Lectures in Economic Geology

4th Class Students "Geology, Geophysics, Geology-Chemistry"

By

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Preface

Economic Geology is a great branch of geology dealing with: a) all possible geological processes that led to form various and huge tonnages of mineral resources; b) the classification and applications of mineral resources; c) factors controlling whether a mineral deposit can be mined or not; d) the possible methods that can be employed to solve the current mineral resource crisis. The mineral resources here include both metallic and non-metallic minerals along with the different rock types "igneous, metamorphic, and sedimentary" that have a wide range of industrial applications. This course will contain exciting and useful outlines for each one needs to build up and widen his/her knowledge regarding the genesis, types and occurrences, mining, and the current industrial application of the mineral resources in Egypt. At this point, you will go in an excited adventure through the following contents to know more and more about the mineral resources in Egypt starting from the Eastern Desert, passing through the Nile Valley, to the Western Desert. I hope you collect and gather all data and information from this course, which can help you after graduation. One more thing else, be competitive and active member during my lectures. Ask more questions, which enable me to clarify and simplify all what you find hard to understand.

My best regards,

Dr. Mahmoud Sabry Abdel-Hakeem "2020"

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NO GAIN WITHOUT PAIN

Contents

1. What is Economic Geology???

The term economic geology refers to a branch of geology that deals with:

- The mineral-forming geological processes "endogenous and exogenous processes".

- The different morphological occurrences of the mineral deposits.

- The distribution of mineral deposits in terms of the ore quality and reserves.

- Factors controlling the amenability of mining and extraction of mineral deposits.

- Factors affecting the metal price and production (e.g. the improvements in the mining and refinement processes of Cu deposits allow extraction up to 0.5%Cu).

- The possible methods that can be followed to face the current mineral resources crisis (e.g. the continuous exhaustion of the high-grade ores).

2. What Is the Difference Between an Ore And an Ore Mineral???

The term ore refers to any naturally occurring, solid material containing a useful commodity that can be exploited for different industrial applications or extracted at profit (e.g. bauxite, feldspars, coal, black shale, limestone, granite…..etc). On the other hand, the ore mineral is a mineralized material from which one or more metals can be extracted at economic scale (e.g. ilmenite, hematite, bauxite, chalcopyrite….etc). By "useful commodity" we mean any substance that is useful or essential to society, such as metals, or energy sources, or minerals with distinctive properties. Petroleum is normally excluded from the definition, which is generally

restricted to solids, but the bitumen recovered in deposits such as the Athabasca tar sands might be considered an ore. So, the term ore include all metallic, non-metallic mineral substances along with the different types of igneous and sedimentary rocks that can be used for building purposes (e.g. granite, basalt, shale, limestone, and chert), energy generation (e.g. coal, black shale, and phosphorites), and land reclamation and soil fertility (e.g. glauconitic sandstone, phosphorites, and black shale).

3. <u>What Is the Difference Between a Mineral Deposit And an Ore Deposit???</u>

The mineral deposit is an accumulation of a given mineral in a sufficient quantity to be mined at profit (e.g. accumulation of barite, phosphorites, glauconites, feldspars, and placer deposits). The ore deposit refers to an accumulation contains high concentration of a given metal/s in sufficient quantity to be extractable at a profit (e.g. accumulation of iron deposits and ilmenite).
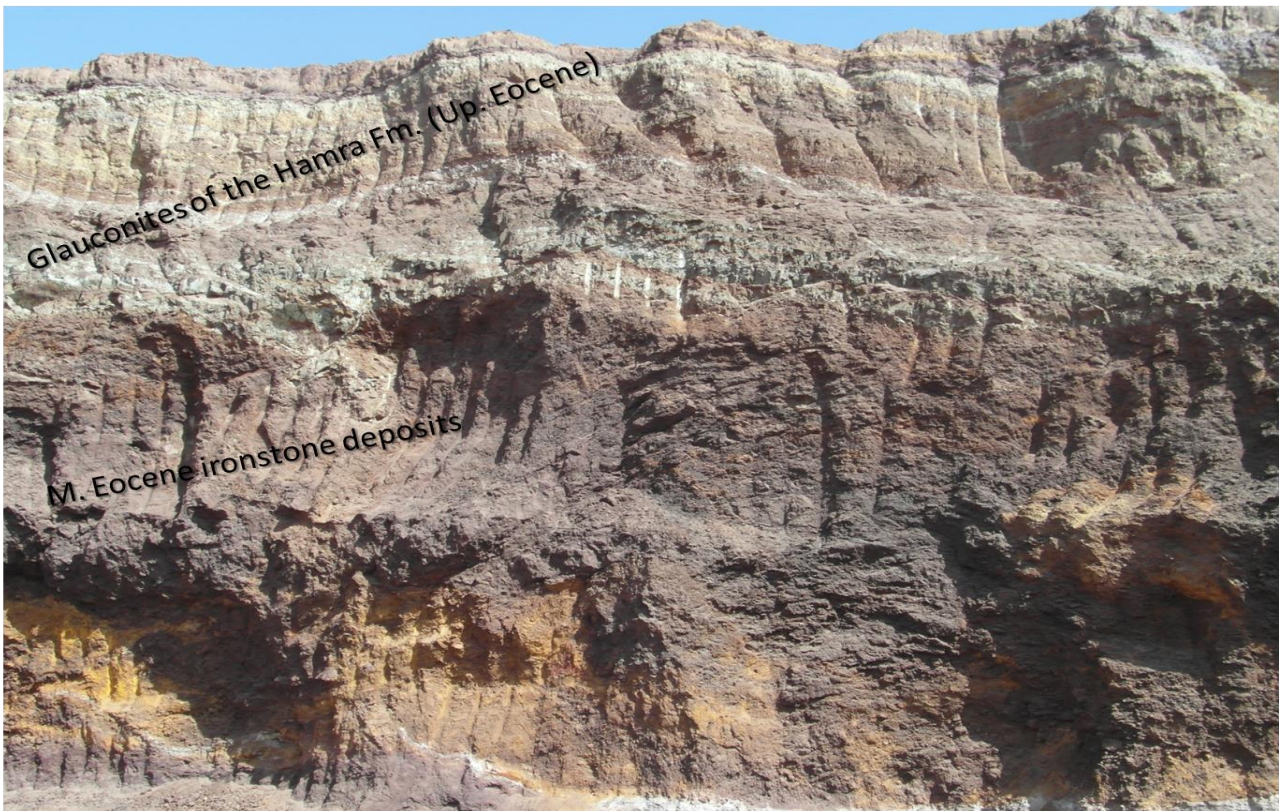
An accumulation of glauconite mineral deposit covers iron ore deposits at El-Gedida iron mine, El-Bahariya Oasis.

An accumulation of glauconite deposits cover the Upper Cretaceous phosphorites at Abu-Tartur mine, Western Desert, Egypt.

Important terms you should know

Syngenetic ore deposits: refers to ore deposits that form at the same time as their host rocks. For example, chromite and ilmenitedeposits enclosed within the ultramafic rocks.

Abu-Ghalagailmenite deposits, Eastern Desert.
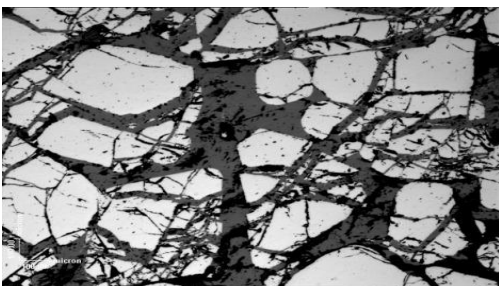
Cumulus chromite fractured crystals surrounded by simultaneous crystallization of olivine

Epigenetic ore deposits: refers to ore deposits that form after their host rocks, such as barite veins cutting through granitic rocks at Aswan or lead-zinc deposits enclosed within Abu-Dabbab Formation at Um Gheig area- Red Sea.

