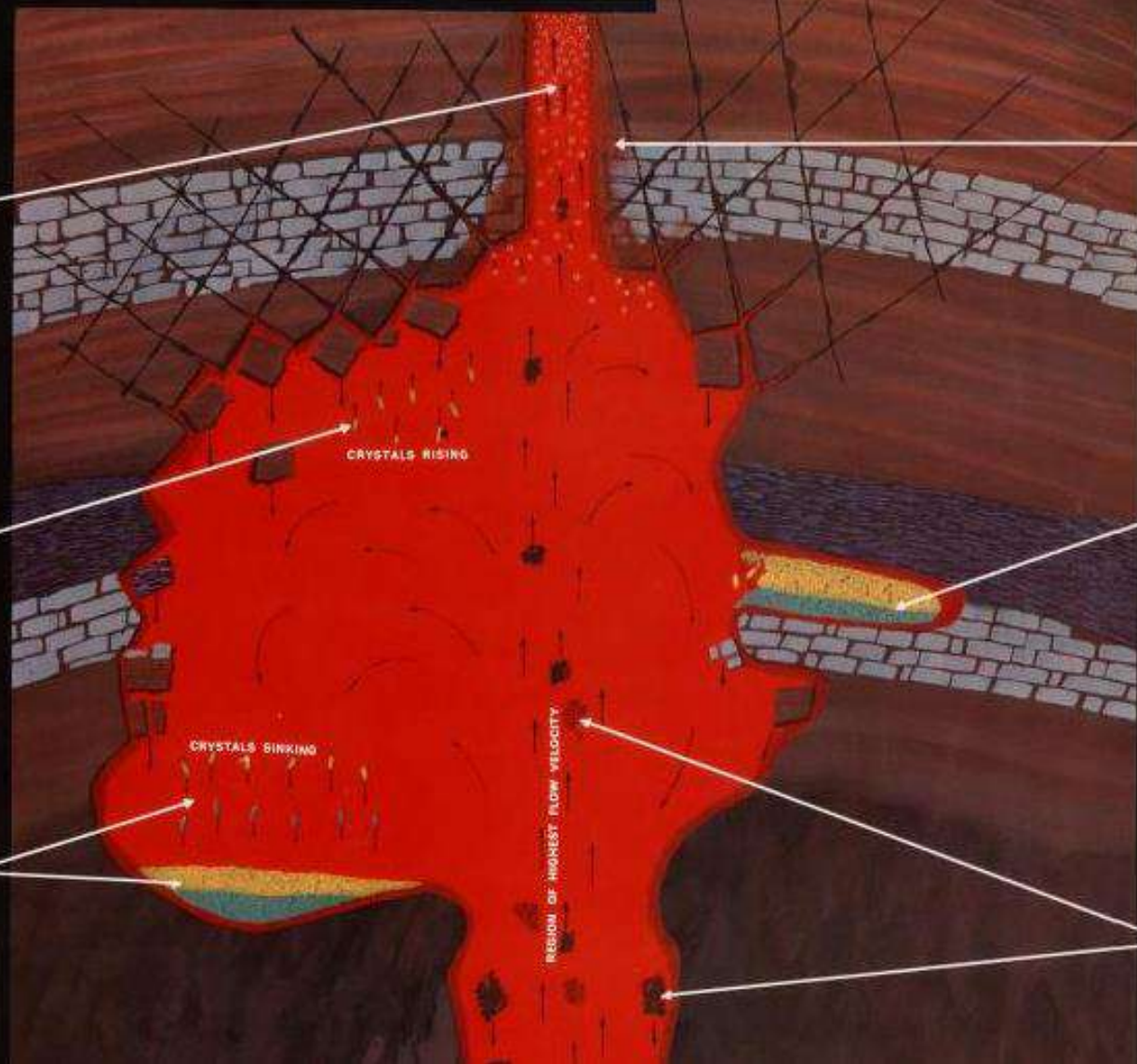
MAGMATIC DIFFERENTIATION

WITHIN LARGE RESERVOIRS OF MAGMA in the continental crust, various processes take place that tend to DIFFERENTIATE or change the composition of the magma. These processes include VESICULATION, CRYSTAL FLOTATION, CRYSTAL SETTLING, DIFFUSION, AND ASSIMILATION OF WALL ROCK.

VESICULATION: Magmas contain volatile constituents such as water (H_2O), carbon dioxide (CO_2), sulfur dioxide (SO_2), sulfur (S_2), and chlorine (Cl_2). As magma rises to the earth's surface, these constituents form gas bubbles or effervesce, similar to the effervescence of soda water. The bubbles tend to rise, carrying with them slightly volatile constituents such as sodium and potassium.

FLOTATION of lightweight crystals containing sodium and potassium tends to enrich the magma in the upper part of the reservoir with these elements.

GRAVITATIONAL SETTLING of heavy crystals containing calcium, magnesium, and iron tends to enrich the magma in the lower part of the reservoir with these elements. Given sufficient time, this process may yield, upon crystallization, bodies of stratified rocks with layers rich in heavier silicate minerals (green) at the bottom, and layers rich in lighter-weight silicate minerals (yellow) at the top.



CRYSTALS RISING

CRYSTALS SINKING

REGION OF HIGHEST FLOW VELOCITY

DIFFUSION, the slow exchange of material between the magma and the confining rock walls of the magma reservoir, is not as effective as other mechanisms of differentiation. It can be somewhat effective, however, if the magma is stirred by convection and circulates near the walls where it can lose some constituents and gain others.

THICK HORIZONTAL SILLS commonly exhibit magmatic differentiation by crystal settling. The thin outer shell represents the original magma frozen against the walls of the reservoir. As the interior cools, the settling of crystals produces layers of heavy silicate minerals (green) at the bottom and layers of lighter-weight silicate minerals (yellow) at the top.

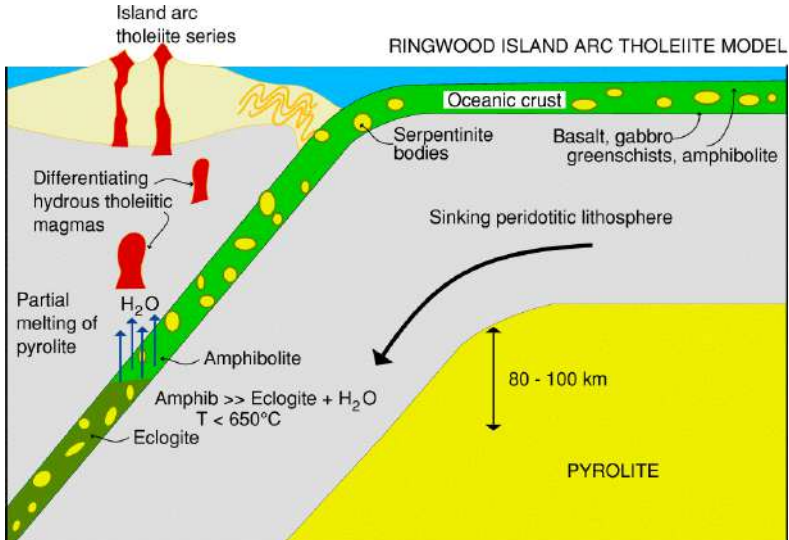
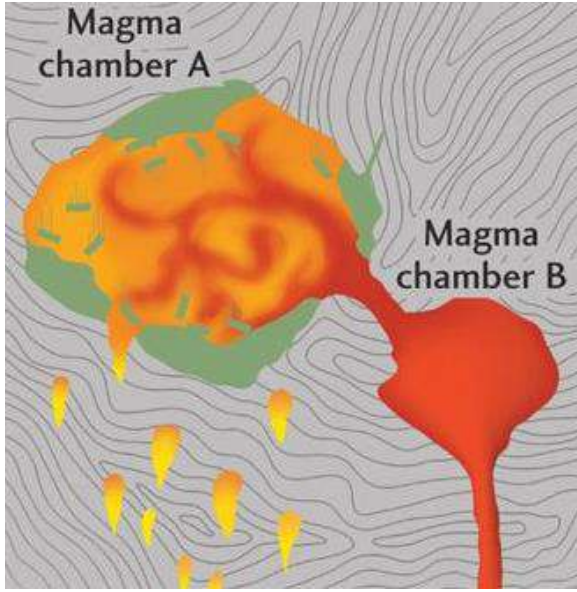
ASSIMILATION OF WALL ROCK: During emplacement of a magma, rocks torn from the walls of a reservoir become incorporated in the magma. These rocks react with the magma, or may be completely dissolved, thereby changing the magma's composition. If the wall rocks are rich in sodium, potassium, and silicon, the magma changes toward a granitic composition. If the rocks are rich in calcium, magnesium, and iron, the magma changes toward a gabbroic composition.

1. Liquid immiscibility:

Liquid immiscibility is the phenomenon of separation of a cooling magma into two or more liquid phases of different composition in equilibrium with each other.

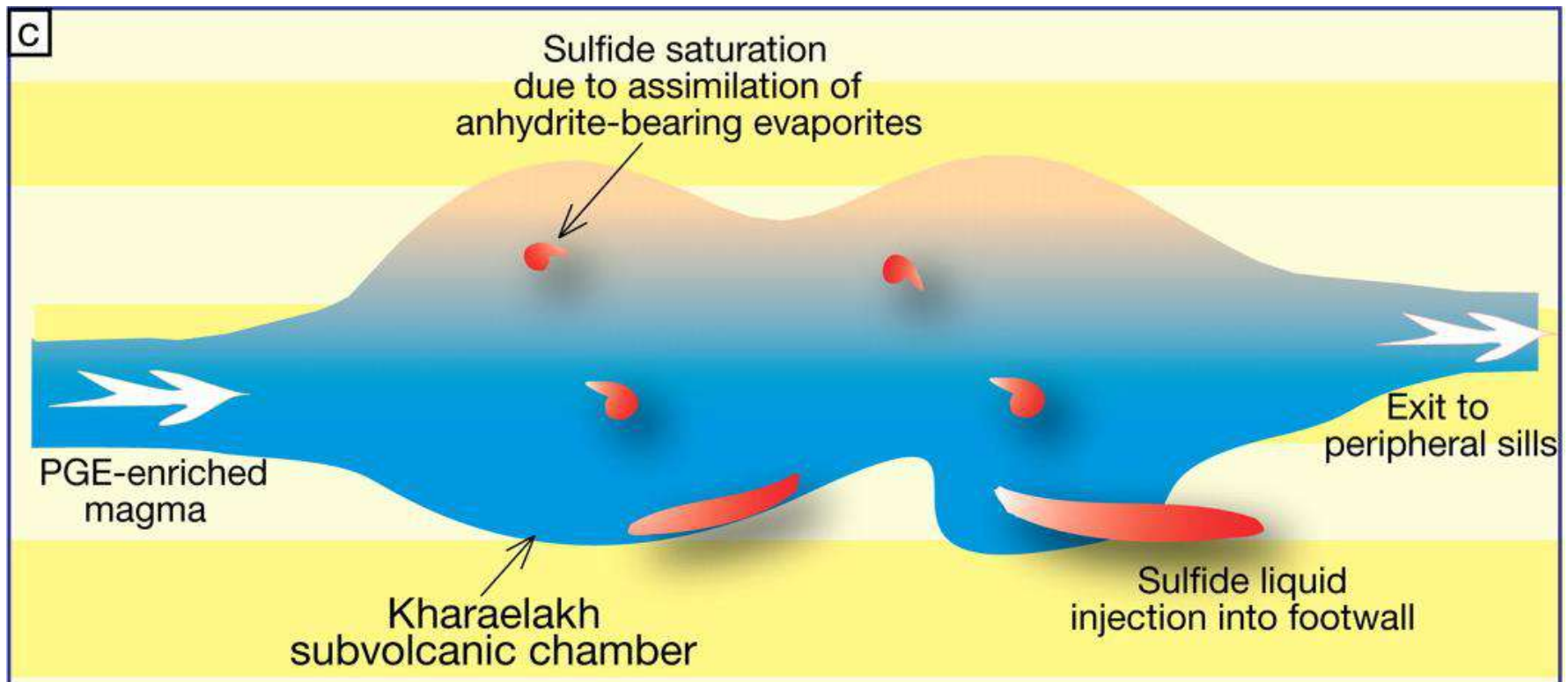
There are three cases of liquid immiscibility under geologically reasonable conditions:

- 1. separation of Fe-rich tholeiitic magmas into two melts/magmas, one felsic (rich in SiO₂) and the other mafic (rich in Fe);
- 2. splitting of CO₂-rich alkali magmas into one melt rich in CO₂ which may account for the origin of carbonatite magmas and the other rich in alkalis and low in silica, which may account for the origin of nephelinite magma; and
- 3. segregation of oxy-sulfide melts containing a few percent dissolved oxygen from sulfide-saturated mafic or ultramafic magmas.



Conditions or processes that are likely to promote **sulfide immiscibility** in a mafic or ultramafic magma are:

- (a) cooling the magma causes crystallization of silicate minerals, which **decreases the magma sulfur solubility, and consequently increases the sulfur concentration in the residual magma**;
- (b) **silica enrichment of the magma by reaction with felsic country rocks**
- (c) **mixing of a more fractionated magma with a less fractionated magma, both of which were nearly saturated with sulfur**;
- (d) **assimilation of sulfur from country rocks**; and
- (e) other processes which can, in theory, cause sulfide saturation are **oxidation and an increase in pressure**.



Fractional segregation of a sulfide-saturated silicate magma occurs during the crystallization of the parent magma. The crystallization of even a small amount of olivine (or other sulfur-free minerals) - from the parent magma - leads to sulfide-saturated magma immiscibility.

A small amount of sulfide melt segregating from a silicate magma is likely to be dispersed as minute droplets (more dense) in the magma. Chalcophile elements (e.g., Ni, Cu) are strongly partitioned into the sulfide melt.

Batch segregation of sulfide melt by immiscibility is induced by a sudden change in intensive parameters (e.g., due to sulfur or silica assimilation from country rocks). Such sulfide segregation may or not be accompanied by silicate crystallization, but sulfide segregation before the onset of significant silicate crystallization would provide a more favorable situation for the formation of magmatic segregation deposits.