Epigenetic gold mineralization

Epigenetic barite mineralization

Hypogene: refers to mineralization caused by ascending hydrothermal solutions, such as hydrothermal mineralization of Um Bogma manganese.
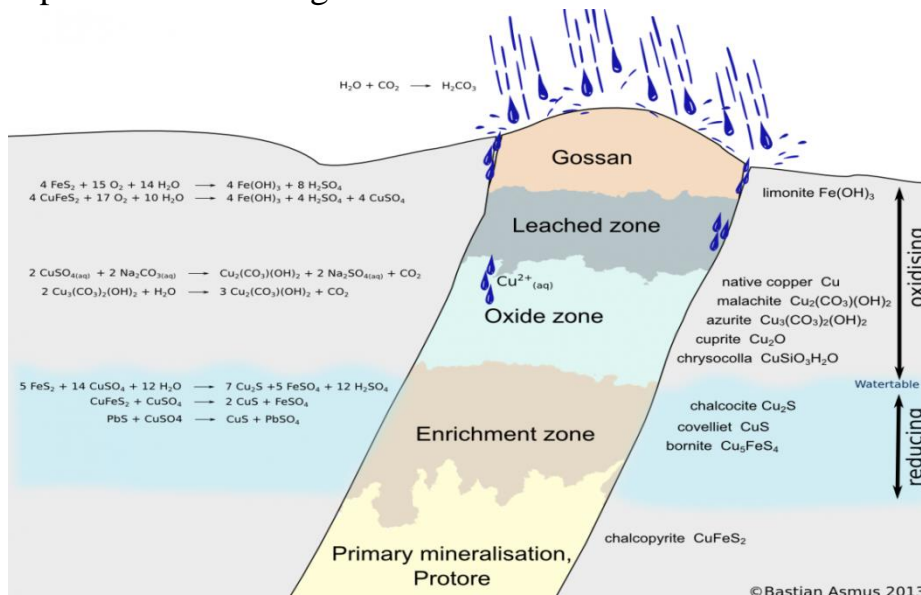

HypogeneStockwork of barite

Hypogene Um BogmaMn deposits

Supergene: refers to mineralization caused by descending solutions, such as lead-zinc deposits at Um Gheig and Gabal El-Rusas in the Eastern Desert of Egypt.

$$H_2O + CO_2 \longrightarrow H_2CO_3$$

Gossan

$$4 FeS_2 + 15 O_2 + 14 H_2O \longrightarrow 4 Fe(OH)_3 + 8 H_2SO_4$$
$$4 CuFeS_2 + 17 O_2 + 10 H_2O \longrightarrow 4 Fe(OH)_3 + 4 H_2SO_4 + 4 CuSO_4$$

limonite $Fe(OH)_3$

Leached zone

oxidising

$$2 CuSO_{4(aq)} + 2 Na_2CO_{3(aq)} \longrightarrow Cu_2(CO_3)(OH)_2 + 2 Na_2SO_{4(aq)} + CO_2$$
$$2 Cu_3(CO_3)_2(OH)_2 + H_2O \longrightarrow 3 Cu_2(CO_3)(OH)_2 + CO_2$$

$Cu^{2+}_{(aq)}$

Oxide zone

native copper Cu
malachite $Cu_2(CO_3)(OH)_2$
azurite $Cu_3(CO_3)_2(OH)_2$
cuprite Cu_2O
chrysocolla $CuSiO_3H_2O$

Supergene mineralization

Watertable

$$5 FeS_2 + 14 CuSO_4 + 12 H_2O \longrightarrow 7 Cu_2S + 5 FeSO_4 + 12 H_2SO_4$$
$$CuFeS_2 + CuSO_4 \longrightarrow 2 CuS + FeSO_4$$
$$PbS + CuSO4 \longrightarrow CuS + PbSO_4$$

chalcocite Cu_2S
covelliet CuS
bornite Cu_5FeS_4

Enrichment zone

reducing

chalcopyrite $CuFeS_2$

Primary mineralisation, Protore

©Bastian Asmus 2013

Endogenetic: concentration caused by processes in the Earth's interior (magmatism or metamorphism), for example, ilmenite, chromite, skarn, feldspar and mica.
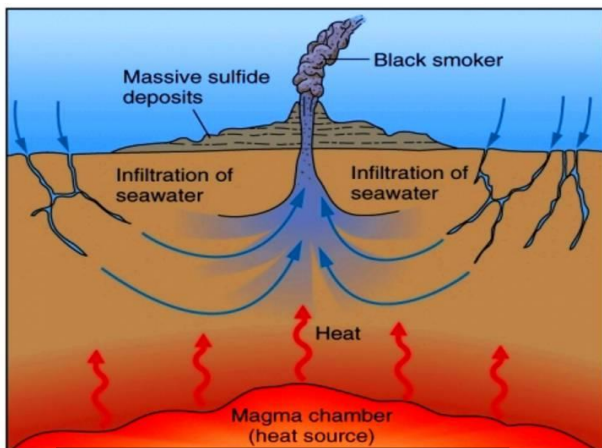

Gravitational settling

Filter pressing

Endogenetic mineralization
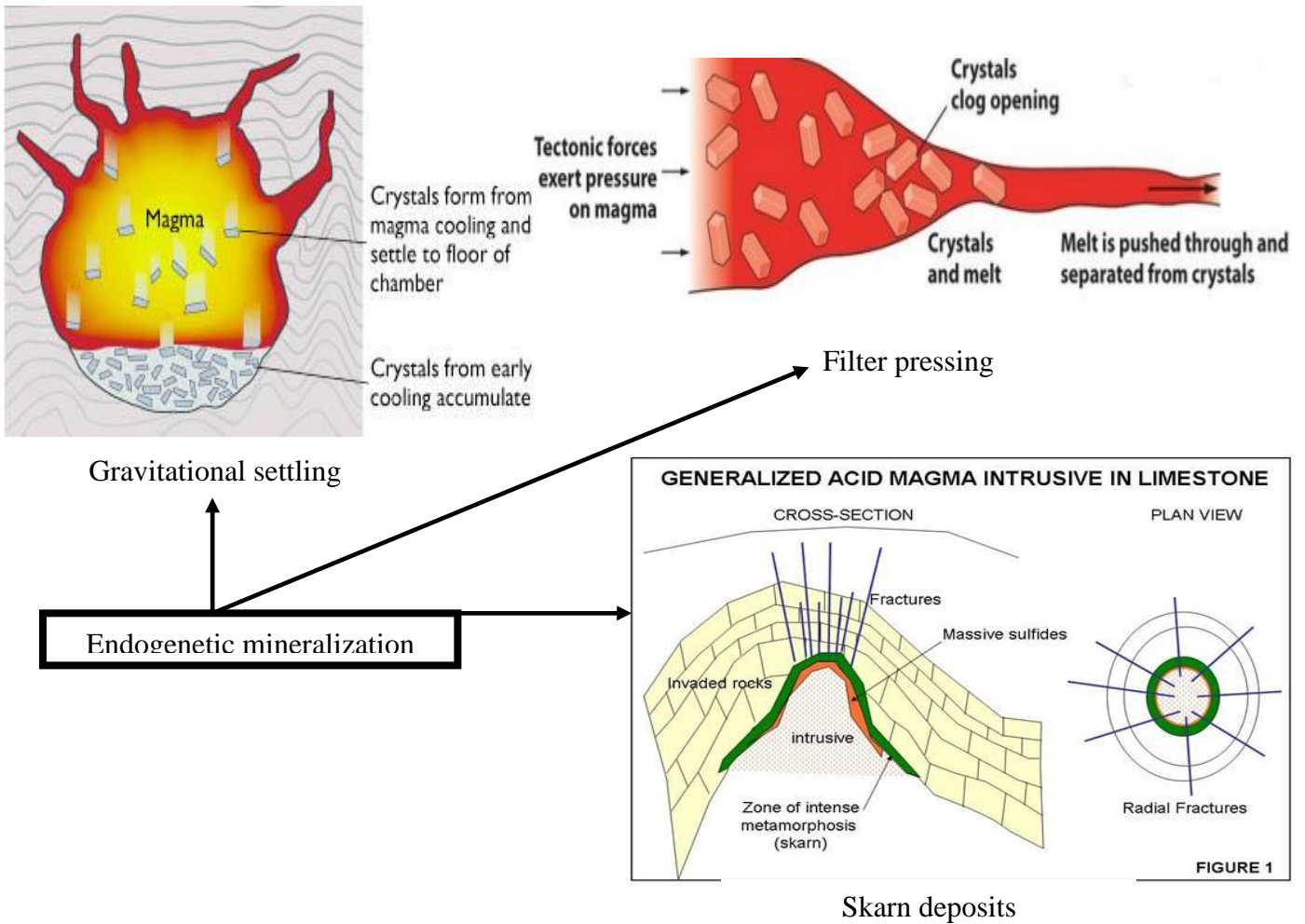
Skarn deposits

Exogenetic: concentration caused by processes at the Earth's surface (sedimentation, hydrothermal activities and weathering) like evaporites, formation of glauconite, phosphorite, black shale and volcanogenic massive sulfides.

Submarine hydrothermal activity "black smokers"

Upper Cretaceous phosphorite, Abu-Tartur plateau

Host rocks: different rock types inside of which specific mineralization occurred such as the Nubia Sandstone at Aswan is a host rock for the Cretaceous iron deposits and the porphyritic granite is a host rock for gold mineralization at MarsaAlam.

Upper Cretaceous Nubia Sandstone "host of Aswan iron deposits	Middle Eocene NaqbFm "host of El-Bahariya iron deposits

Country rocks: different rock types associated with a specific mineralization suchas andesite and rhyolite are associated with the sulfide mineralization at Um Samuki area, Eastern Desert.

Overburden: valueless geological material occurs at varied thickness and covers the mineral/ore deposits. For example, shale and oyster limestone over phosphate deposits at Abu-Tartur and Eastern Desert.

Classification of Mineral Deposits in Egypt

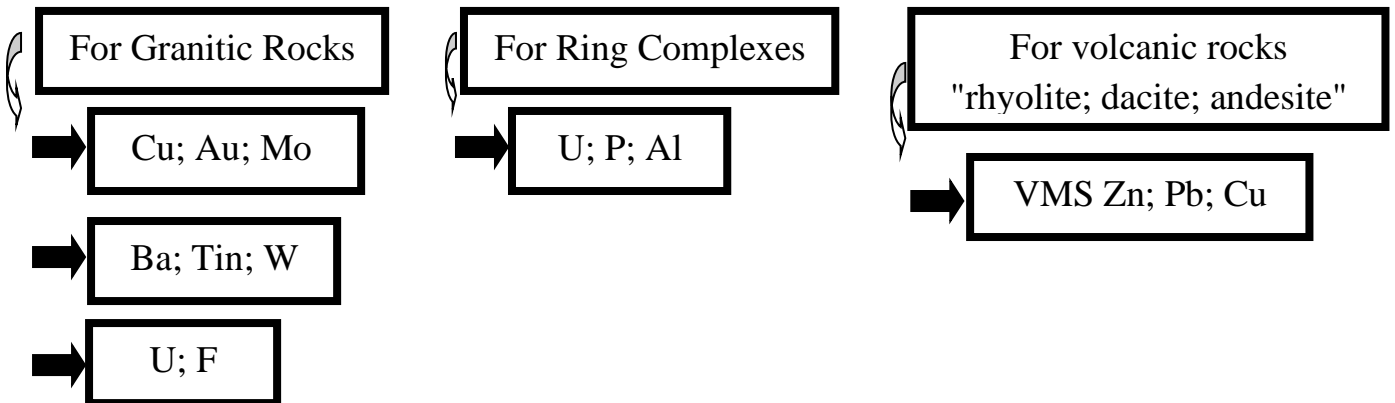Mineral deposits in Egypt are mainly confined to:

- ► **Precambrian mafic-ultramafic rock associations.**

- ► **Precambrian felsic rock associations.**

- ► **Precambrian metamorphic associations.**

- ► **Phanerozoic sedimentary rock associations.**

Accordingly, **five**groups of mineral deposits can be recognized:

1-Mineral Deposits Associated with the Precambrian mafic-ultramafic rocks:

Ophiolite Mineral Deposits		Mineral Deposits of layered mafic rocks

➡ Podiform chromite

➡ Ti-Fe oxides deposits

➡ Serpentinites, talc, magnesite and asbestos

➡ Cu-Ni sulfides

➡ Cu-Ni sulfides
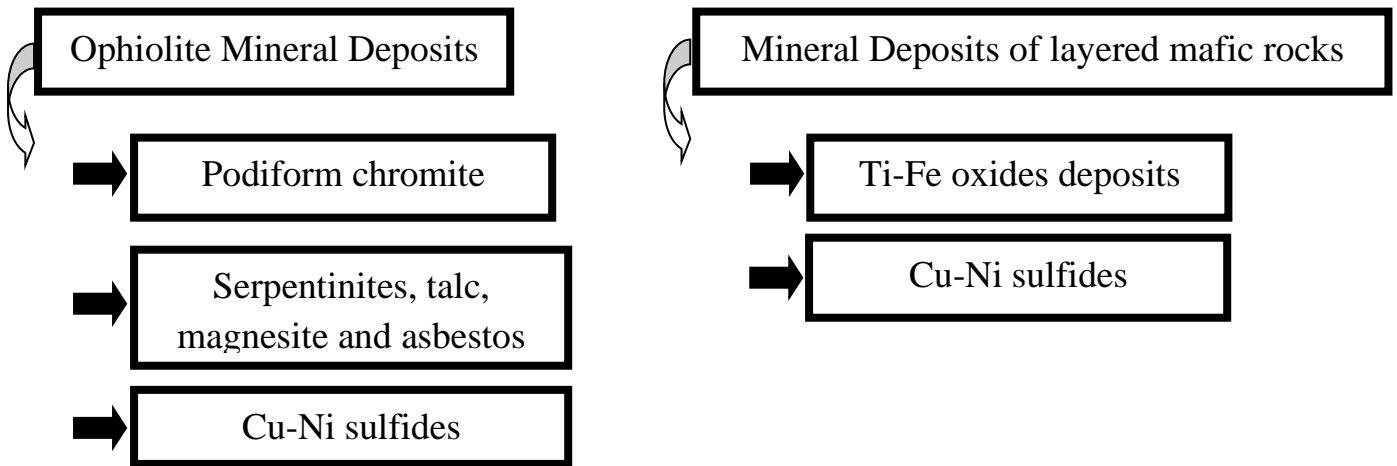
2-Mineral Deposits Associated with the Precambrian felsic rocks:

For Granitic Rocks	For Ring Complexes	For volcanic rocks "rhyolite; dacite; andesite"

➡ Cu; Au; Mo

➡ U; P; Al

➡ VMS Zn; Pb; Cu

➡ Ba; Tin; W

➡ U; F

3-Mineral Deposits Associated with the Precambrian metamorphic rocks:

➡ Metamorphosed BIF

➡ True Marble
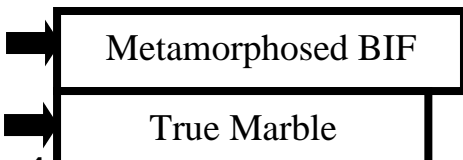
4-Stratabound Mineral Deposits Associated with the Phanerozoic sedimentary rocks:

➡ Lead-zinc deposits

Barite &S deposits

5- Phanerozoic Sedimentary Mineral Deposits

➡ Fe- &Mn-deposits

Phosphate; Coal

Clastic&placer deposits

Evaporites

<u>Your Comments</u>

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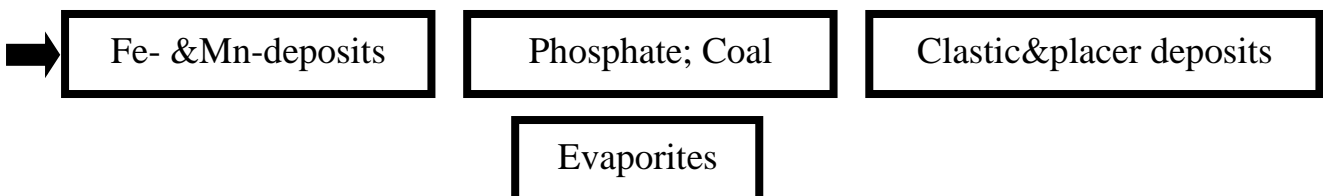
Three main factors influence the ore mineability:
- ► Tenor and tonnage of ore.
- ► Nature of ore deposits.
- ► Locality of ore deposits.

1-Tenor Ore Deposit:

- **Tenor means the ore grade** "the average concentration of a specific metal in the ore deposit". For example, if ilmenite ore deposit contains 55wt% TiO_2, the ore grade will be 55wt% of titanium metal. The ore grade is determined using the different chemical analyses techniques (e.g. XRF, ICP-OEM, and atomic absorption).

- It is known that the mined ore deposits can be undergone different physical (e.g. magnetic separation, shaking table, flotation) and chemical processes (e.g. chemical leaching by suitable acids or bases) to remove the associated gangues and upgrade the mined ore, **this is called ore dressing**. This process results in two main fractions: **valuable mineral-bearing concentrate**; **gangue mineral-bearing tailing**. In addition to chemical assays, the metal grade can be numerically estimated during the ore dressing processes in the concentrate and tailing by the equation:

> Metal grade %= [wt of mineral in the concentrate*the conc. of metal in its mineral/wt of concentrate] *100

Wt. of mineral can be estimated by the semi-quantitative XRD.

- ✓ For example, consider 1000gm feed sample of galena and calcite was undergone flotation, resulting in 750gm concentrate of which 700gm assigned for galena and 50gm for calcite, and 250gm tailing of which 200gm of calcite and 50gm of galena. Consider that the lead "Pb" grade in a pure galena "PbS" is 86.6%. Calculate the metal grade of galena in the concentrate.

- The ore grade is classified essentially as low, medium, and high grade in relative to the required level of metal/s concentration. Example, the iron metallurgy is conducted on iron deposits assaying 50-60wt% Fe, and hence the deposits contain lower than 50wt% Fe are of low grade, between 50-60 wt% Fe of medium grade, and equal to/or higher than 60wt% Fe of high grade.

- In addition to ore grade, we must know another term called ***the metal recovery***. It has two definitions depending on the mineral type. In the case of the concentration of a metallic ore, is the percentage of the total metal contained in the ore that is recovered in the concentrate; a recovery of 90% means that 90% of the metal in the ore is recovered in the concentrate and 10% is lost in the tailings. The recovery, when dealing with non-metallic ores, refers to the percentage of the total mineral contained in the ore that is recovered into the concentrate. The metal recovery can be calculated using the equation:

  R%= [c*C/F*100] *100, c "metal assay in concentrate", C "wt% of concentrate", F "metal assay in the feed sample".

  Crushed sample of phosphate rock was subjected to dry, high-intensity magnetic separation at different magnetic intensities. The overall results are listed in the following table. Calculate the P2O5 recovery for the concentrate and tailing fractions.

Magnetic intensity "T"	Magnetic fraction		Non-Magnetic fraction	
	Wt %	Wt% P_2O_5	Wt %	Wt% P_2O_5
3	60	28	40	13
3.4	79	26	21	6
4	85	25	15	4

- The ore grade and recovery are in a reversible relationship.