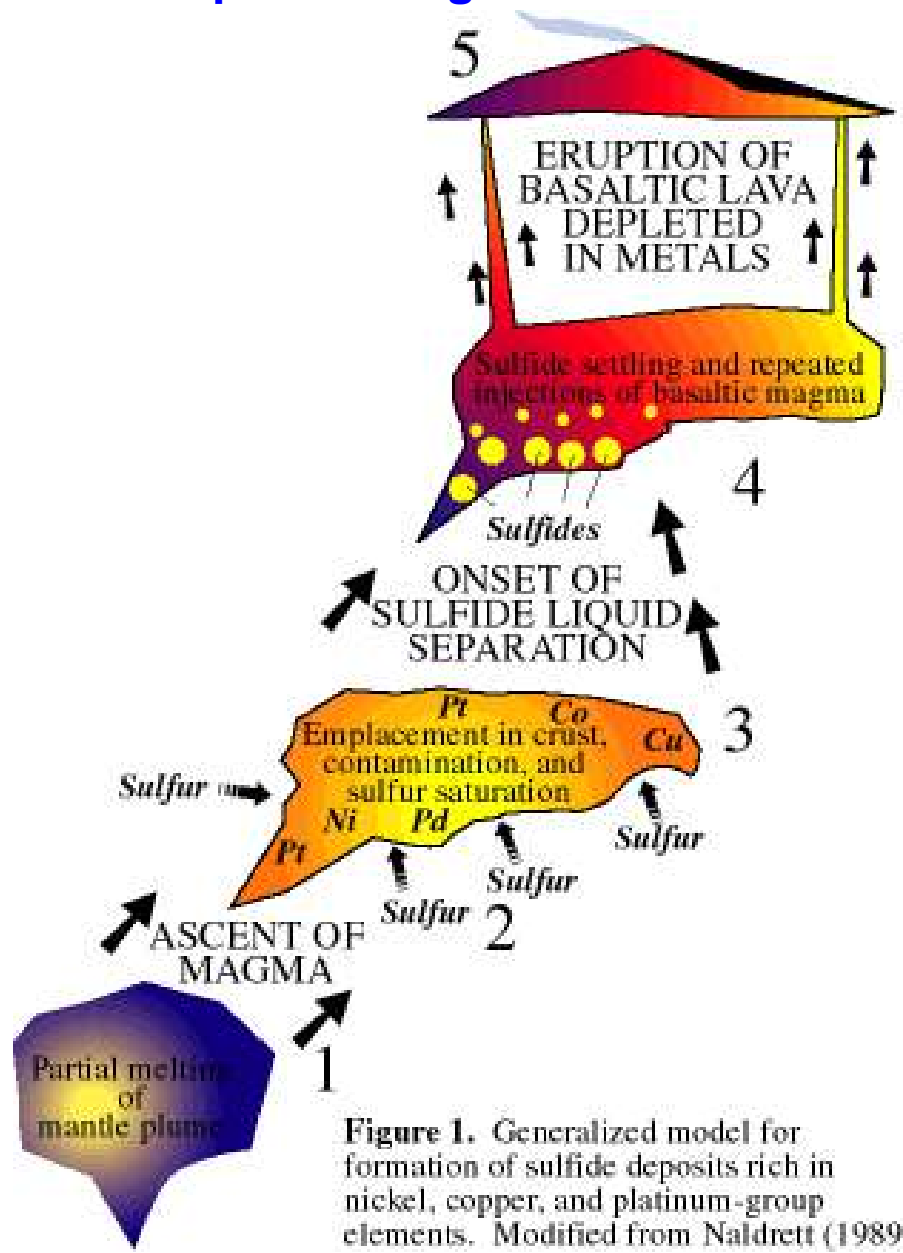


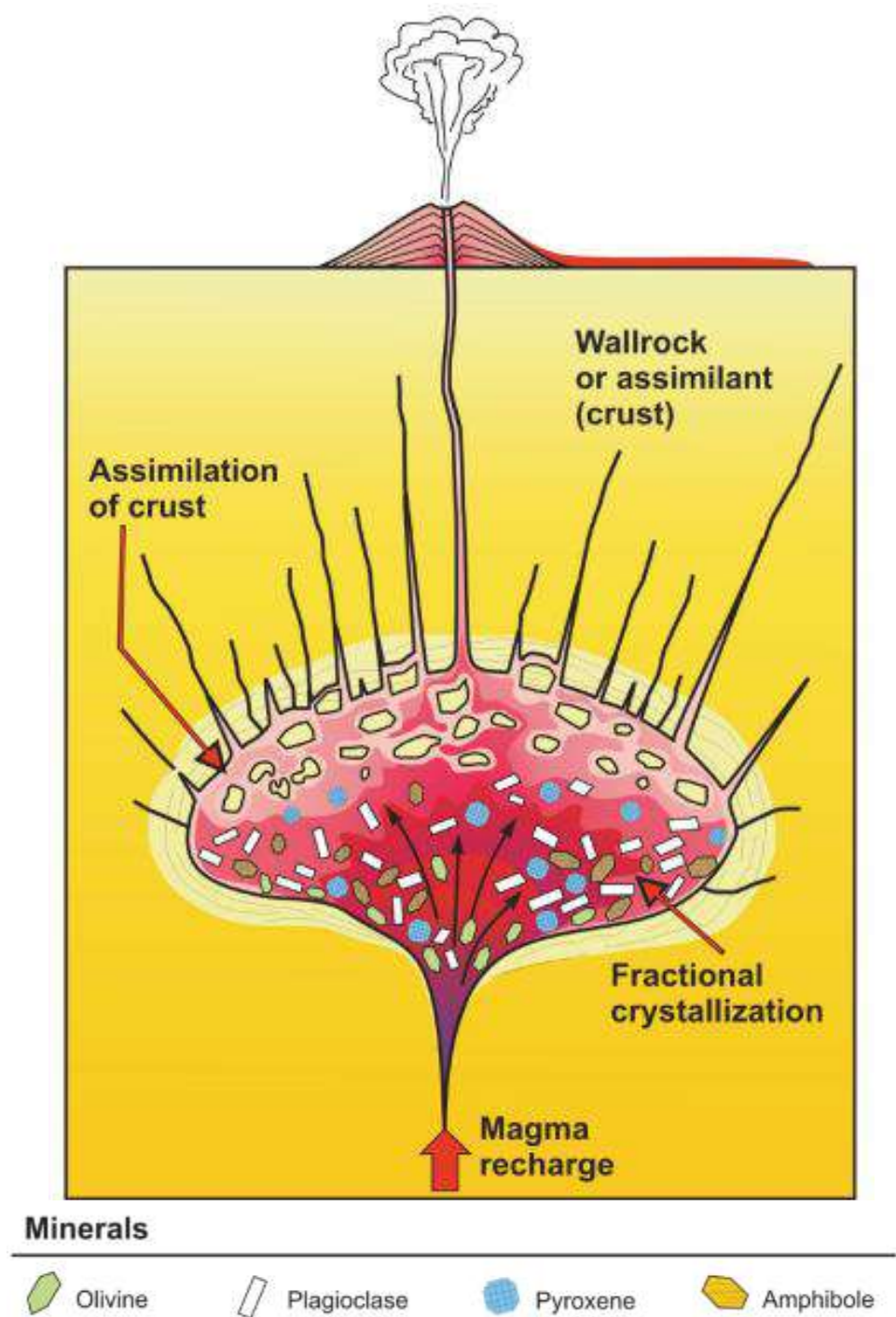
Figure 1. Generalized model for formation of sulfide deposits rich in nickel, copper, and platinum-group elements. Modified from Naldrett (1989).

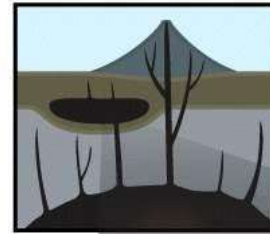
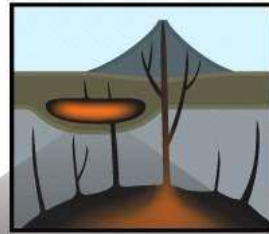
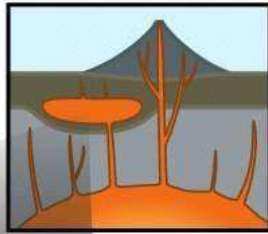
2. Gravitational settling:

The formation of **massive deposits** of magmatic crystallization products, **such as chromite and sulfides**, requires that they are concentrated by some mechanism in a restricted part of the magma chamber.

A possible mechanism of **crystal/liquid separation** in a magma undergoing crystallization is **gravitational settling (or floating) of crystals** by virtue of their density differences relative to the liquid.

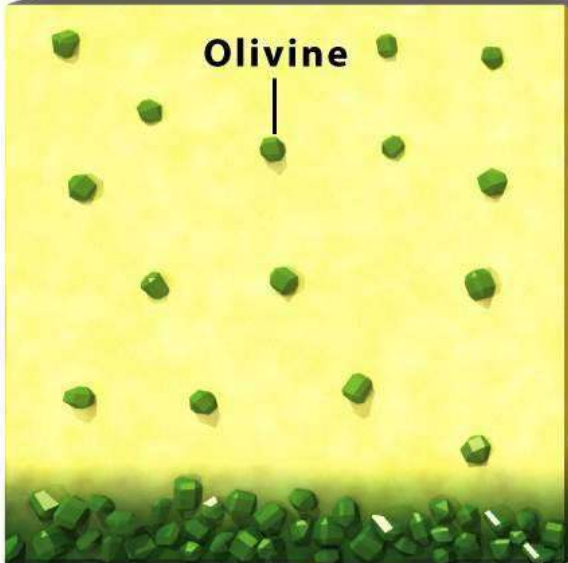
Cumulate layers, including chromite rich layers, in large differentiated complexes such as the **Bushveld** and the **Stillwater**, have generally been regarded as products of **gravitational crystal settling**.





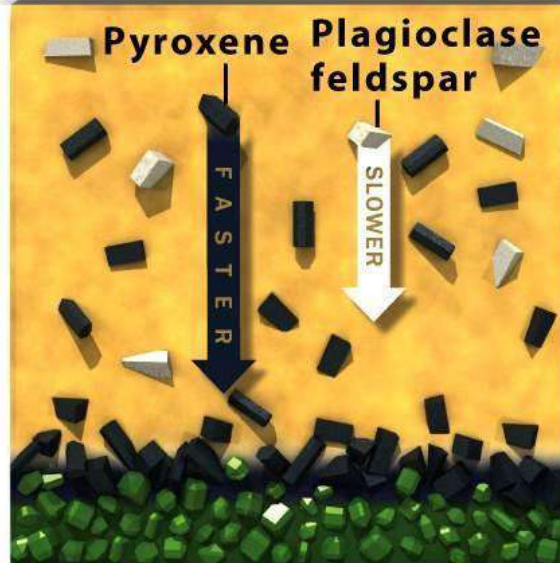
1200°C

Olivine



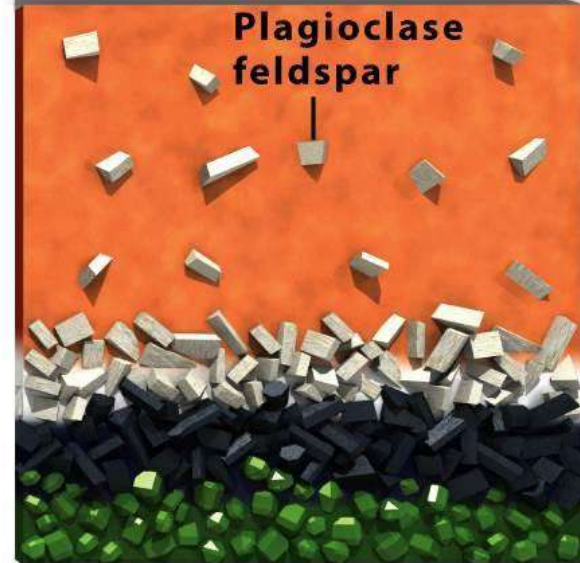
900°C

Pyroxene
Plagioclase
feldspar



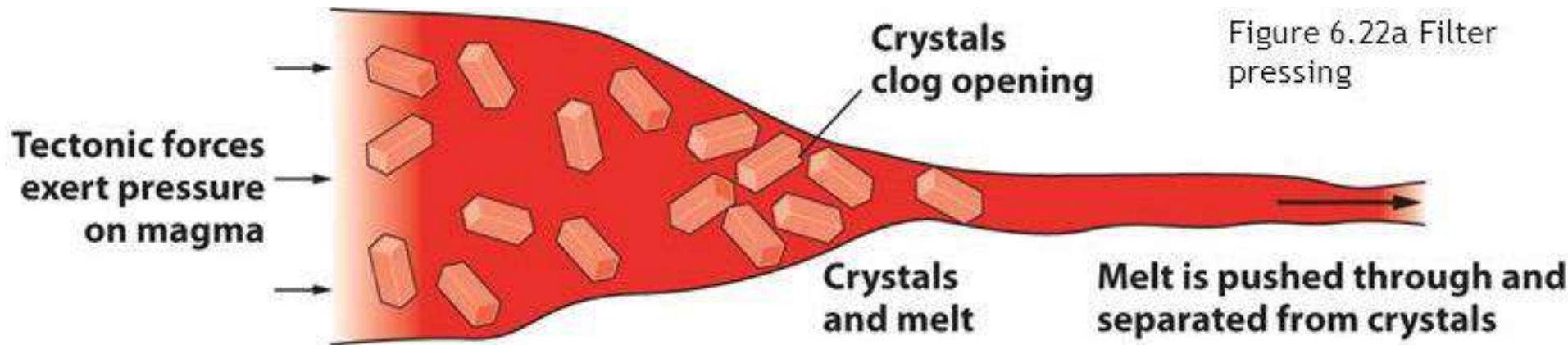
600°C

Plagioclase
feldspar

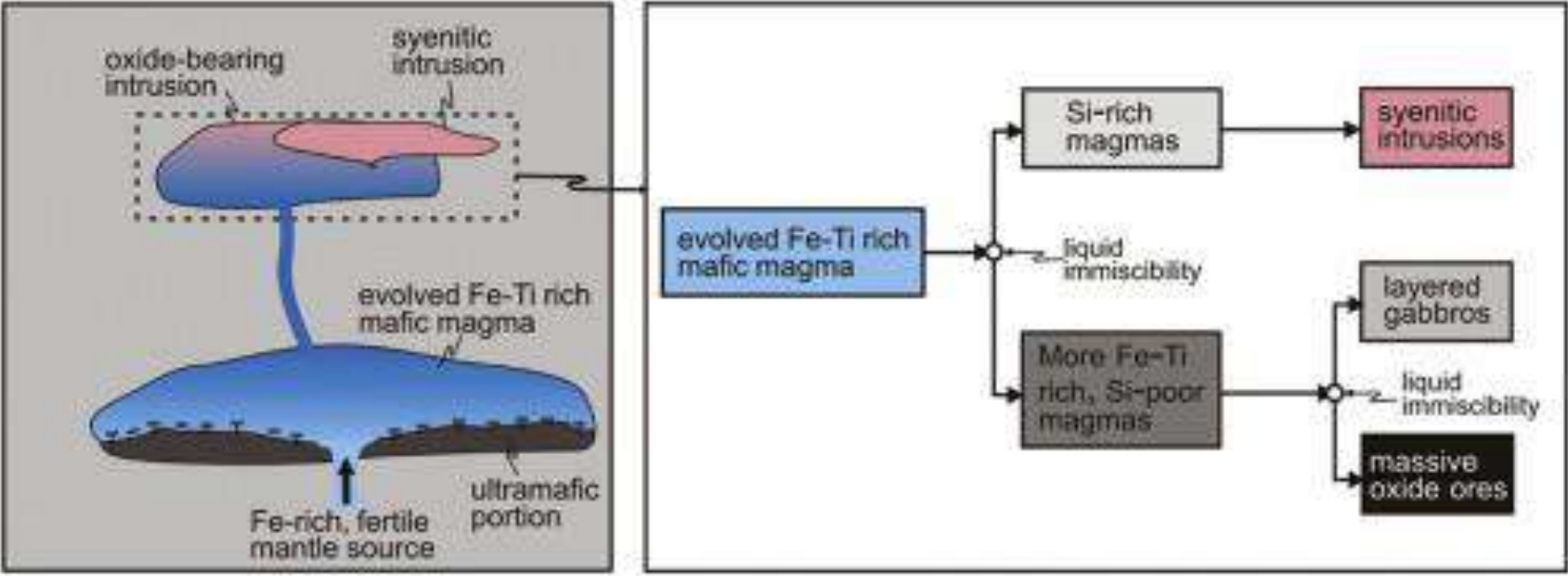


3. Filter pressing:

Magmatic segregation deposits may also form by crystallization of residual magmas. A mafic magma without a high enough O_2 for early crystallization of Fe-Ti oxide minerals would produce enrichment of iron and titanium in the residual magma. This heavier liquid, then, may drain downward, collect below as a segregation resting on a solid floor of early formed sunken crystals, and crystallize into a layer with significant concentration of Fe-Ti oxide minerals.