Theoretical Grade-Recovery — Gangue Mineral — Ore Mineral
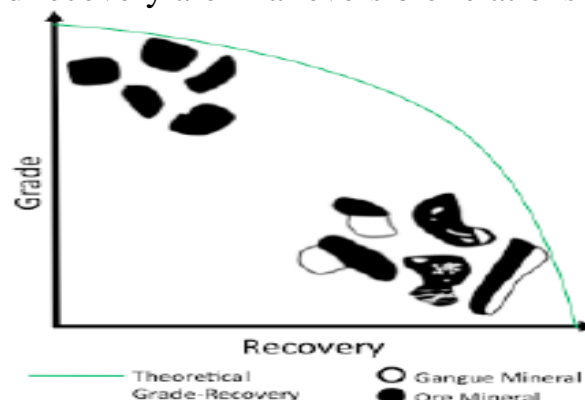
2-Cut-off-grade

- It is considered a critical parameter controlling the mineability of mineral deposits. **It can be defined as the minimum metal concentration that is required to achieve the mining costs.**It is used to discriminate between the ore and the waste. The cut-off-grade represents a material of lower concentration that is left on the ground after mining the high-grade ore. So, the cut-off-grade material must be in lower quantities for the mining to be effective and profitable. For instance, the cut-off-grade of copper deposits is about 0.5wt% Cu. So, the accumulated amounts of Cu deposits of grade above 0.5wt% must be higher than that of 0.5wt%. However, if the price increases, the cut-off grade decreases because lower-grade material can then be mined at a profit. As a consequence, the amount of mineable material in the deposit increases.

  The cut-off-grade for a specific commodity can be calculated using the following equation:

  Cut-off-grade= (milling cost + mining cost)/ (metal price + marketing price)*recovery. For example, consider the following parameters for gold mine:

  -Milling cost= 19.0 $/ton; -Mining cost= 4$/ton; -Price= 600$/oz (1oz=34.28gm); -Sales cost= 5$/oz; -Recovery= 90% "0.9". Calculate the cut-off-grade for gold mining.
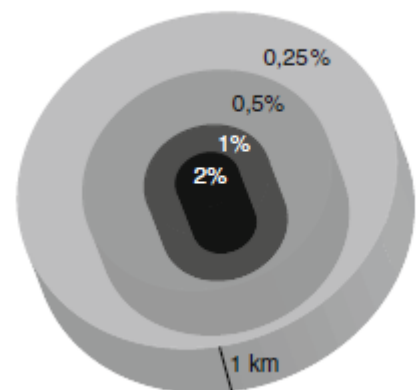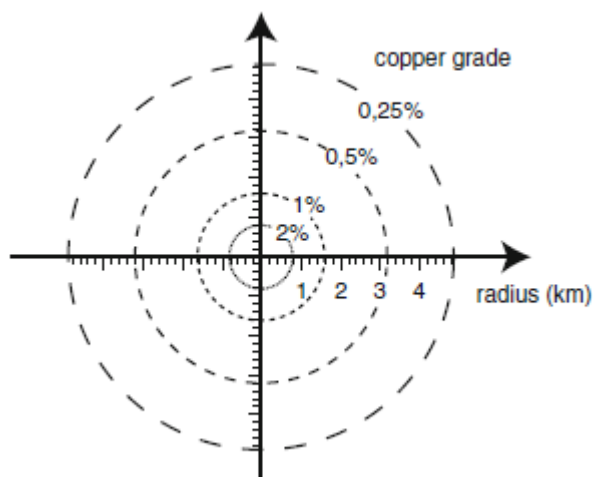
3-Ore Tonnage or Reserve

- It indicates the calculated amount of an ore accumulation in a specific area.**The total reserve= area * thickness*density.**

> If chromite deposit covers about 500 km^2 area with average thickness of chromite layers about 1.5m and average density 4 gm/cm^{3}the total tonnage = 500 *1.5*4= 3000 ton cubic meters.

- Like grade and recovery, there is a reversible relationship between the ore grade and its tonnage.
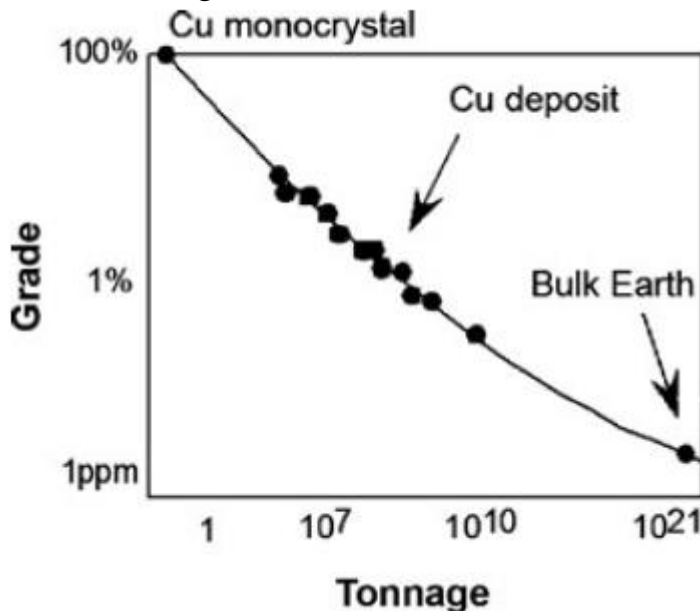
- For a given ore deposit to be mineable at a profit, the grade must be higher than the cut-off-grade with considerable tonnages sufficient for a long period of time. Example, consider that there are four different localities of ilmenite with different grades and reserves as following:

> A) 2 million tons of ilmenite of 70wt% TiO_2.
> B) 10 million tons of ilmenite of 55wt% TiO_2.
> C) 120 million tons of ilmenite of 35wt% TiO_2.
> D) 80 million tons of ilmenite of 50wt% TiO_2.
>
> 45wt% TiO_2 cut-off-grade

Which type you will select????????????????????

Methods of Ore Reserve Estimation

- The ore tonnage estimation in the drill holes is accomplished by three methods:

1-Polygonal method:

- ♦ In this method we construct a polygon around each hole to determine an area of influence for that hole; and then the total volume directly beneath the polygon.We begin with a map showing the surface location of the drill holes, and our task is to construct polygons around each hole. The relevant characteristic, say grade, inside of that entire polygon will be the same as the value of that characteristic in the drill hole sample.<u>We start our work by arbitrarily selecting a drill hole, and then drawing lines between that hole and all the adjacent holes, as shown here.</u>
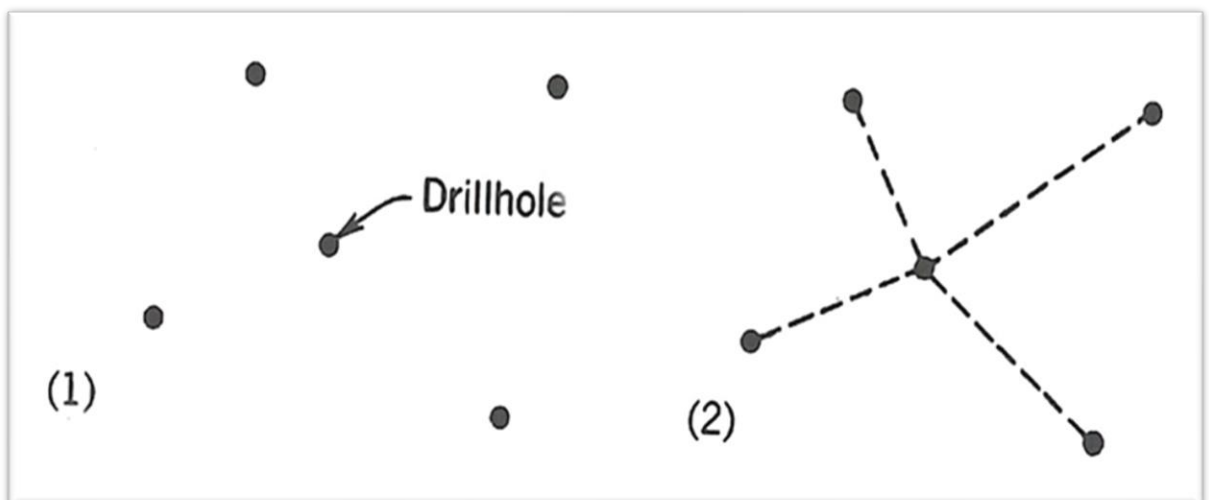
- ♦ Next, we draw perpendicular bisectors though each of these lines, drawing the bisector line long enough to intersect the other perpendicular bisectors, as shown.
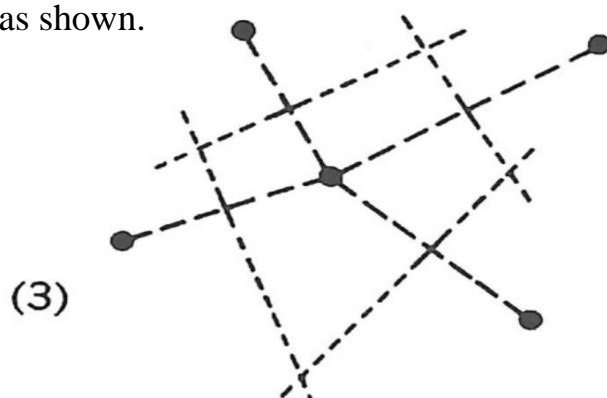
♦ The corners of the polygon are defined by the intersection of the perpendicular bisectors, as shown:
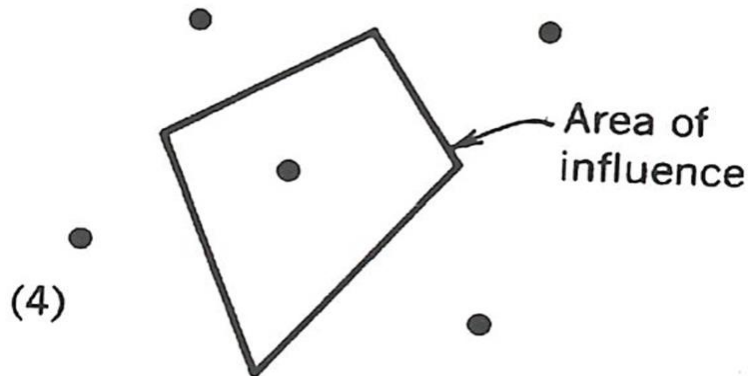
♦ We repeat the process for each hole. Note that if the hole is adjacent to the property boundary, then that boundary line will form a side of the polygon. The result will be a property containing as many polygons as holes, as illustrated here.

(b)
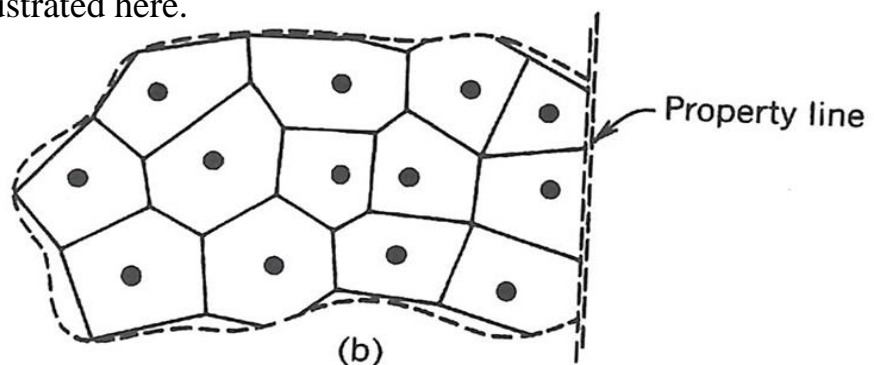
Finally, the area of each polygonal is calculated using palnimeter or the cube-counting method. The obtained area is multiplied by the ore thickness at each hole "the depth here" and by the specifcgravity of the ore to obtain the tonnage of the influence polygonal area. The total tonnage is a summition of all the influence area tonnages.

2-Triangle method:

♦ The triangle method include connection each three adjacent drill holes to form triangle. Hence, the average thickness is calculated from the three apical corners. The triangle area is estimated by planimeter. The tonnage

of each triangular influence area is estimated by multiplying the average thickness by the triangle area and the ore density.
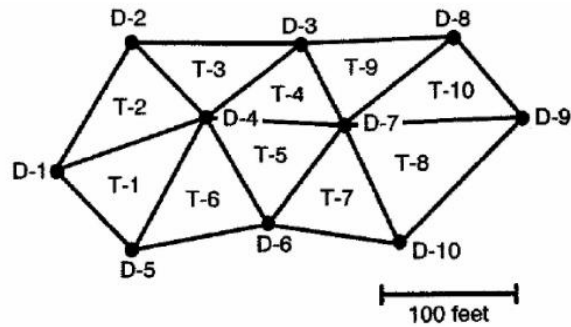
Calculate the tonnage at triangle T-1 if you know that the ore thickness at D-1, D-2, and D-2 is measured at 100m, 80m, and 75m, respectively, also consider the ore density is 3.5 g/cm3.

3-Cross-section method:

♦ If a deposit has been systematically drilled on sections, reserve calculations will be based on cross-sections along these lines. To each cross-section is assigned an area of influence corresponding to half the distance to the two adjoining sections. The limits of the blocks thus defined lie exactly halfway between the drill holes (see Fig. 2.3). The surface areas of the blocks on the section are given in Table 2.1. If we assume the distance between neighbouring sections to be 50 m and the density of the ore to be 4.0 g/cm3, we arrive at a tonnage on this profile of: T= 50 X 5595X4= 1119000 million ton.

True thickness observed		Thickness attributed to block
Outcrop	22 m	I
DDH A3	11 m	II
DDH A4	27 m	III
DDH A5	7 m	IV

Block	Surface area (m²)
I	55 × 22 = 1 210
II	(55 + 50) × 11 = 1 155
III	(50 + 45) × 27 = 2 565
IV	(45 + 50) × 7 = 665
Total	5 595
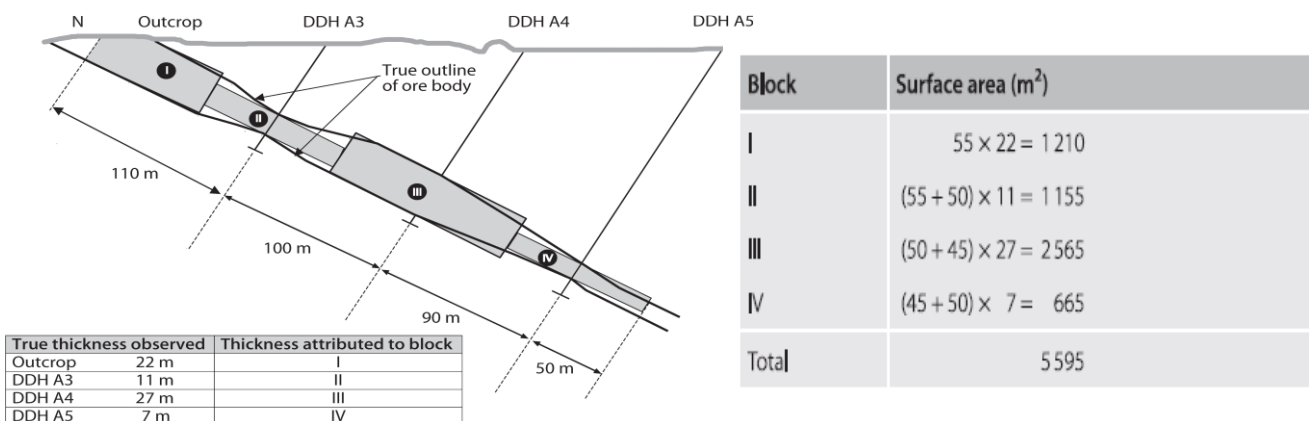
How Much of the Mineral Deposit Can be Mined at Profit????

- Till now we discussed the different methods employed for the reserve estimation of an ore deposit. Lets us now talk about how much of the mineral deposit can be mined economically. This can be done by what so-called **the stripping ratio and stripping cost** in case of the surface or shallower mining.

- **Stripping** is the removal of waste rock from above and around the orebody.

- **Stripping ratio** is defined as the volume of waste rock to be mined, divided by the volume of ore to be mined from the pit. This is defined as overall stripping ratio "cubic meter". For example, if we have 100 m^3 of shale above 50m^3 of coal seams, thus the overall stripping ratio equal 2; this means that to mine 1m^3 of coal it is necessary to remove 2m^3 of shale.

- The stripping cost can be estimated by the equation:

$$SC = Vc * D * SP / Vob$$

Where:

SC = stripping cost, \$/yd^3

V_{ob}= volume of overburden that will be removed at breakeven

V_c= volume of coal that will be exposed by the removal of Vob

D = tonnage factor (density) of the coal, tons/yd^3

SP = selling price of the coal, \$/ton

The Life Time of a Mine

The mine life is defined as the time in which the ore reserves—or such reasonable extension of the ore reserves will be completely extracted.

L = Total ore tonnage/ (C*350), where C is the daily short tons production.

For example, iron mine contains about 70 million tons of iron ore with daily capacity of 50 ton. So, the life time of that mine will equal= 4000 days = 4000/350= 11 year.

2-Nature of the Ore

- Another factor that strongly influences the viability of a deposit **is the nature of the ore**. Characteristics to be considered include *the type of mineral*, *the grain size*, and *the texture of the ore*, all of which influence the cost of mining and the extraction of the valuable commodity.

- The lowest extraction costs are for ores in which the extracted element is only mechanically bound into its gangue (e.g. free-milling gold ores or placer deposits).

- The highest extraction costs are for ores in which the element is chemically bound to silicates because these bonds are much stronger than metal-sulfur bonds.

- The grain size and the hardness of the ore influence the cost of grinding it to the fine powder that is fed into the refinery or smelter.