In some situations, the residual magma may be squeezed out by filter pressing and form magmatic injection deposits. The Fe-Ti oxide deposits associated with anorthosites and anorthositic gabbros are believed to have formed by gravitative accumulation and injection of residual magmas.

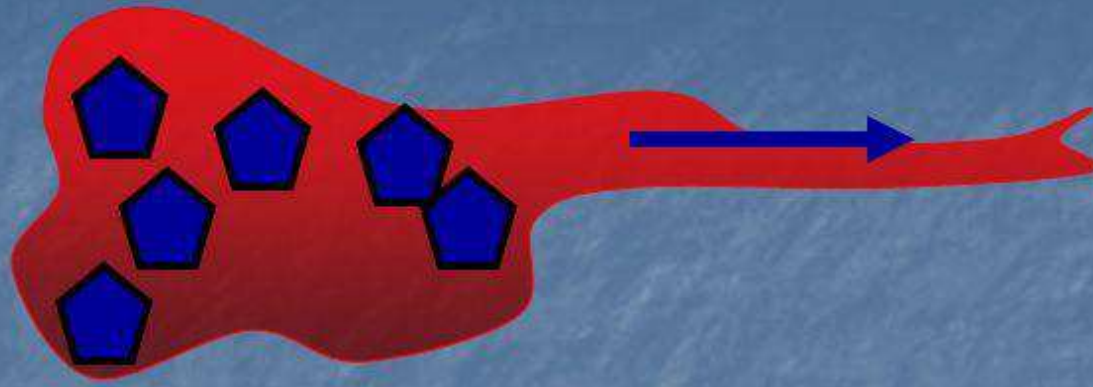




During the initial period of the slurry filtration, the mineral solid particles are trapped within the pores forming the cake. The liquid passes through the bed of the solid and through the filter medium. Then, the filter cake is removed by back flushing. As the thickness of the cake increases, the rate of filtration decreases

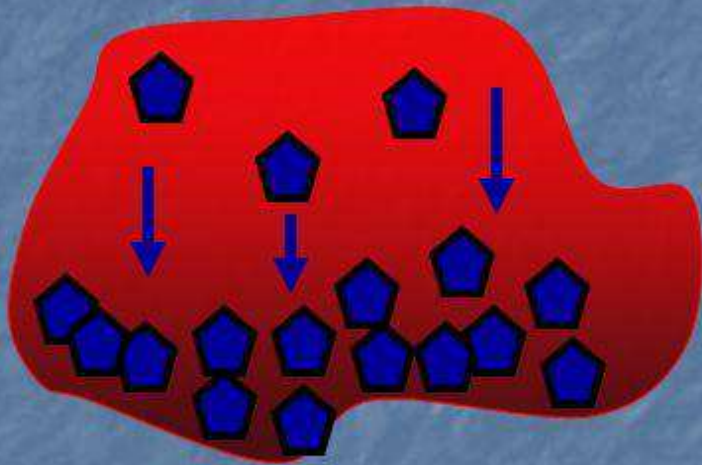
Three ways crystals separate from a melt:

34



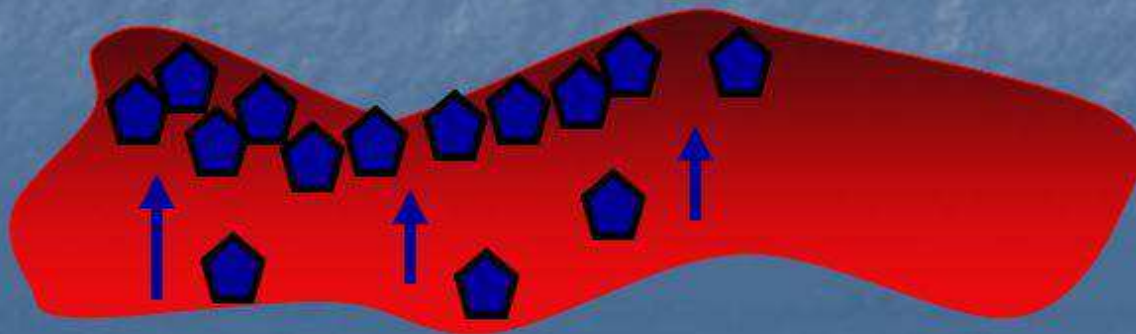
Filter pressing:

- Remaining melt is pushed through a fracture and separated from xalized melt.



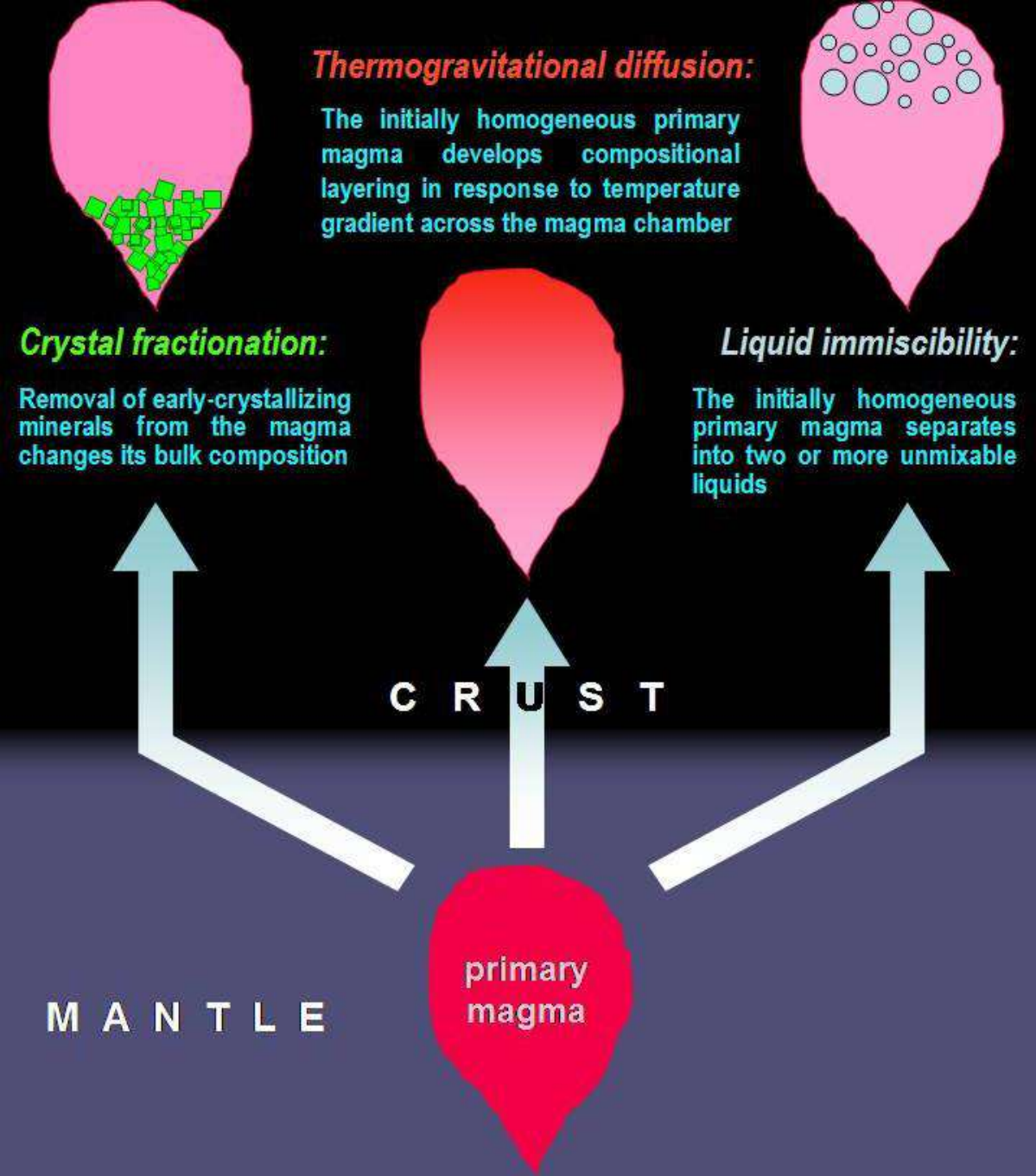
Crystal settling:

- The first minerals to xalize are denser and sink to the bottom.



Crystal floatation

- The first crystals are less dense and rise to the top.



Magmatic Ores

TABLE 2.3. Examples of deposits formed predominantly by orthomagmatic processes

Host rock association	Ore type	Important examples
Mafic-ultramafic complexes		
Layered intrusions	Chromite	Bushveld, South Africa Great Dyke, Zimbabwe
	Ni(-Cu) sulfide	Sudbury, Canada Bushveld, South Africa
	Pt-Pd	Bushveld, South Africa Stillwater, USA
Ophiolites	Chromite	Kempirsai, Ural Mountains Kavak, Turkey
Tholeiitic-komatiitic suites	Ni-sulfide	Kambalda district, W. Australia Pechanga, Russia
Kimberlites	Diamond	Kimberly, South Africa Yakutia, Russia
Carbonatite complexes	Nb	Oka, Canada
	Rare earth elements	Sulfide Queen, USA
	Cu	Palabora, South Africa
Anorthosite complexes	Ilmenite	Allard Lake, Canada Sanford Lake, USA
Alkali igneous complexes	Fe-Ti oxide - Apatite	Kiruna district, Sweden Roseland district, USA
Granitic pegmatites*	Sheet mica, beryl/emerald, spodumene (Li), niobite-tantalite (Nb-Ta), cassiterite (Sn)	Kings Mountain district, USA Petaca district, USA Nellore district, India

* Some pegmatites, such as those of the Petaca district, appear to have formed in two stages: an early magmatic stage involving crystallization of a water-rich residual melt derived from a granitic magma; and a later hydrothermal stage involving precipitation from related magmatic-hydrothermal fluids (Jahns 1946).

VIII. Magmatic Ore Formation Systems

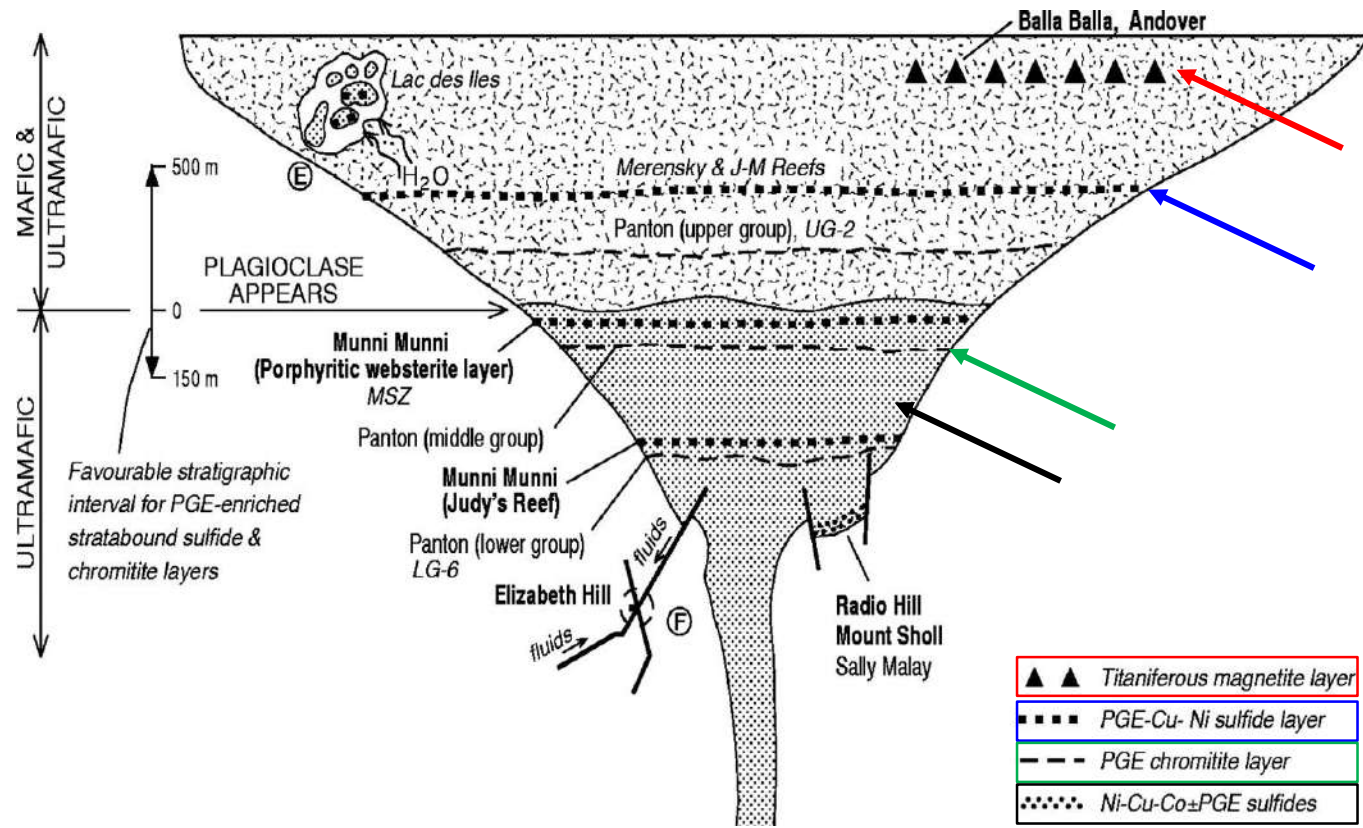
1. **Orthomagmatic ore formation**
2. **Ore deposits at mid-ocean ridges and in ophiolites**
3. **Ore formation related to alkaline magmatic rocks, carbonatites and kimberlites**
4. **Granitoids and ore formation processes**
5. **Ore deposits in pegmatites**
6. **Hydrothermal ore formation**
7. **Skarn- and contact-metasomatic ore deposits**
8. **Porphyry copper (Mo-Au-Sn-W) deposits**
9. **Hydrothermal vein deposits**
10. **Volcanogenic ore deposits**

1. Orthomagmatic Ore Formation



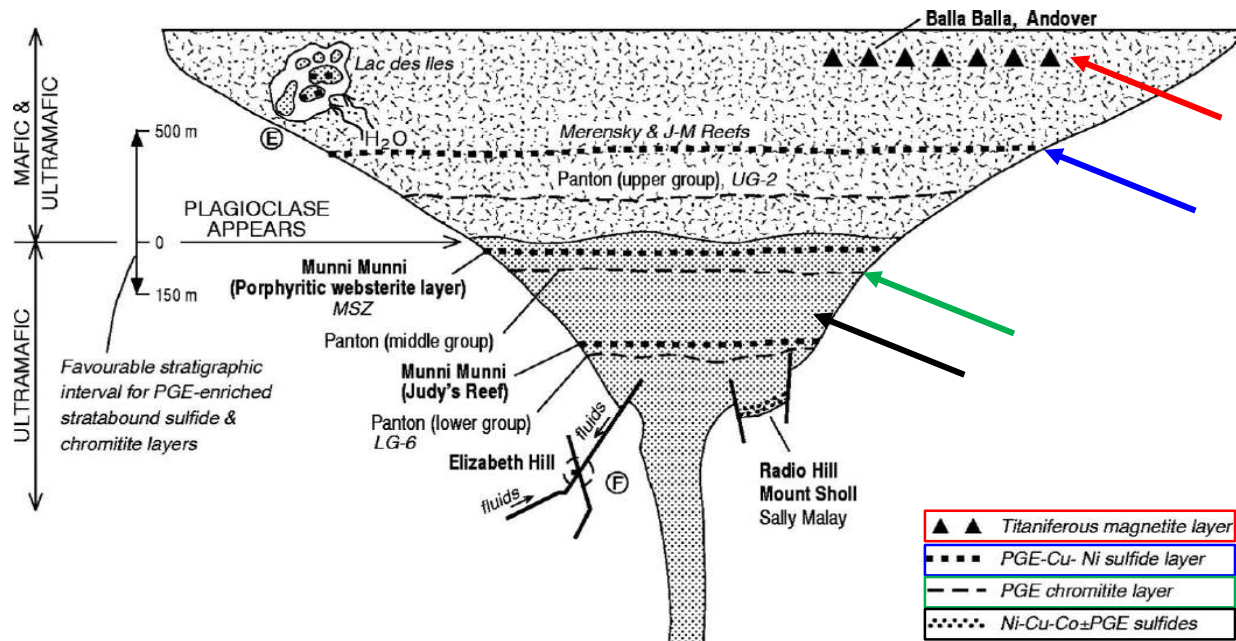
A- Mafic-Ultramafic Complexes: Chromium, Nickel, Copper and Platinum Group Elements (PGE)

Oxide (magnetite, ilmenite, chromite), base metal sulphides (Ni, Cu), and ore of precious metals (Pt, Pd, Au) is often found in ultramafic and mafic igneous rocks. These ores were formed at magmatic temperatures, while the melt was essentially liquid and before total solidification. Therefore, this class of ore deposits is called "orthomagmatic". Enrichment processes concentrate/segregate low metal traces from a large mass of silicate melt into small volumes.



Many parameters influence the **ore accumulation processes**, these are:

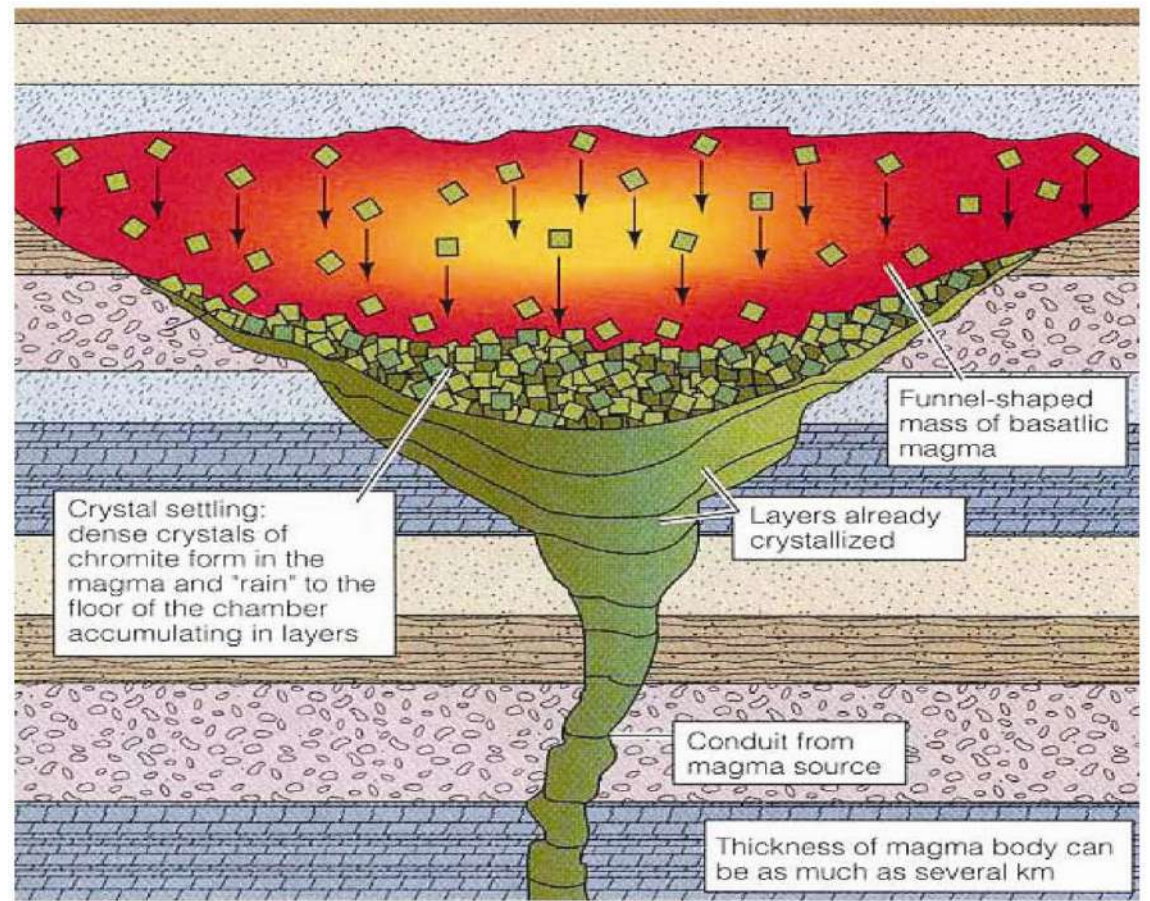
1. the depth of intrusion,
2. tectonic activities,
3. the temperature gradient in space and time,
4. fractional crystallization,
5. dynamics of the melt body (e.g. convective flow),
6. repeated injection of fresh melt, assimilation of country rocks,
7. sulphur or external fluids,
8. liquid immiscibility of ore and silicate melts and
9. mixing or redissolution



Because of their higher density compared to the inheriting silicate liquids, **ore melt droplets** or **solid ore phases** typically **cumulates** **below** **still liquid** **magma**

(gravitational accumulation/segregation). Consolidation of **cumulate minerals** can lead to expulsion of inter-cumulus liquid **(filter pressing).**

As the **system (magma) cools,** **ore melts themselves may then separate into cumulates** (e.g. Fe-sulphides) and residual liquids (Cu-rich sulphide melt).



Gravitational accumulation/segregation of chromitite

Concentration of metals such as **PGM (platinum group metals)**, Au, Ni and Cu in sulphide melt is controlled by the Nernst partition coefficient (D) between sulphide and silicate liquids, and by other kinetic factors. In addition, a disequilibrium is controlled by silicate/sulphide liquid mass ratio "R-factor".

A **zone refining model** is appropriate when **sulphide droplets** sink through a **magma chamber** and **collect chalcophile metals** (**Ag, As, Bi, Cd, Cu, Ga, Ge, Hg, In, Pb, Po, S, Sb, Se, Sn, Te, Tl** and **Zn**). This is followed by **resorption** **نشع** of **iron-sulphide liquid** in under-saturated magma leading to concentration of limited **base metal** (**Ni, Cu, Zn,...**) together with very high content of **PGM** (**Pt, Pd**) and **precious metals** (**Au**) enrichment.

Most **orthomagmatic ore deposits** are found in **intrusive rocks**. **Gravitational settling** can explain many features of ore formation in layered **mafic intrusions**. Often, the formation and segregation of a sulphide melt, enriched with metal, - outside/far from the silicate melt - is the key to enrichment of exploitable metals.

Volcanic/eruptive equivalents are also notable, such as the **Ni-Cu-Fe sulphides** in **komatiitic lava** flows, or the **magnetite and haematite lavas** and **tuffs** in **andesitic-rhyolitic volcanoes**. (**komatiite** is a type of **ultramafic mantle-derived volcanic rock** with high to extremely high **Mg** content).

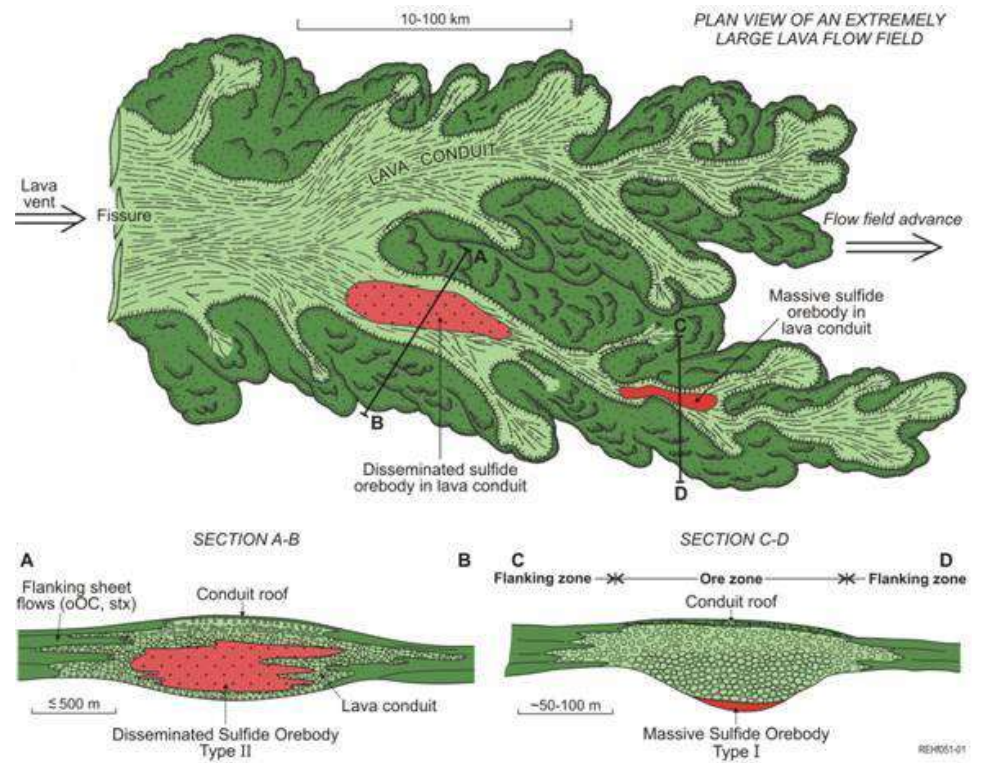
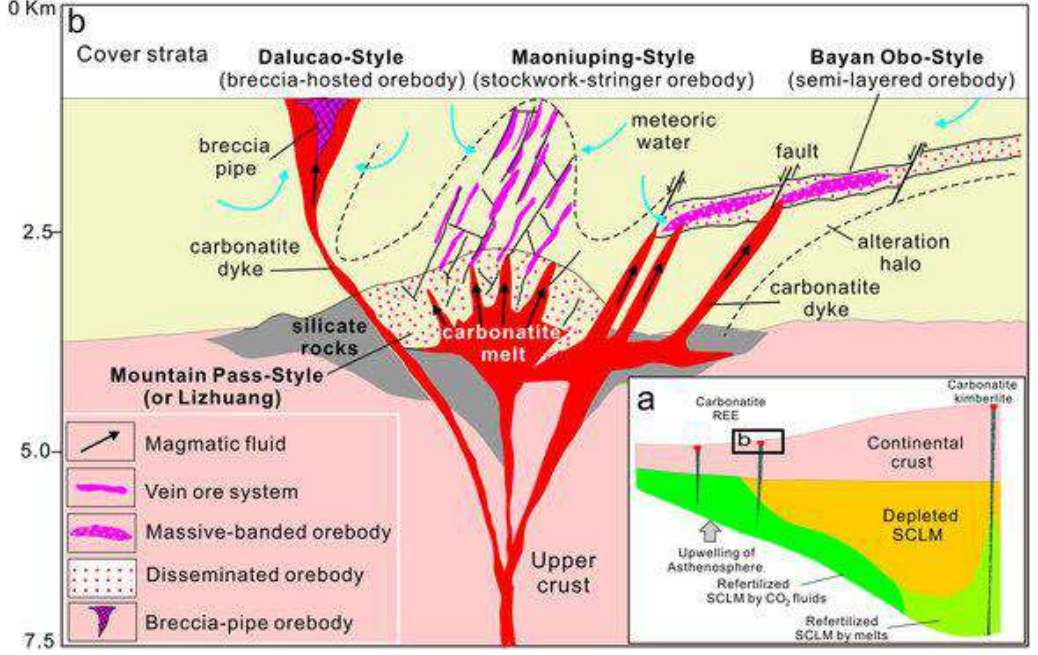


Komatiite

Basic shapes of orthomagmatic ores

ore bodies are layers in stratified magmatic rocks (often formed as cumulates), lenses or cross-cutting dykes and veins. This depends on the morphology of the segregation (sedimentation) surface and on dynamic factors during ore formation.

Massive ore is the product of highly efficient unmixing of ore particles or melt droplets and silicates, whereas disseminated mineralization reflects lower efficiency. Highly complex ore body shapes can be found in flow channels and pipes of mafic lavas.