- Mineralogy is essential for the mineability of Ti deposits, for example, Ti minerals present in sand deposits are liberated by nature, and the mining work can be done on the low grade sands (sand ilmenite) if the Ti mineral is of high quality.Ilmenite sand deposits can be mined at 5% ilmenite.We can conclude that the separation and liberation of Ti minerals from sand deposits are easy and low cost.In controversy, the ilmenite hard rock deposits (such as Abu Ghalga deposit) require crushing, grinding, sieving and hydrometallurgical processes.
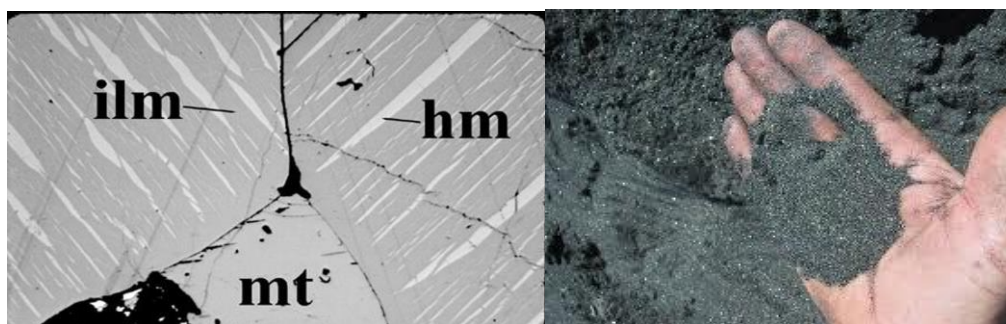
Hard ilmenite deposit on left and loose ilmenite sand at right

- Other examples are represented by the sedimentary iron deposits in the Western Desert and the banded iron formation in the Eastern Desert of Egypt. The western Desert iron deposits are moderate to soft in nature and can be upgraded during the cumminution process followed by screening and magnetic separation, while the BIF is hard and contains silica disseminations that make the crushing and beneficiation is too cost. So, the current iron mining in Egypt is focused on the Western Desert deposits.
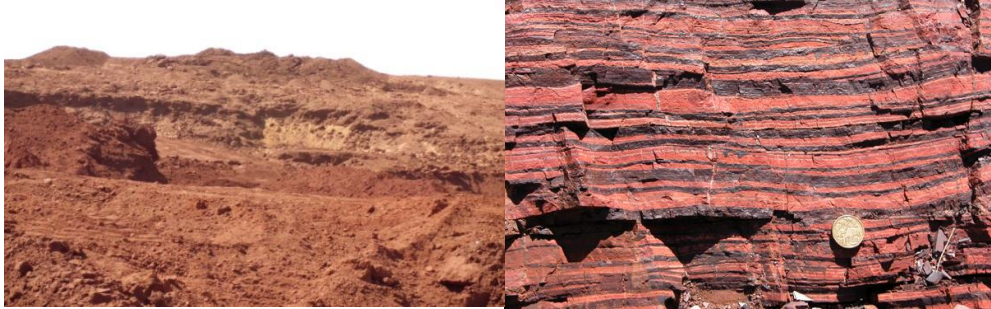
Western Desert iron deposits on left and Eastern Desert BIF on right.

3-Location of the Ore Deposit

Its value, and its very viability, decreases if it is far from centres of industry or population, or in a harsh climate, or in a politically unstable region. All these factors increase the cost of mining or of bringing the metals to market; or they render the operation of a mine too dangerous or risky.

For example Haliab region, Mn ore deposits are mainly hosted by Miocene sedimentary rocks at G. Elba.The main Mn minerals are pyrolusite, cryptomelane and psilomelane while gangues include hematite, goethite, quartz and calcite.The Mn content reaches up to 74% MnO (high grade ore).Mn ore deposits occur as veins in sedimentary rocks and occasionally in granitic rocks.The extraction of Mn at G. Elba began 1955 and then was stopped due to:

1. The remoteness of mine locality.
2. Un favorable conditions of the mining area.

Your Comments

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All the common ore-forming elements are present in the Earth's crust and magmas, in amounts ranging from a few parts per billion "ppb" to several thousands of parts per million "ppm", see the attached table.

Distribution of selected ore-forming elements in different rock types, in ppm.			

Element	Crust (a)	Granite (b)	Diabase (c) (Basalt)	Shale
Al	81,300	74,300	79,400	80,000
Fe	50,000	13,700	76,600	47,200
Ti	4,400	1,500	9,400	4.600
Mn	950	195	1,280	850
S	260	58	123	2,240
C	200	200	100	1,000
V	135	17	264	130
Cr	100	20	114	90
Ni	75	1	76	68
Zn	70	45	86	95
Cu	55	13	110	45
Co	25	2.4	47	19
Pb	13	48	7.8	20
U	1.8	3.4	0.6	3.7
Sn	2	3.5	3.2	6.0
Mo	1.5	6.5	0.6	2.6
W	1.5	0.4	0.5	1.8
Hg	0.08	0.1	0.2	0.4
Ag	0.07	0.05	0.08	0.07

For these elements to form mineral/ore deposit, they need some degrees of concentration or what so-called *the concentration factor*, which defined as the ratio of the average concentration of a specific elements in a mineable mineral deposit to its average crustal abundance. Note that the concentration factors for the geochemically abundant elements (e.g. Fe & Al) range between 5-10, and that for the less abundant elements (e.g. copper, zinc & uranium) range between 100-1000.

The **_concentration factors_** are resulted by different geological processes (_magmatic, hydrothermal, metamorphic, and sedimentary processes_)through three main steps:

A. Extraction of the elements from magmas, rocks, and oceans;

B. Transport of the elements in a fluid medium from the source region to the site of deposition;

C. Crystallization and deposition of valuable minerals at certain favorable sites.

Geological processes responsible for formation of several ore types can be classified into endogenetic and Exogenetic processes.

> **_A) Endogenetic Processes_**: occur through the Earth's interior.

1. Magmatic Processes

First of all, magmas are defined as silicate melts with variable amounts of ore metals and other elements, water and other volatiles (e.g. CO_2, H_2S, SO_2, and HF). There are two main magma types: _mafic and felsic magmas_. **_Mafic magma_** is generated by partial melting of the top 100-200km of the upper mantle through adiabatic decompression "**_pressure-release melting_**".The upper mantle rocks are characterized by low water contents. So, it is seldom to find hydrothermal activity-related mafic magma, but mineral deposits such as chromite and ilmenite are commonly observed.**_Felsic magma_** is created by partial melting of lower crustal material. It is accepted that the felsic magmas are related to some kinds of hydrothermal mineralization (e.g. U, tin, W, Au, and REEs) due to the water-richness crustal rocks.
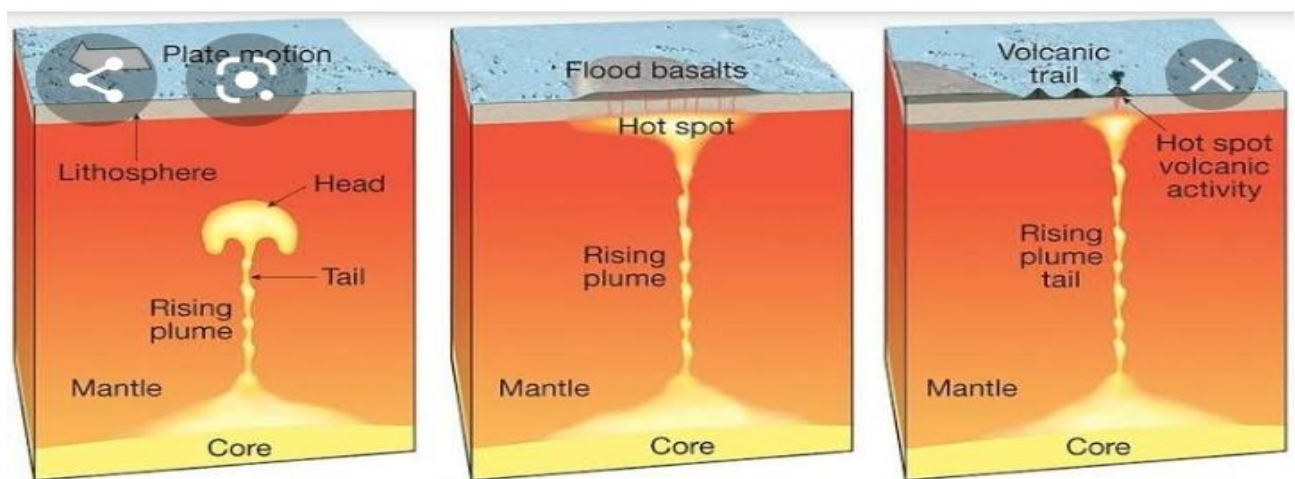
Mineral deposits directly crystallized from magma are called ***orthomagmatic*** mineral deposits (e.g. chromite, pentalendite and Ti-Fe oxides). Three mechanisms by which orthomagmatic deposits are magmatically concentrated:

A) Liquid immiscibility

Liquid immiscibility is the phenomenon of separation of a cooling magma into two liquid phases of different composition. Three cases of liquid immiscibility:

► Separation of Fe-rich tholeiitic magmas into two liquids, one mafic "rich in Fe" and the other felsic "rich in SiO_2".

► Splitting of CO_2-rich alkali magma into one melt rich in CO_2 and the other rich in alkalies and silica, which may account for the origin of carbonatite magma.

► Segregation of sulfide melts from sulfide-saturated mafic or ultramafic magmas.

Lets us focus on the sulfide immiscibility during magma crystallization. Sulfide minerals (e.g. pentalendite; pyrrhotite) are concentrated mainly from mafic or ultramafic melts <u>due to the sulfur-richness of the upper mantle rocks</u>. This takes places under one or more of the following condition:

► Cooling of the magma, which not only decreases its sulfur solubility, but also causes crystallization of silicate minerals, thereby increasing the sulfur concentration in the residual magma.