Examples of orthomagmatic ores

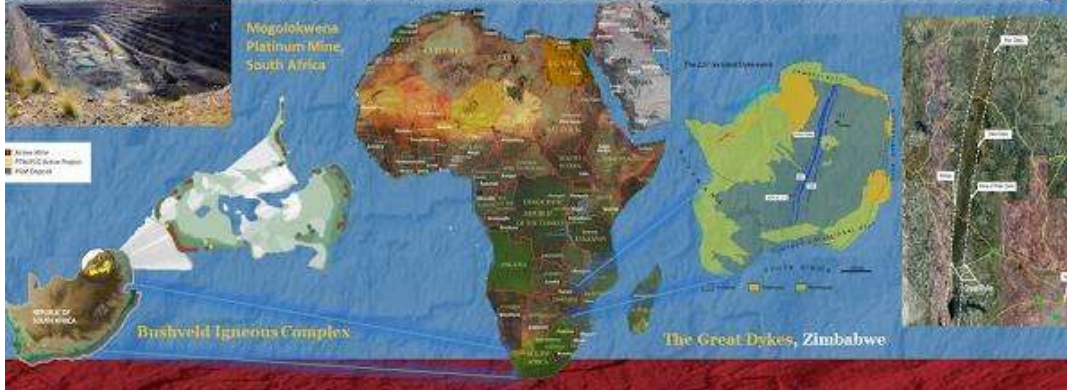
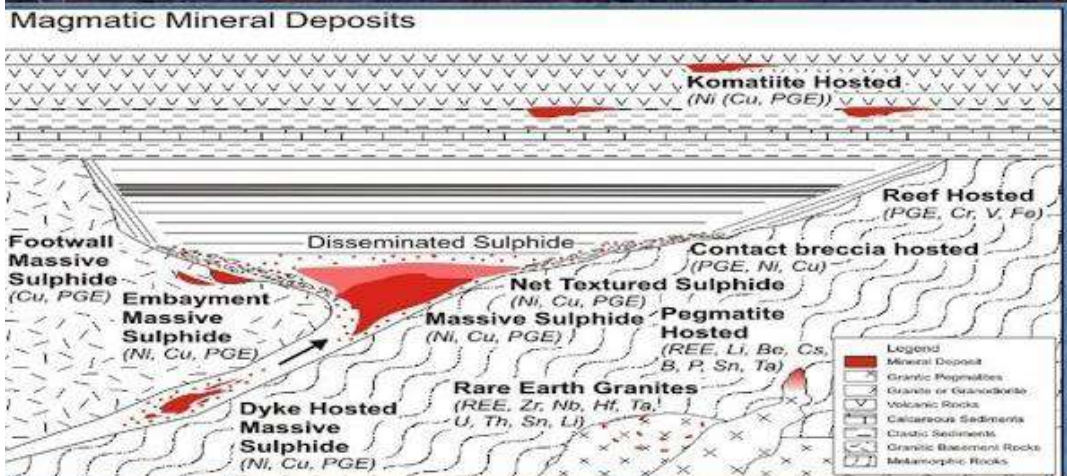
1. Cr-PGE deposits at Bushveld Igneous Complex, South Africa,

2. Ni-Cu-PGE deposits at The Great Dykes, Zimbabwe,

3. Ni-PGE-Cr deposits at Sudbury "(meteorite impact-unusual), Canada,

4. Ni-Cu-PGE deposits at Stillwater Igneous Complex, Montana, US.

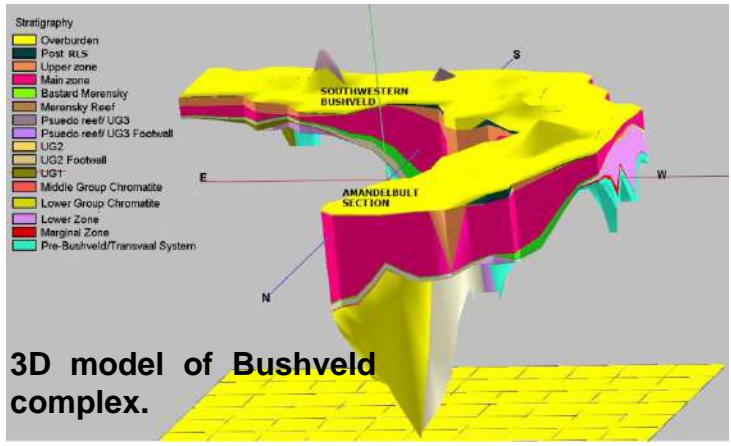
5. chromitite in Ophiolite sequence



The largest preserved layered intrusion in the world is the **Bushveld Complex of South Africa**, hosting an exceptional variety and mass of high grade metal ores.

- Bushveld complex**

The Bushveld Intrusive Complex comprises the **layered mafic-ultramafic intrusion which contains enormous metal resources**. These mafic layers are overlapped by granites containing host less important fluorite and tin ores.



3D model of Bushveld complex.



Interlayering between chromitites and anorthosites, upper Critical Zone



The MG2 and MG3 chromitite layers are intercalated with discrete layers of anorthosite, norite, and feldspathic pyroxenite. The Middle Group Anorthosite is a persistent marker in the Critical zone (Tweefontein).

In Bushveld complex, **the ultramafic-mafic sequence** reaches a thickness of 9000 m. It is strongly layered. The major units from bottom to top comprise:

1. the Lower Zone with dunite, bronzitite, and harzburgite;
2. the banded **Critical Zone** with a lower part of orthopyroxenite, **chromitite bands** and some harzburgite, and a higher part marked by the first cumulus plagioclase and by cyclic layering of economically significant **platiniferous chromitite**, harzburgite, bronzitite, norite and anorthosite in this order (cyclic units); its upper boundary is marked by the **Merensky Reef (Pt, Ni, Cu)**;
3. the Main Zone with gabbronorite and minor layering;
4. the Upper Zone with **magnetite (ferro) gabbro and ferrodiorite, which contains numerous magnetite (V-Ti) layers.**

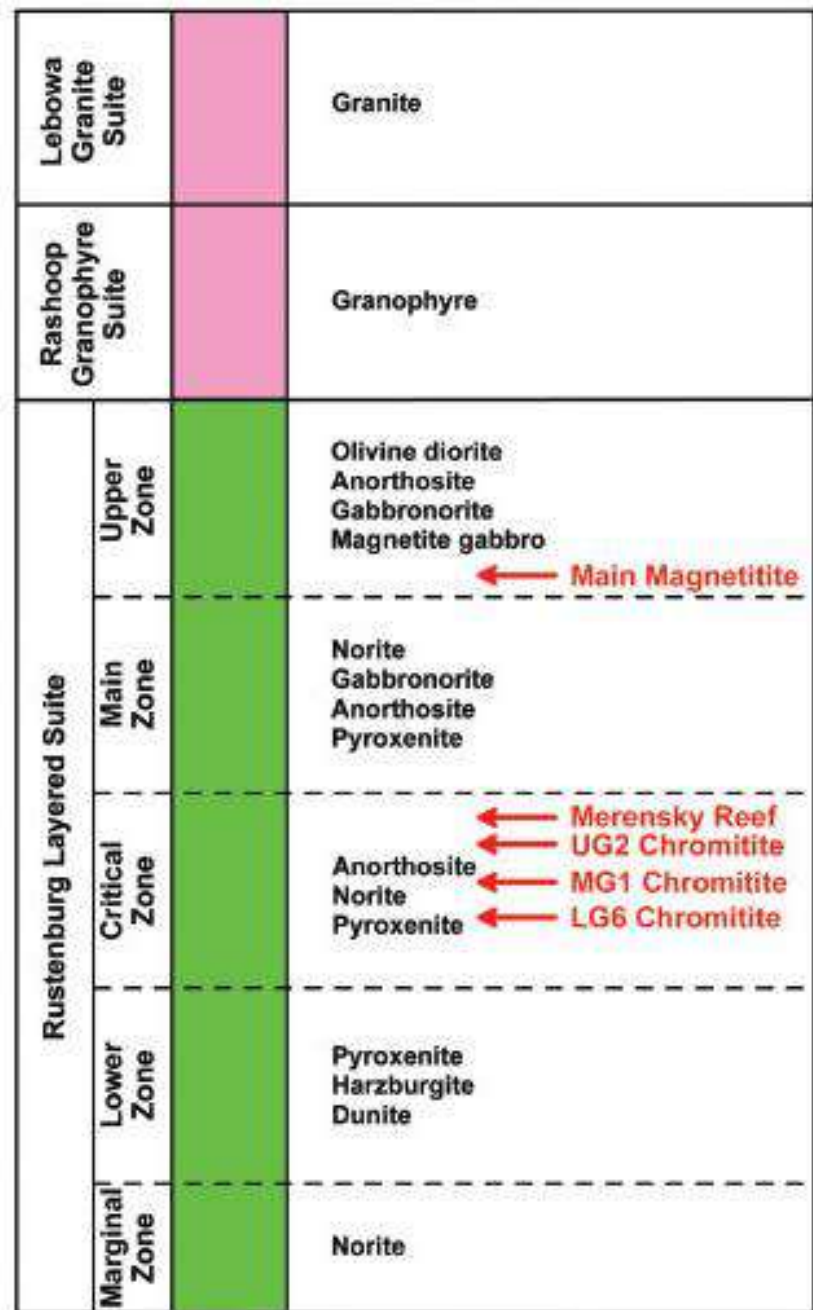
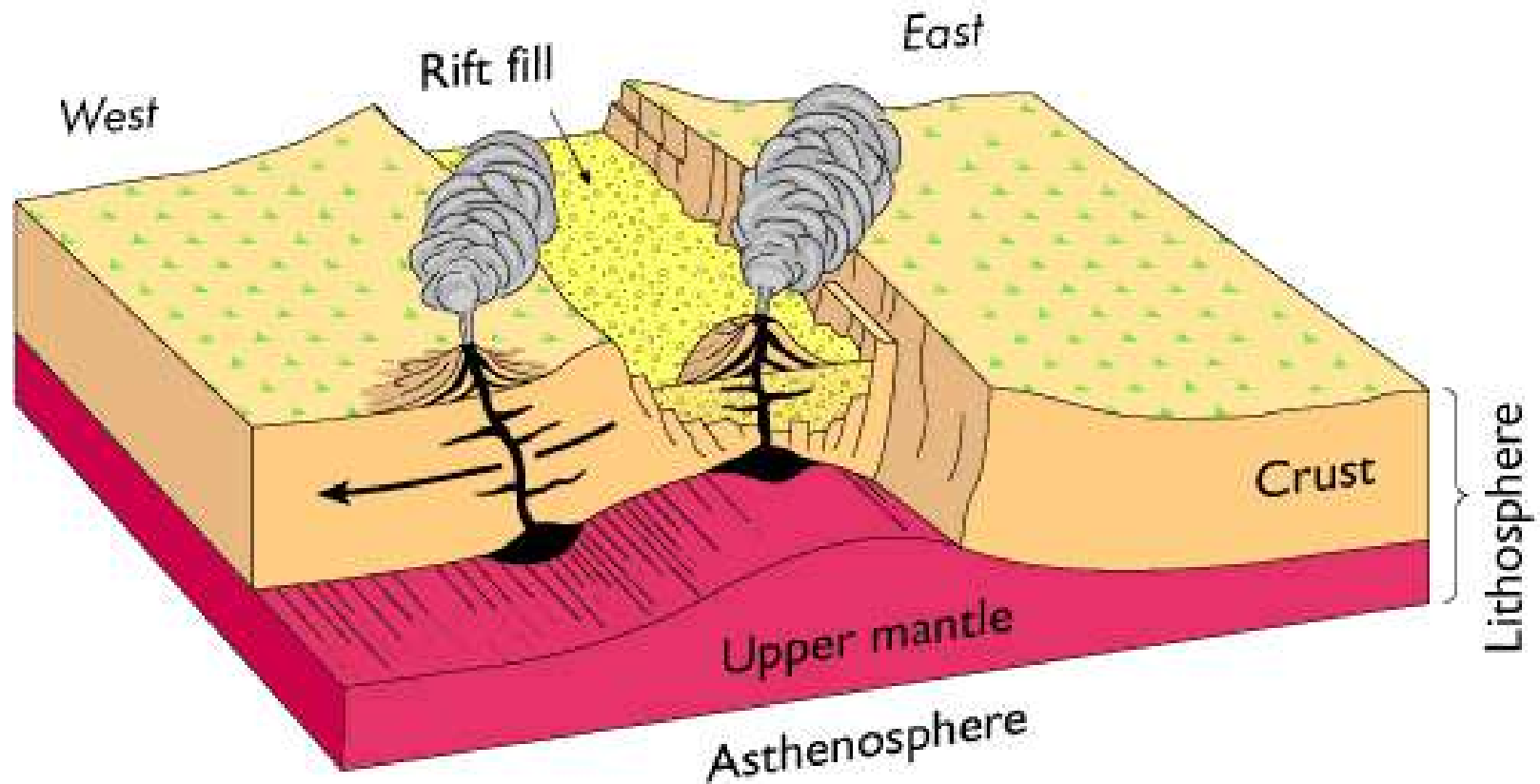


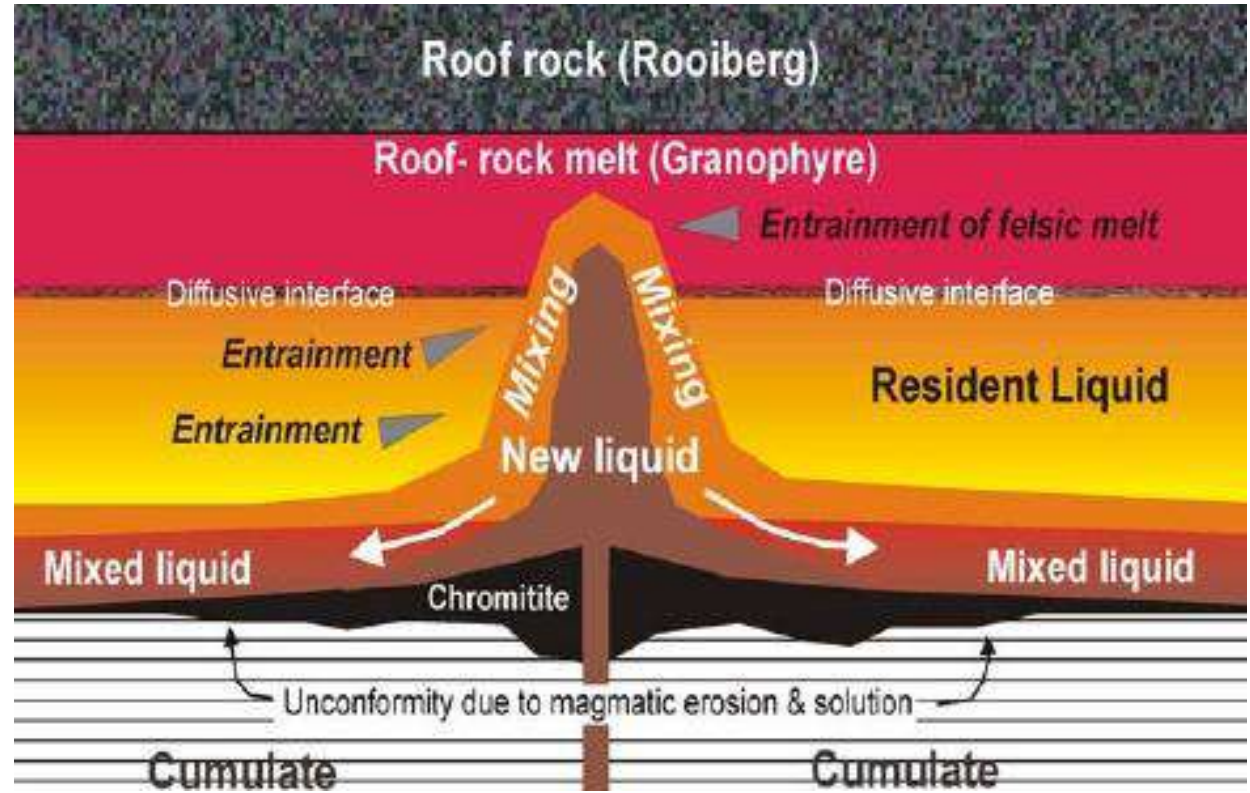
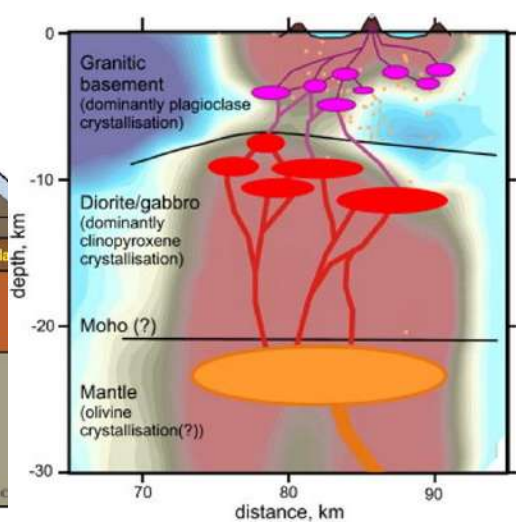
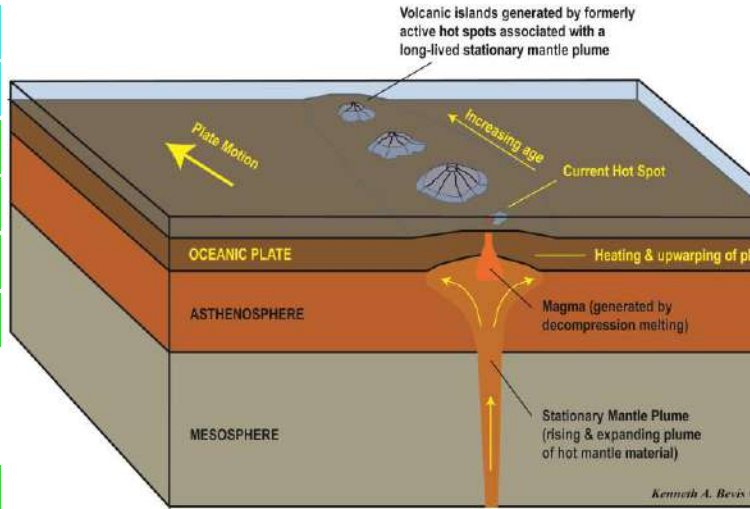
Figure 2 – Generalized stratigraphic column for the Bushveld Complex indicating predominant rock types (after SACS, 1980). Red arrows schematically show the relative position of major ore-bearing layers

There is no consensus of opinion on the number, nature, volume and source of the different magma types and the plate setting for magmatism of Bushveld complex.

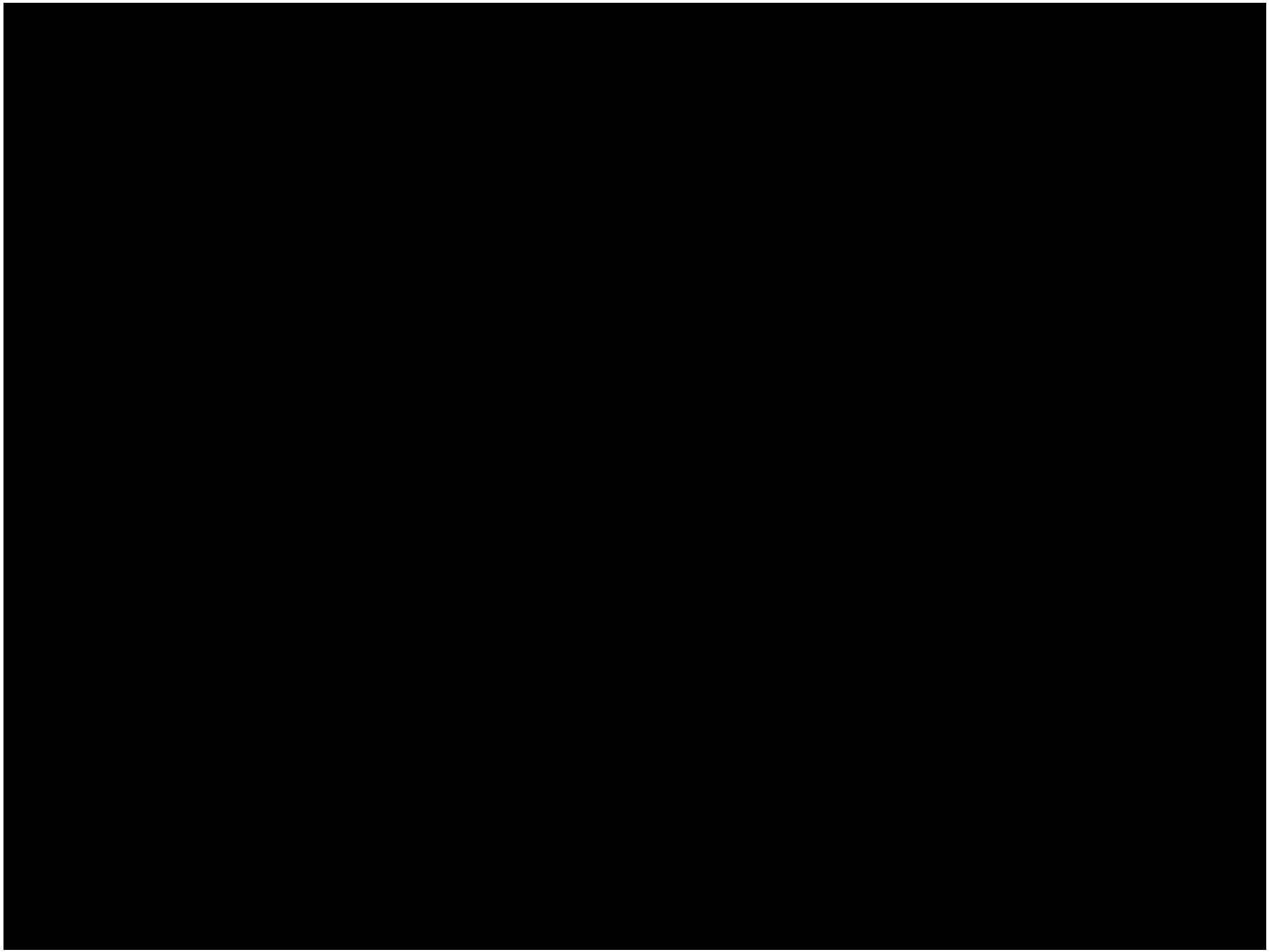
One opinion is the occurrence of **cratonic extensional associated with strike-slip movement**. The occurrence of A-type granites, which are generally associated with crustal extension, is consistent with this hypothesis



The volume of magma formed the Bushveld suggests the interaction of a mantle plume with lithosphere that has been thinned to between 110 and 50 km. A hot Lower Zone Magma derived from a mantle diapir which halted in the lower crust, flattening of the diapir led to the melting of the lower crust and the formation of the lower Critical Zone magma. During the accumulation of the Lower and Critical Zones, the magma chamber was continually fed by olivine- and orthopyroxene-crystallizing magmas that formed the Lower and Critical Zones.



Schematic diagram of chromitite formation resulting from a fountain of magma into the chamber that partially melts roof rocks causing contamination and mixing.



Progressive mixing of new and residual fractionated magma resulted in the slow evolution from a harzburgite/orthopyroxenite dominated Lower Zone, through a feldspathic orthopyroxenite dominated lower Critical Zone, to a norite/anorthosite dominated upper Critical Zone.

Rock type	Major minerals
Felsic rocks	Quartz, feldspar
Granite	Quartz, plagioclase/alkali feldspar (mica)
Granophyre	Quartz, alkali feldspar
Mafic rocks	Feldspar, pyroxene, olivine
Anorthosite	Plagioclase feldspar
Norite	Plagioclase feldspar, orthopyroxene
Gabbro	Plagioclase feldspar, clinopyroxene
Gabbronorite	Undifferentiated gabbro/norite
Diorite	Plagioclase feldspar, pyroxene, olivine
Ultramafic rocks	Pyroxene, olivine
Pyroxenite	Orthopyroxene and/or clinopyroxene
Peridotite	Olivine, pyroxene
Harzburgite	Olivine, orthopyroxene
Wehrlite	Olivine, clinopyroxene
Dunite	Olivine
Ore-bearing units	
Magnetitite layers	Magnetite
Merensky Reef	Pyroxene
Chromitite layers	Chromite (pyroxene)

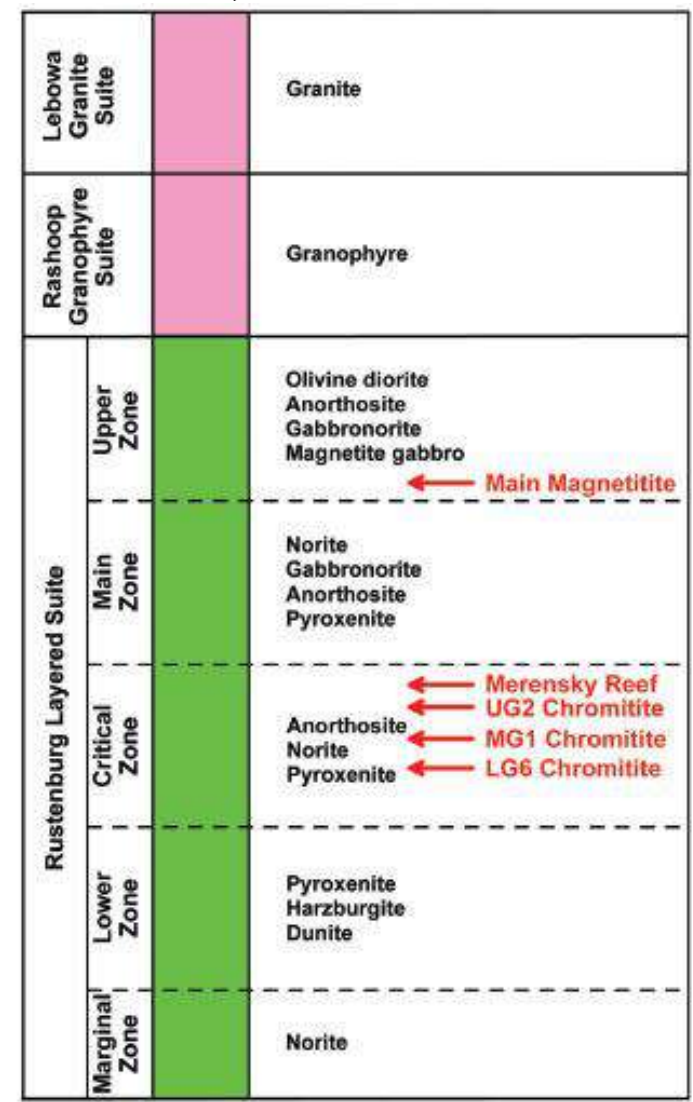


Figure 2 – Generalized stratigraphic column for the Bushveld Complex indicating predominant rock types (after SACS, 1980). Red arrows schematically show the relative position of major ore-bearing layers

Tectonic setting

In general, layered mafic intrusions occur in several geodynamic settings:

1. Archaean greenstone belts;
2. intracratonic regions (the Bushveld);
3. at passive margins of continents; and
4. in active orogenic belts.

Intracratonic regions that experienced tensional tectonics can also exhibit very complex mafic-ultramafic intrusions with Cu-Ni PGM ores.

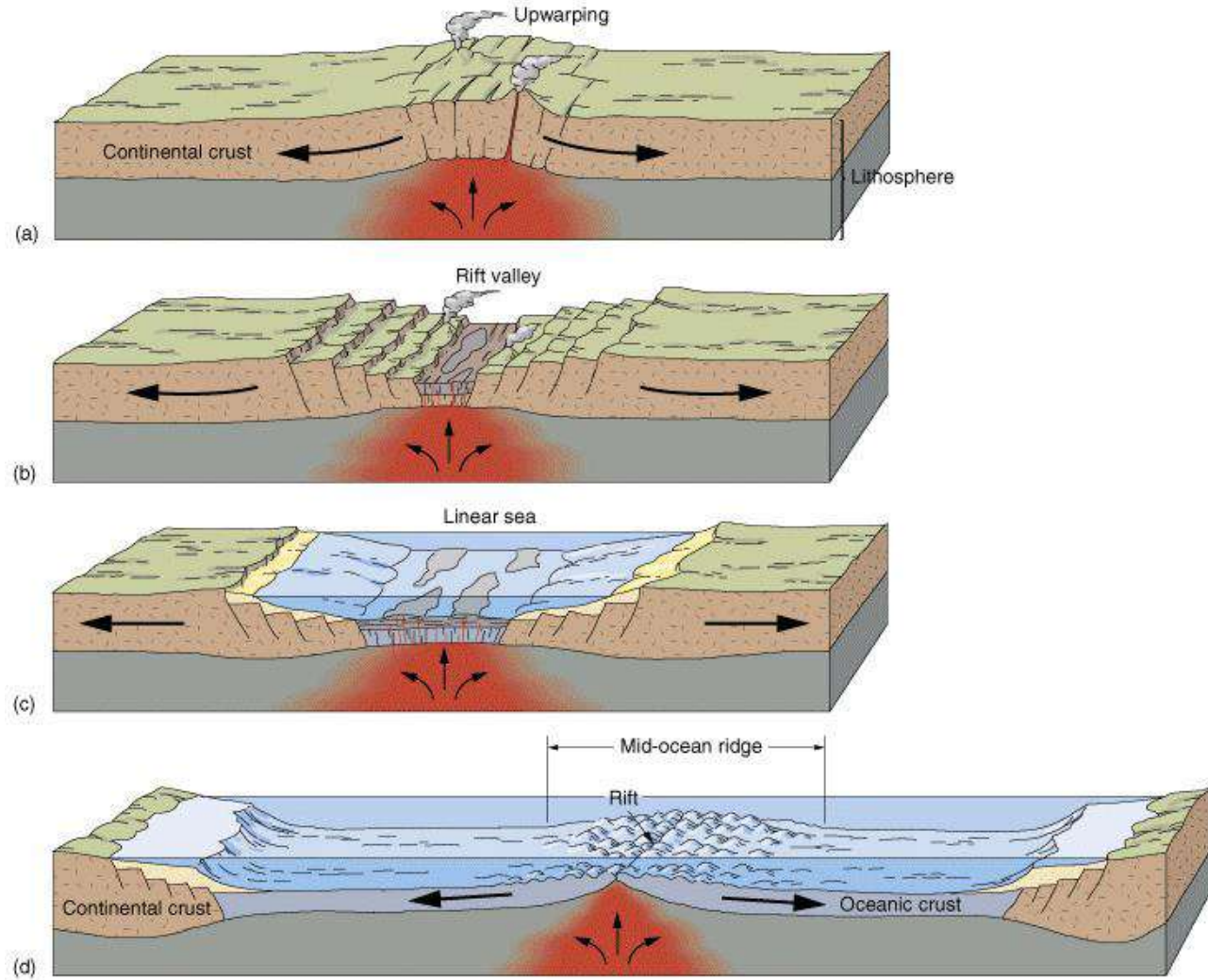


Diagram of an opening rift valley: at **stage B** the valley is dominated by rivers, and at **stage C** by shallow marine environments.