► Silica enrichment of the magma by reaction with felsic country rocks.

► Mixing of more fractionated magma with less fractionated magma, both of which were nearly saturated with sulfur.

► Assimilation of sulfur from country rocks.

Why Sulfide minerals are first segregated from magma as drops not crystals??

If saturation is reached at a temperature above the melting point of the mineral, a drop of liquid precipitates instead of a mineral grain. The composition of this immiscible drop is not exactly that of the pure mineral, because the liquid tends to scavenge and concentrate many elements from the parent magma, and this process can lead to rich ore deposits. Iron sulfide is the principal constituent of most immiscible magmas, and the metals scavenged by iron sulfide liquid are copper, nickel, and the platinum group. Immiscible sulfide drops can become segregated and form immiscible magma layers in a magma chamber in the same way that cumulus layers form; then, when layers of sulfide magma cool and crystallize, the result is a deposit of ore minerals of copper, nickel, and platinum-group metals in a gangue of an iron sulfide mineral.

Types of sulfur segregation from magma:

♦ **Batch segregation**: Significant amount of sulfide is segregated from the parent magma in a single stage due to an abrupt increase in the sulfur content during the initiation of magma cooling (note that olivine crystallizesafter sulfide settling). The segregated sulfide drops are in equilibrium with the surrounding melt, in other words, the segregated drops scavenges the chalcophile elements from magma and then settle on the floor of magma chamber.

Batch sulfide segregation
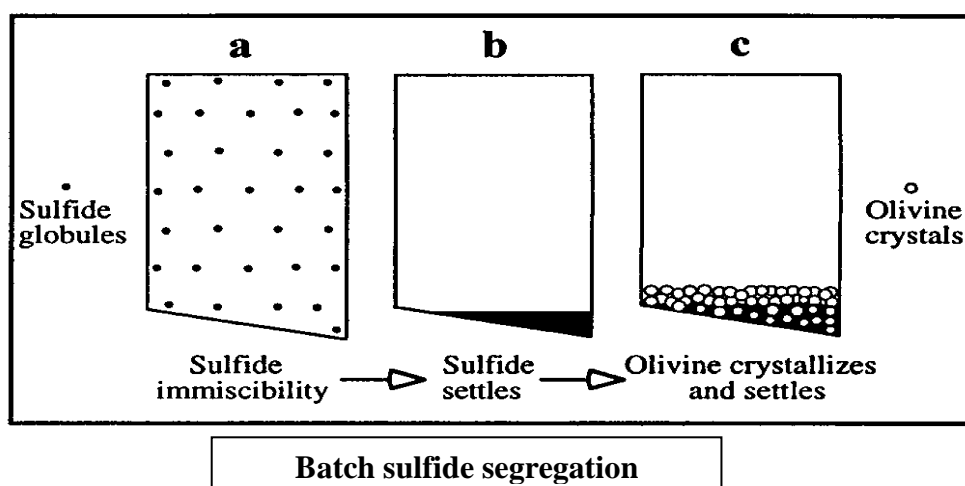
♦ **Fractional segregation**: very small amounts of sulfide become continuously immiscible, equilibrate with the silicate magma, and then are removed from the

system by settling on the floor of magma chamber. The sulfide segregation here is triggered by olivine crystallization. This is the common segregation during the crystallization of sulfide-saturated magma.

Fractional sulfide segregation
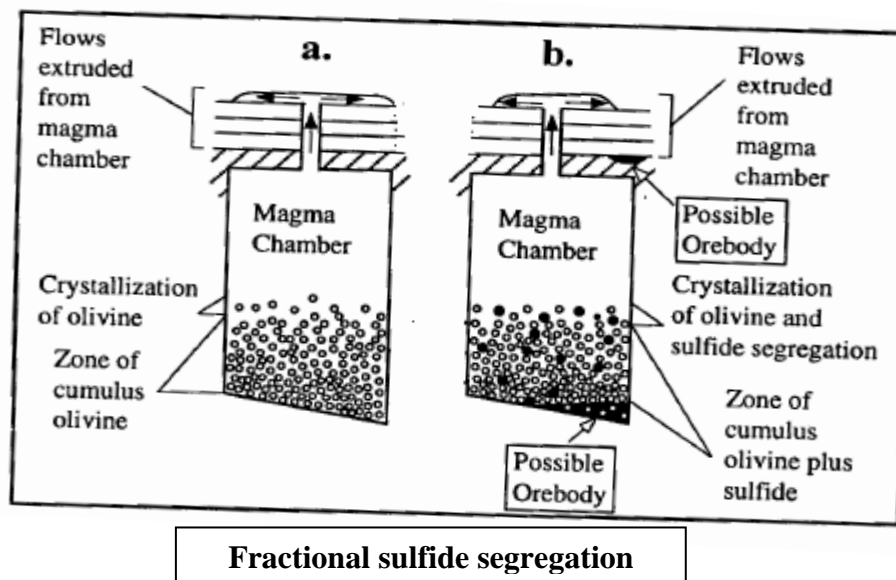
Criteria of sulfide immiscibility:

-Globular texture of sulfide deposits in the mafic-ultramafic intrusions.

-Depletion of chalcophile elements (Ni &Cu) in the resultant mafic-ultramafic rocks due to their scavenging by the immiscible drops

B) Gravitational Separation

Gravitational Separationincludes fractionationprocesses that occur when crystalsdevelop with significantly different densitiesthan the surrounding magma. Gravitational separation includes crystal settlingand crystal flotation processes.**Crystal settling** occurs when higher density,ferromagnesian crystals settle to the base of a magma chamber relative to the lower densityliquid magma. Crystal settling may result in discrete layers of crystal mush such thatbanded or layered cumulus crystals may precipitatevia magmatic "sedimentation" on thepluton floor. **Crystal flotation**can occur if early formed crystals, suchas plagioclase, are less dense than the magma.As a result crystals may float towards the roofof a magma chamber, effectively segregatingthem from the remaining melt.

Both crystal settling and crystal flotation imply that individual crystals migrate through a low viscosity magma that has a different density than the crystals. However, in most cases, the differences in density between crystals and magma are vanishingly small and the viscosity of most magmas impedes crystal migration. However, gravitational migration may be possible for large clusters of early formed crystals with higher settling or flotation velocities in very high temperature, low viscosity magma. Crystal migration is far less likely to occur in lower temperature, higher viscosity magmas. The most commonly mineral deposits formed by gravitational settling are chromite deposits.

Model for Gravitational settling and crystals migration
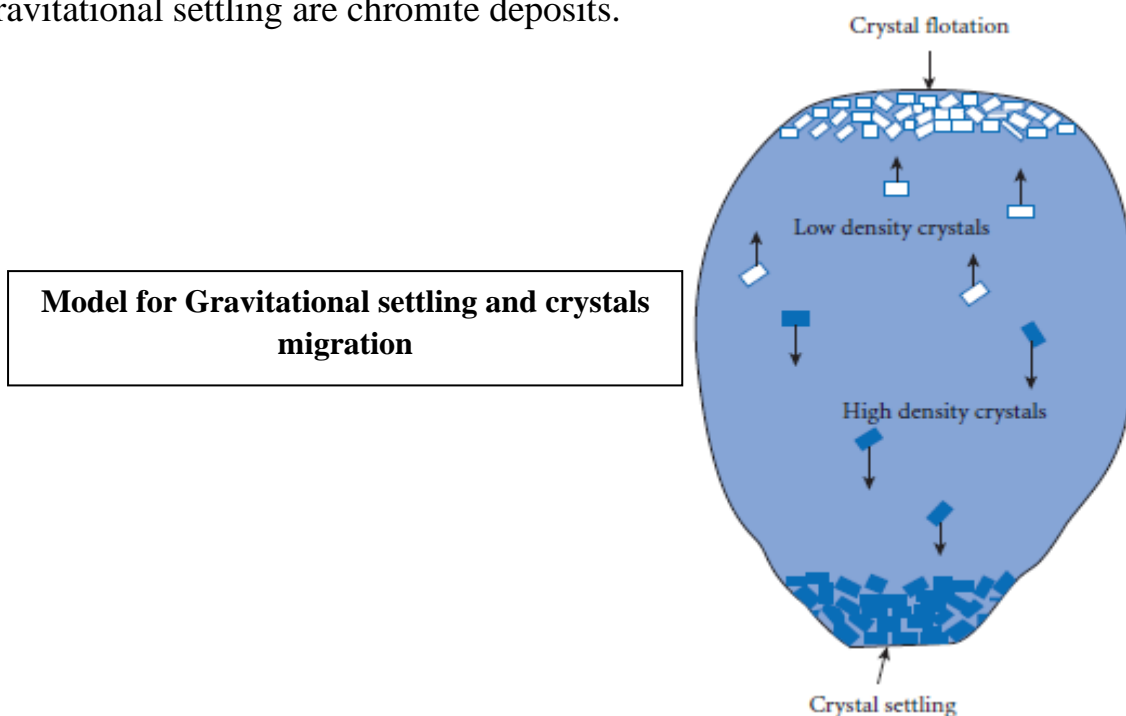
C) Filter Pressing