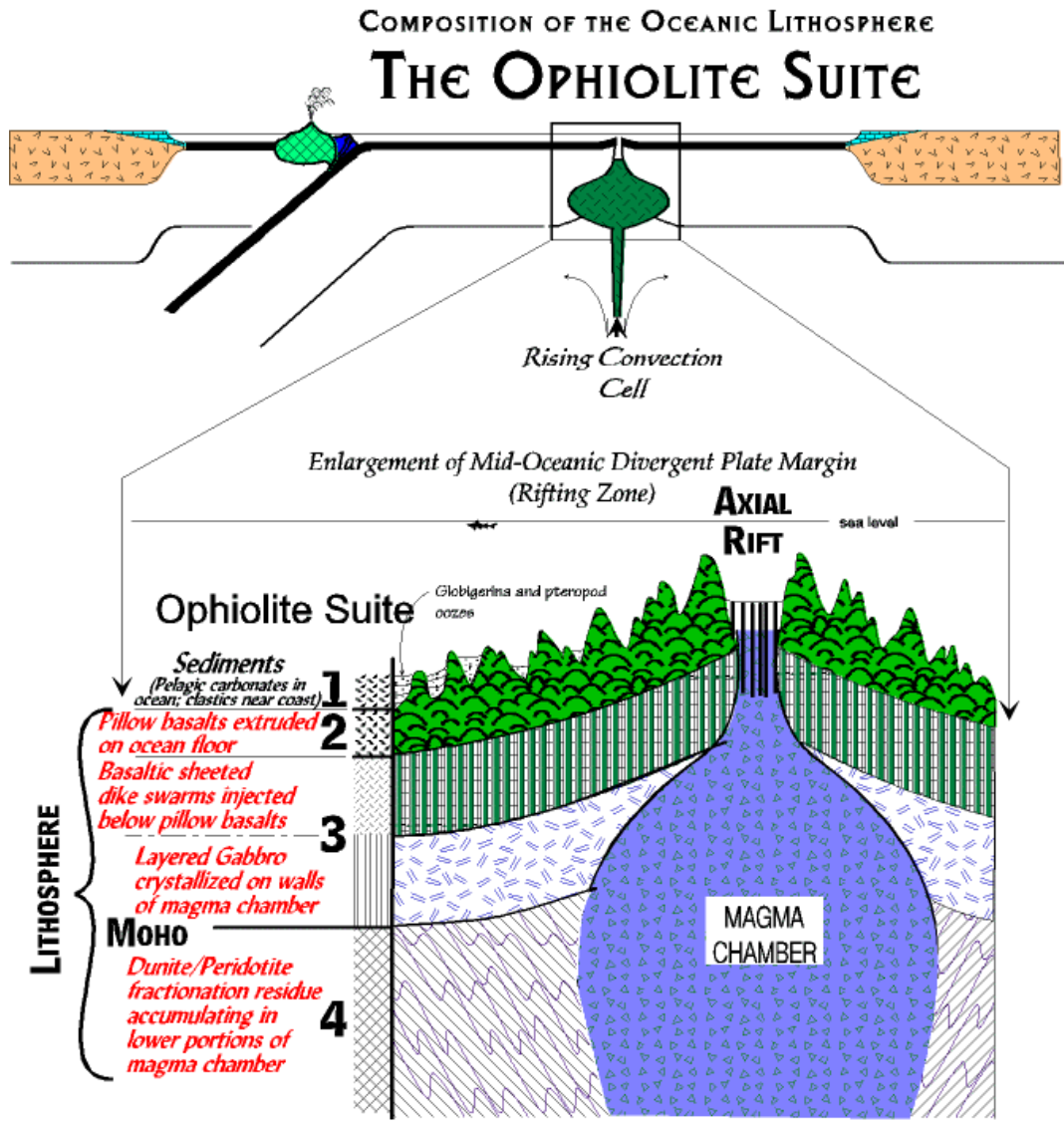
• **Chromitite in Ophiolite sequence**

Lower sections of ophiolites also contain orthomagmatic ore deposits.

Lower section of ophiolite includes diapiric dunite bodies with streaky or lenticular disseminated and massive chromitite. The dunites occur mainly within deformed harzburgite of tectonized mantle.

Tabular chromitite seams may occur in the lowermost ultramafic cumulates of the mid-ocean gabbroic magma chamber.

Both cases are considered to be a consequence of chromite segregation from the melts that rise from the mantle beneath mid-ocean spreading ridges.



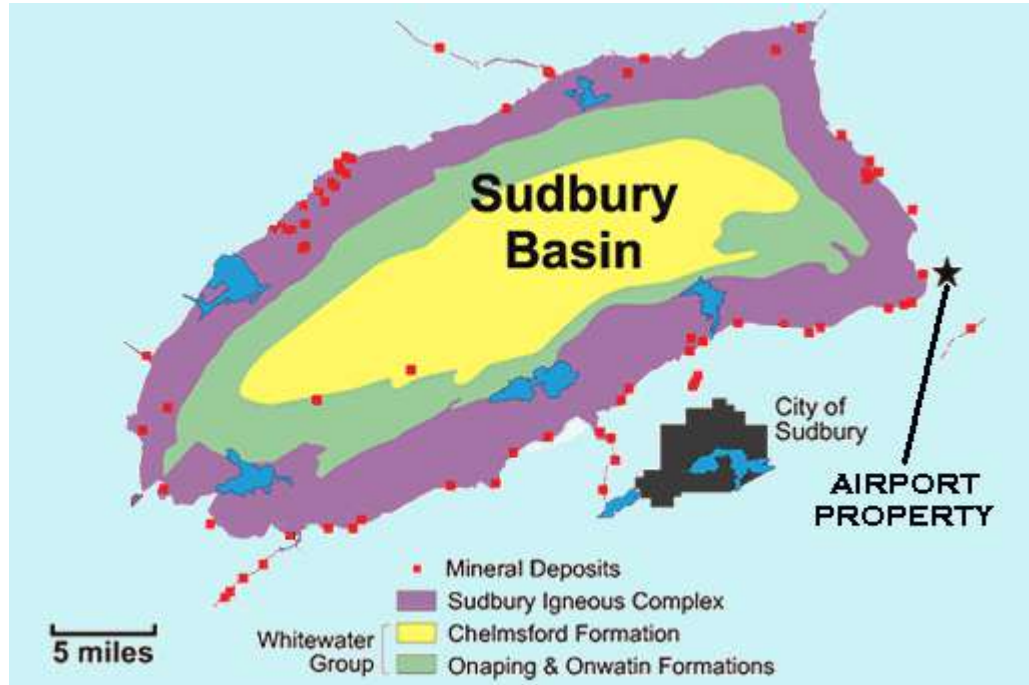
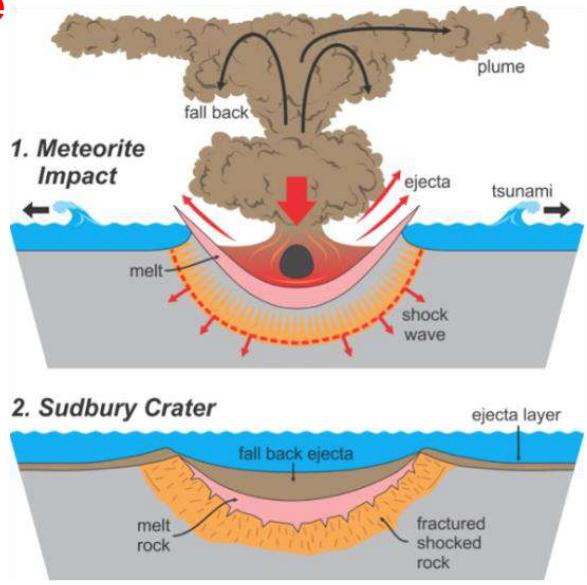
• **Impact magma bodies with orthomagmatic ore deposits: Sudbury**

Mineralized impact structures are very rare. A giant example is the **Sudbury Igneous Complex (SIC)** of Ontario, Canada, the **second largest source of nickel+copper+platinum** in the world.

The **SIC** is the remnant of a voluminous melt body that has been produced by the **impact of a meteorite into continental crust.**

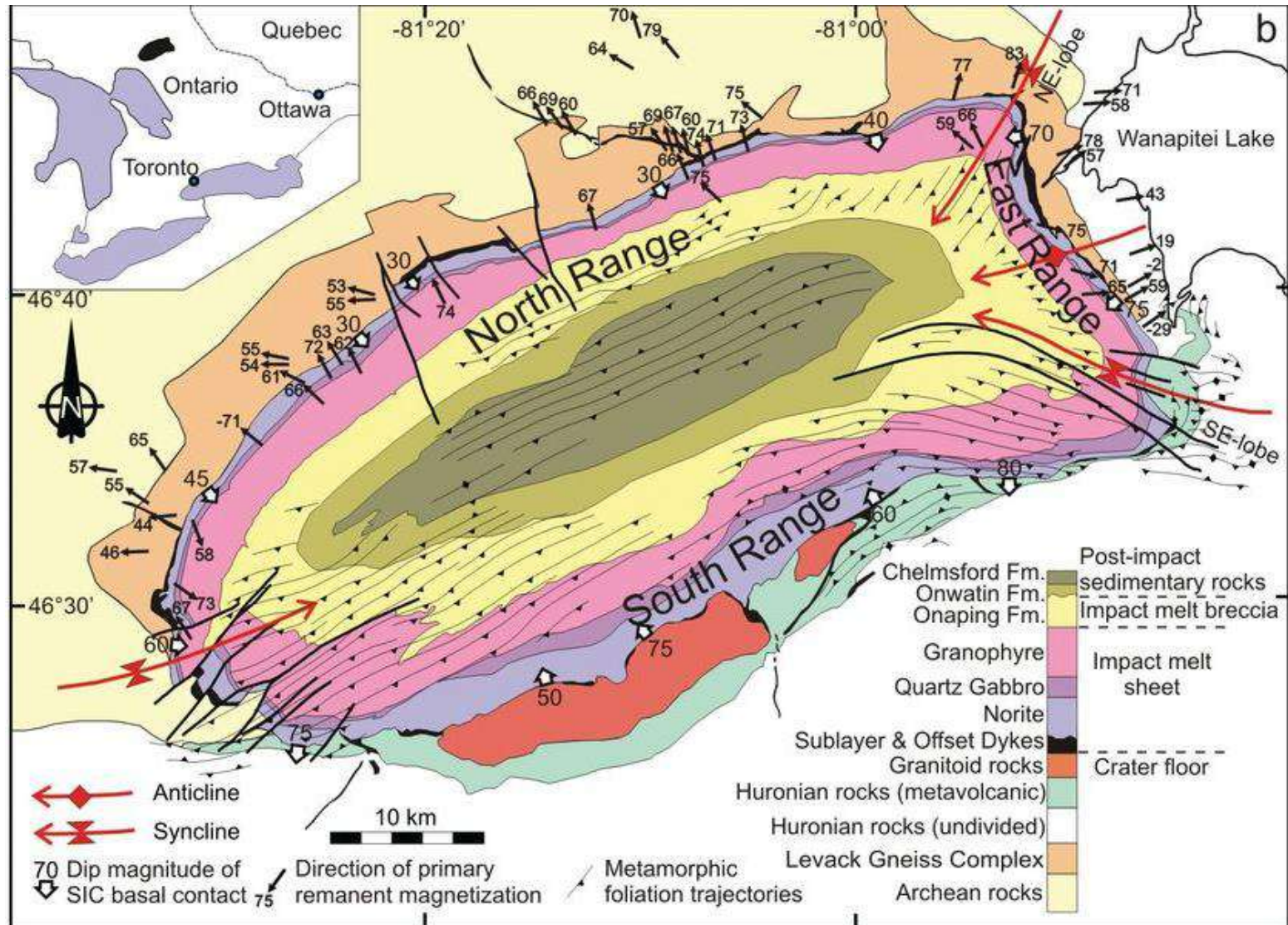
Ore deposits occur mainly in embayments of the footwall contact of the intrusion, in radiating dykes “offsets” and within intensely brecciated footwall rocks up to 2km from the contact.

Total past production and current reserves of the Sudbury District are estimated at >1700Mt of **Ni, Cu, Co, Pt, Pd, Au and Ag ore**. Among approximately 90 known Ni-Cu-PGE deposits, 14 are currently worked.



Overview map of the Sudbury impact structure, Canada, one of the giant nickel-copper mining districts of the world.

At **Sudbury**, lithologic zonation is interpreted to be due to **gravity separation of mafic and felsic liquids that formed an emulsion immediately after the impact.** The ore-bearing sublayer displays typical features of **mafic cumulates and gravity segregation of sulphide liquids.** Offset dykes and footwall deposits host an important part of metal resources.

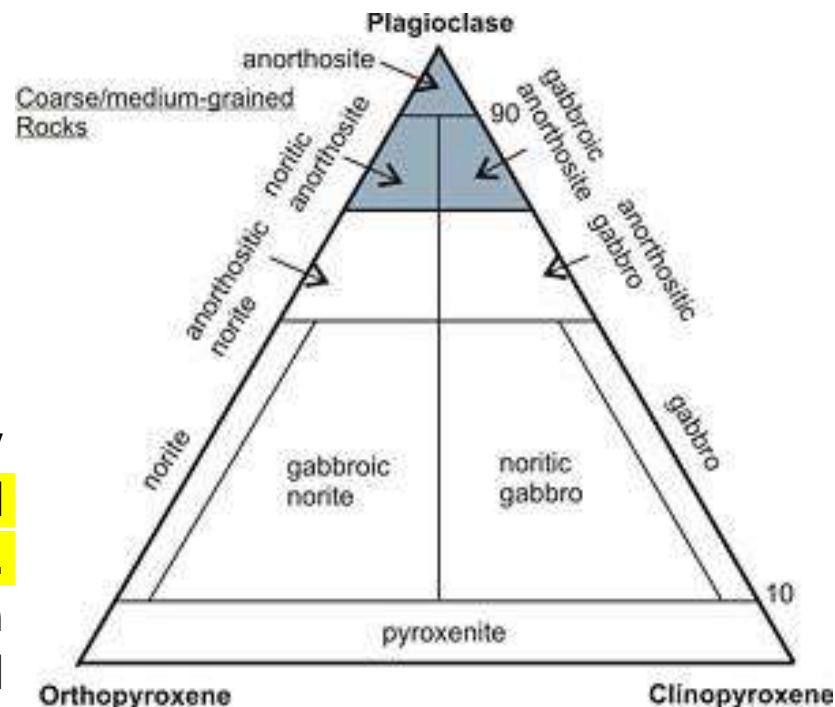
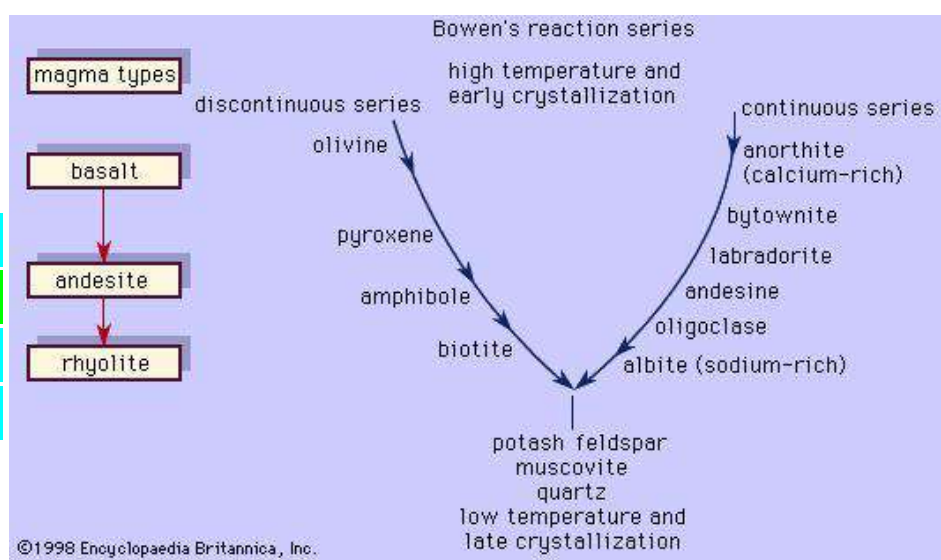


B- Anorthosite-ferrodiorite complexes

Many rocks contain small amounts of titanium locked in silicate minerals (e.g., biotite, amphibole), but the economically found in anorthosites as Ti-rich oxide minerals (Fe-Ti oxides, magnetite and ilmenite-hematite solid solution series) and Ti-oxides (mainly rutile).

Anorthosite is an intrusive igneous rock characterized by a predominance of plagioclase feldspar (90–100%), and a minimal mafic component (0–10%). Orebodies consist of ilmenite and/or rutile, magnetite or haematite, and a gangue of apatite and some graphite.

The anorthosites are commonly coarsely crystalline, rather massive than layered and consist of >90wt.% andesine to labradorite. Anorthosite plutons may be associated with coeval intrusions of ferrogabbro and ferrodiorite.



Because of their high density, the ore melts accumulate near the base of the magma chamber. Resulting ore bodies are stratiform and either massive or disseminated (Sanford Lake (New York, USA) and Lac Tio (Quebec, Canada)).

From anorthosite rocks, 50% of the world's titanium supply is derived; they also contain about half of the total titanium resources.

The origin of anorthosite is not fully understood; one hypothesis presumes late to post-orogenic partial melting of tongues of lower crust in the mantle.



Anorthosites are the products of **basaltic magma** after the “**mechanical removal**” of **mafic minerals**. Since the mafic minerals are not found with the anorthosites, these minerals must have been left at either a deeper level or the base of the crust.

A typical theory is as follows: **partial melting of the mantle generates a basaltic magma**, which **does not immediately ascend into the crust**. Instead, the basaltic magma forms a large magma chamber at the base of the crust and **fractionates large amounts of mafic minerals, which sink to the bottom of the chamber**. The **co-crystallizing plagioclase crystals float**, and eventually are emplaced into the crust as **anorthosite plutons**. Most of the sinking mafic minerals form ultramafic cumulates which stay at the base of the crust.

Anorthositic Origin

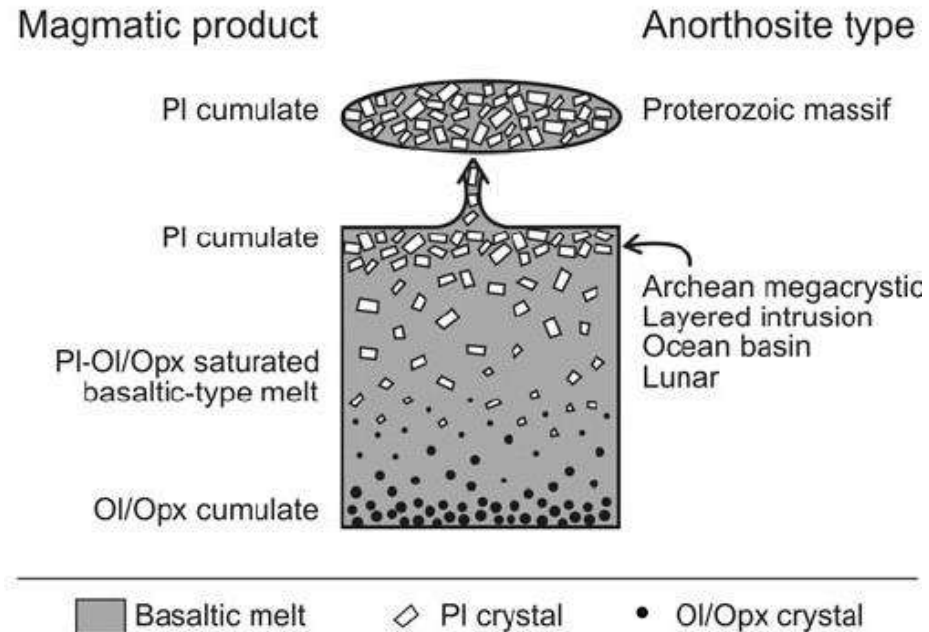
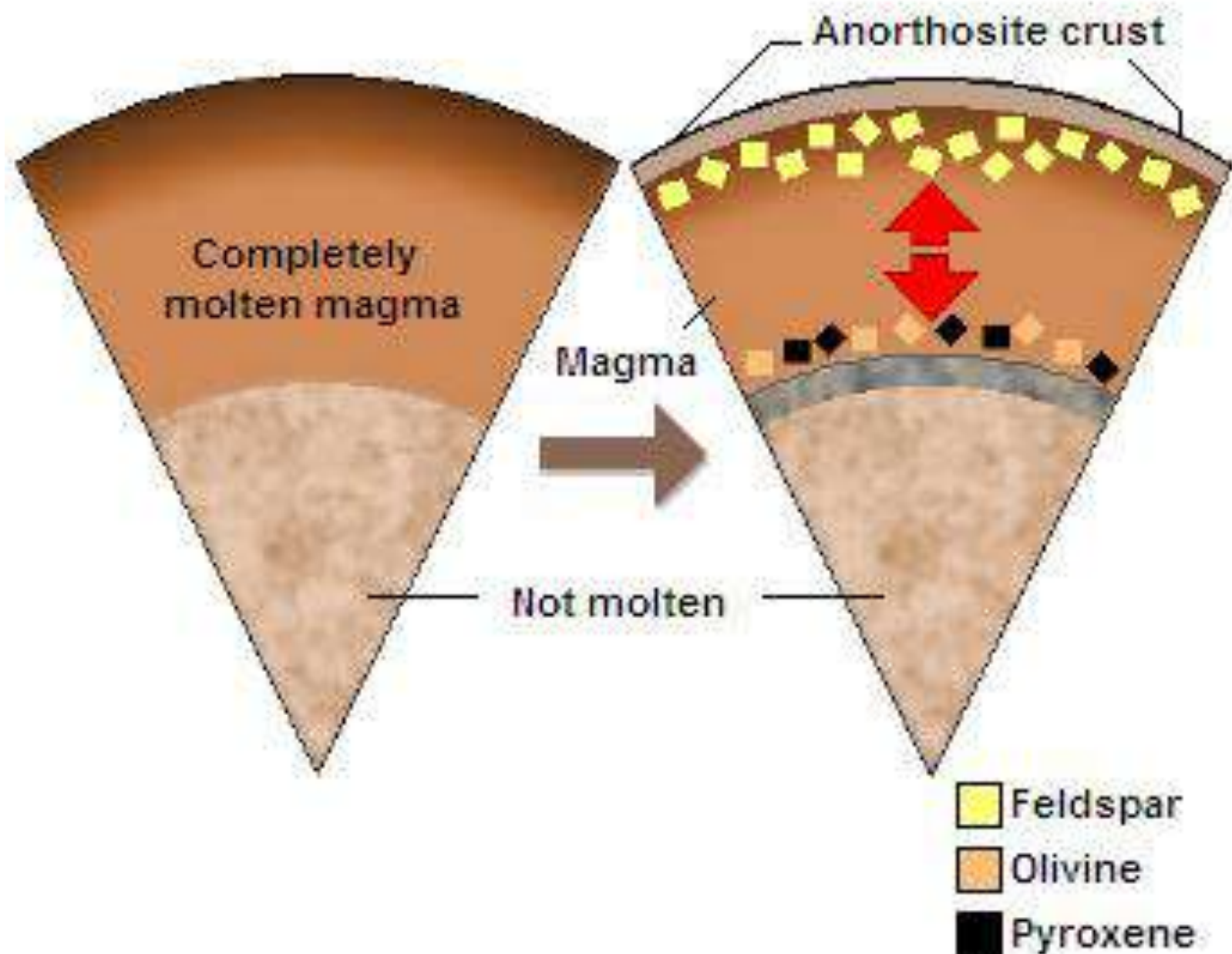


Fig. 1. Schematic model showing the differences between petrogenesis of Proterozoic massif-type and other types of anorthosite (Archean megacrystic, layered intrusion, ocean basin, lunar). Abbreviations; Pl = plagioclase, Ol = olivine, Opx = orthopyroxene.

Anorthosite crust formation



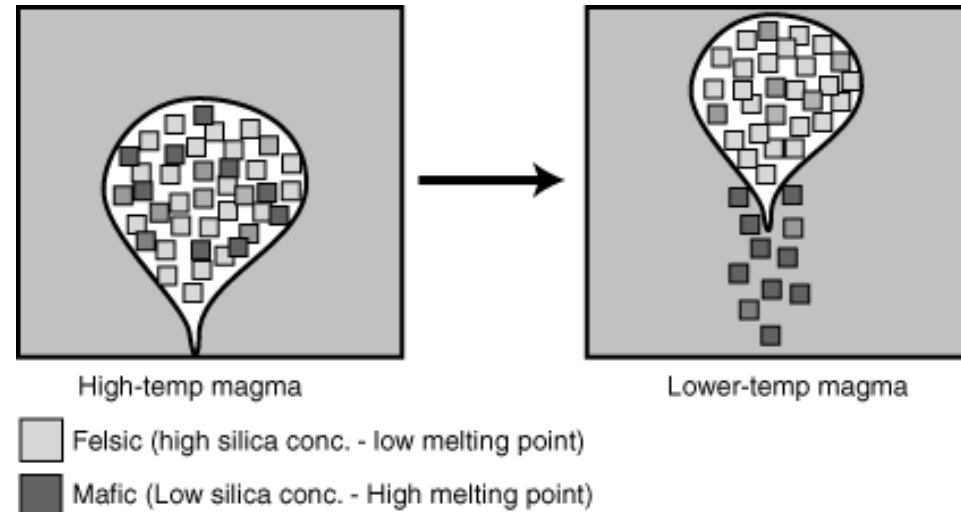
C- Fe-rich melts segregated from intermediate to felsic magmas

The metallogeny of Fe-ore segregated from intermediate to acidic melt is an ambiguous case of orthomagmatic ore formation. Although it is possible that FeOx rich melt would separate from acidic magma when the acidic magma is enriched in O₂ there is no general agreement that this is a path to the formation of large ore deposits.

This debate is attributed to the difficulty of segregating Fe-ores by gravity in high viscosity of SiO₂-rich magma. However, such segregation is possible when:

- i) The magma is sheared by slow convection so that the low-viscosity FeOx liquid may be concentrated; and
- ii) the possible high content of sodium and phosphorous acts as fluxing agents for iron melt.

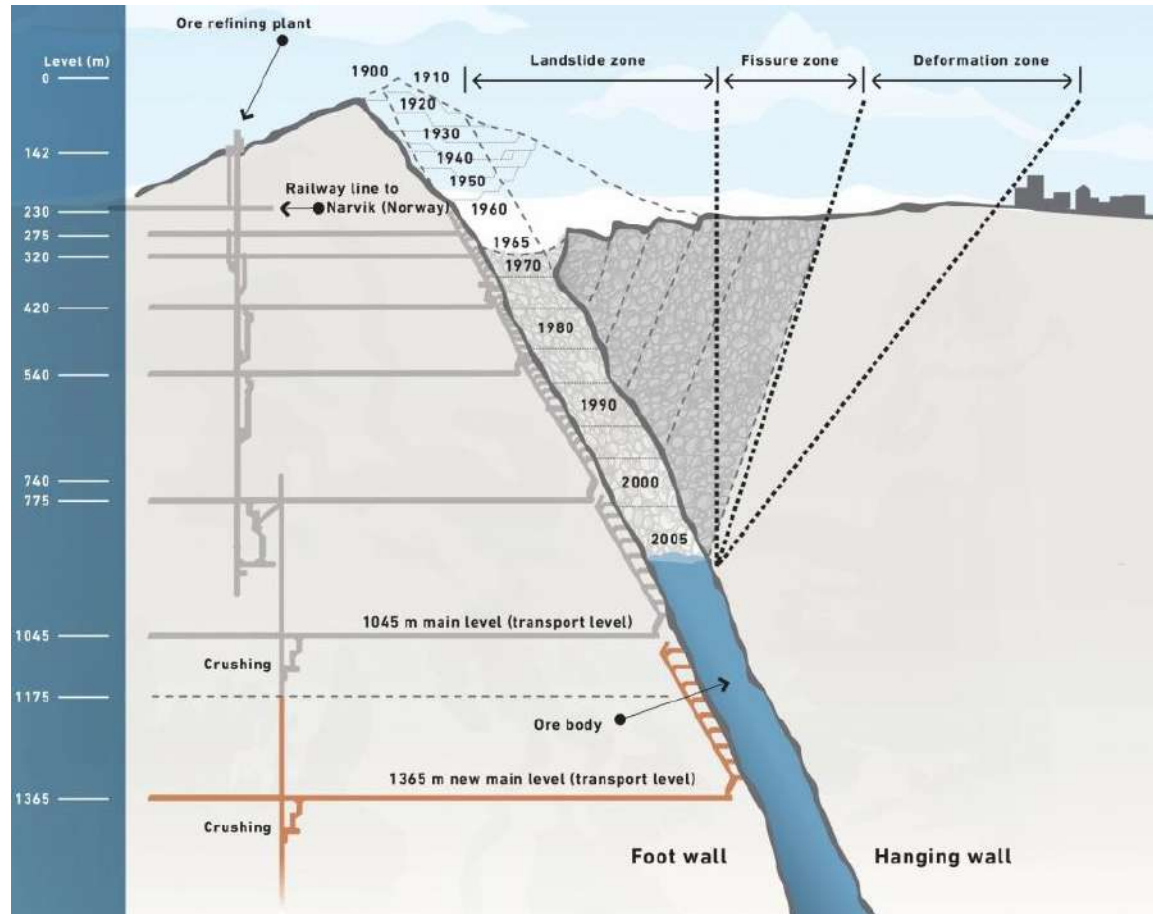
Mineral segregation under these conditions would produce ore of magnetite and apatite in the proportion of about 2 : 1, as exploited in the Kiruna District (Sweden).



High fluorine and chlorine content of the apatites, and the presence of minerals such as amphibole and scapolite, imply an important role of magmatic volatiles (H_2O , Cl, F, CO_2 , etc.) which promote segregation and mobility of ore melt.

Kiruna in northern Sweden, is considered as the largest iron ore of orthomagmatic origin in felsic intrusions, because the ore is co-genetic with the host rocks trachyandesite and rhyodacite.

Lower Ti and V concentrations distinguish this type of iron ore - in felsic intrusions - from massive iron oxides segregated from mafic magmatic melts. As well, this type of Fe-ores (in Kiruna) is also characterized by lack Cu and Au when compared with that formed by hydrothermal solutions.



Fe-ore in Kiruna, northern Sweden

An **extrusive origin** is also considered for magnetite ore bodies at El Laco, Chile in acidic rocks.

Magnetite or haematite-apatite ores have been described as massive and vesicular lavas, veins, crystal tuffs and pyroclastic agglomerates deposited by volcanoes built of rhyolite.

In conclusion, orthomagmatic deposits of **iron oxides and apatite in intermediate to felsic igneous rocks** (intrusive and extrusive types) may originate by **mixing and mingling of ultra-mafic and silicic melt**.



Volcanic ash from El Laco, Chile, composed of fine-grained magnetite (gray), small amounts of apatite (thin white layer at right), sublimated iron phosphate (violet hue at center), and a horizon with orange lumps of an iron-phosphorus-sulfur mineral (below the apatite layer). The ore ash is cut by a chimney-like degassing channel, coated by crystals of magnetite that are oxidized to red hematite on the surface. The iron ore, formed by a volcanic eruption ca. 2 million years ago, is of the same type as the Kiruna ore.

End of Lecture