This process is happened during the later stages of magma chamber cooling, where crystals are separated from the residual melt by tectonic squeezing. For example, during the later stages of mafic magma crystallization, the residual melt is enriched in Fe-Ti constituents. This heaver melt first moves down and crystallizes above the early formed cumulus and then pressed out by tectonic force to form magmatic injection deposits in the associated mafic rock assemblages (e.g. Abu-Ghalagailmenite deposits in the associated layered gabbro).
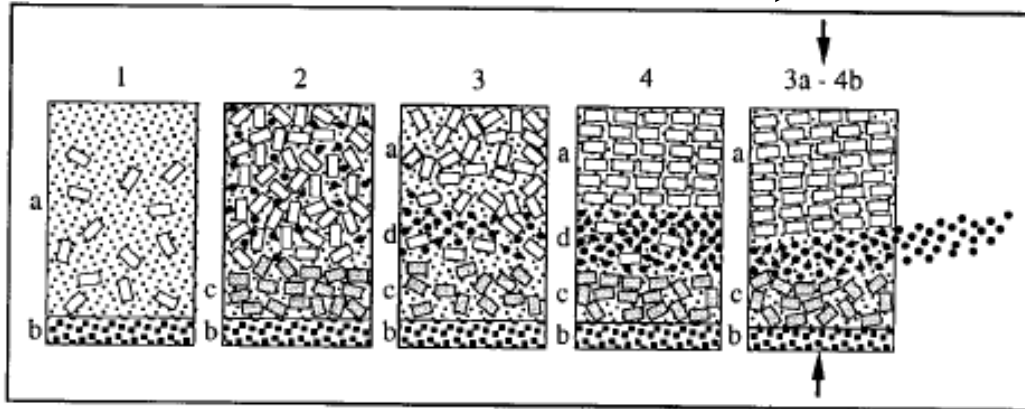
Stages of filter pressing of Fe-Ti mineral deposits

2. Pegmatitic Processes

Pegmatite is defined as the residual magma left behind after the crystallization of most granitic magma (e.g. separation most of the major minerals of which granite rocks are composed). This residual melt is rich in alkalies, silica, uranium, REEs, and water. The water saturation of pegmatite makes the cooling process to occur at slow rate, resulting in well-developed crystals of feldspars and mica as commercial deposits as well as U and REE-bearing mineralization.
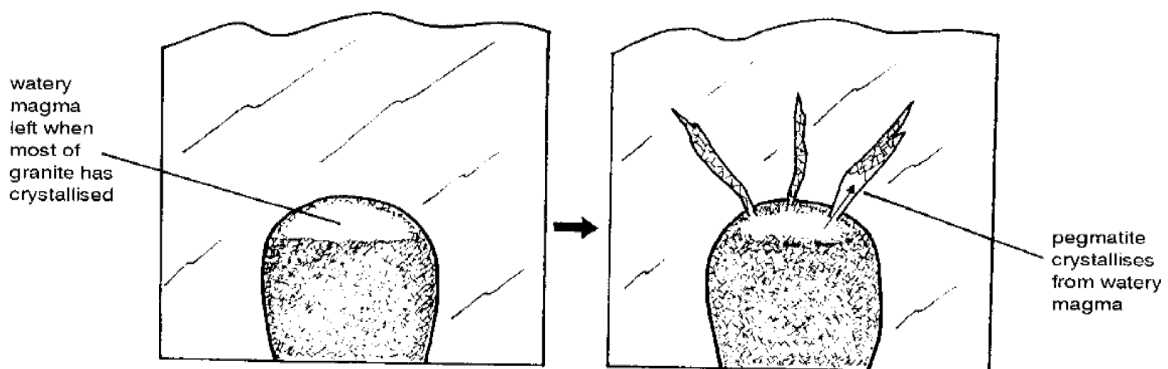
Stages of pegmatite melt formation

Your Comments

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Ore Deposits-Endogenetic Forming Processes: Magmatic-Non Magmatic Hydrothermal Processes

1-Definition of Hydrothermal Solutions

► Hydrothermal solutions are hot brine solutions capable of dissolving, transporting, and concentrating various precious deposits (e.g. sulphides, oxides, Au, and Cu).

► The salinity of hydrothermal solutions refers to the total dissolved solid components in wt%. It is varied (<5wt%-to->40wt%), but the major dissolved components are chlorine, sodium, calcium, magnesium, and potassium.

► Hydrothermal solutions are an important endogenetic process responsible for formation of the majority of mineral deposits. This can be attributed to the continuous flowing of these solutions here and there throughout the crustal rock units, resulting in scavenging and concentration of various precious metal-bearing deposits.

2-Classification of Hydrothermal Solutions

Depending on the concept of fluid continuum from high magmatic temperatures at depth to lower temperatures near the surface, hydrothermal deposits can be classified into:

A-Hypothermal deposits, formed at great depths (300-500 ^{o}C, very high pressure).

B-Mesothermal deposits, formed at intermediate depths (200-300 ^{o}C, high pressure).

C-**Epithermal deposits**, formed at shallow depths (50-200 ^{o}C, moderate pressure).

D-**Telethermal deposits**, formed at low temperature-pressure end of the fluid spectrum (<50 ^{o}C).

Further, Hydrothermal solutions can also be divided, depending on the source of water, into:

A-Magmatic hydrothermal solutions:

The magmatic hydrothermal solutions acquire their water from dehydration of silicate minerals (e.g. hornblende, amphiboles, biotite, and muscovite) during the partial melting process of the lower continental crustal levels. Such solutions are enriched in various incompatible elements (e.g. Cu, Au, W, and REEs) during the course of magmatic evolution from low volatiles and CO_2-CH_4 basaltic magma to the formation of granites and pegmatities.

The partly melted peridotite rocks are seldom to generate magmatic hydrothermal solutions???????????????????
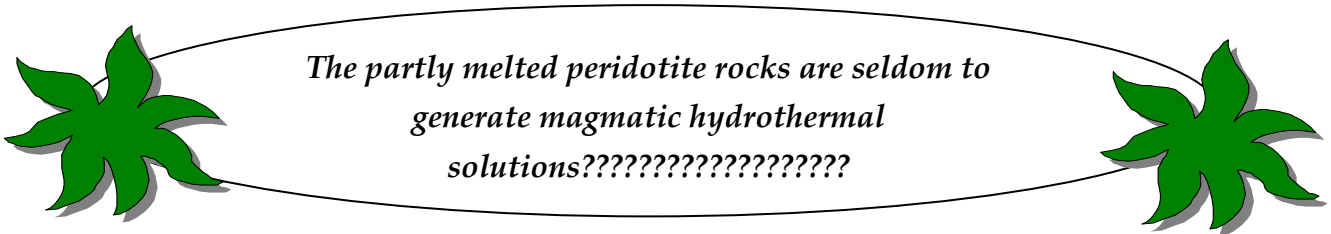
B-Non-magmatic hydrothermal solutions:

This solution type is created by the downward percolate of rainfall, groundwater, and seawater until become closer to hot igneous intrusion. On heating, water become a powerful solvent, and can leach various precious metals from the surrounding country rocks by its circulating movement. Once it is emplaced on/near the surface, the dissolved mineral loads are deposited. As such example, the volcanogenic massive sulphide deposits form via scavenging Pb, Zn, and Cu from the oceanic crust rocks by the action of the descending seawater, which deposit its sulphide load "black in color" as black clouds once the ascending hot hydrothermal solution comes in contact with the cold seawater.
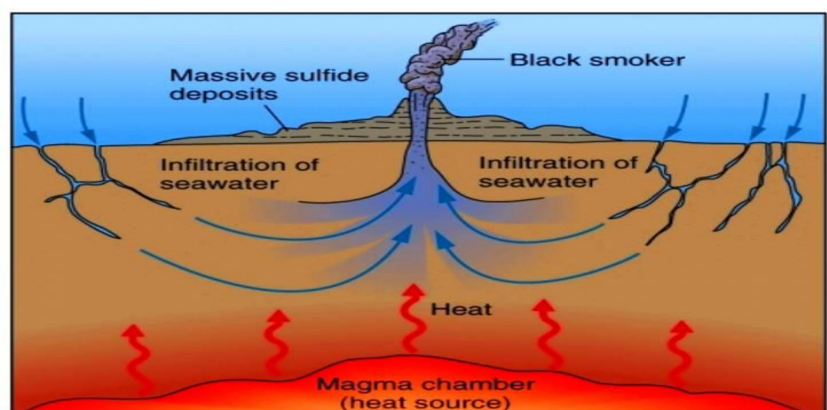
3-Key Factors in the Formation of Hydrothermal Ore Deposits

A-Water Source of hydrothermal fluids

Water accounts for more than 50% of the hydrothermal fluids constituents. Using a variety of geological and geochemical techniques, particularly the analysis of fluid inclusions in ore and gangue minerals, it has been possible to identify the following types of fluid:

• *Magmatic fluids* released at various stages during the cooling and crystallizationof granitic magmas

• *Meteoric (rain) water*

• *Seawater*

• *Connate water*, the interstitial water in pore spaces in sedimentary basins

• *Metamorphic fluids*, which are released by dehydration reactions in deepercrustal sections.

Different water types of hydrothermal fluids.
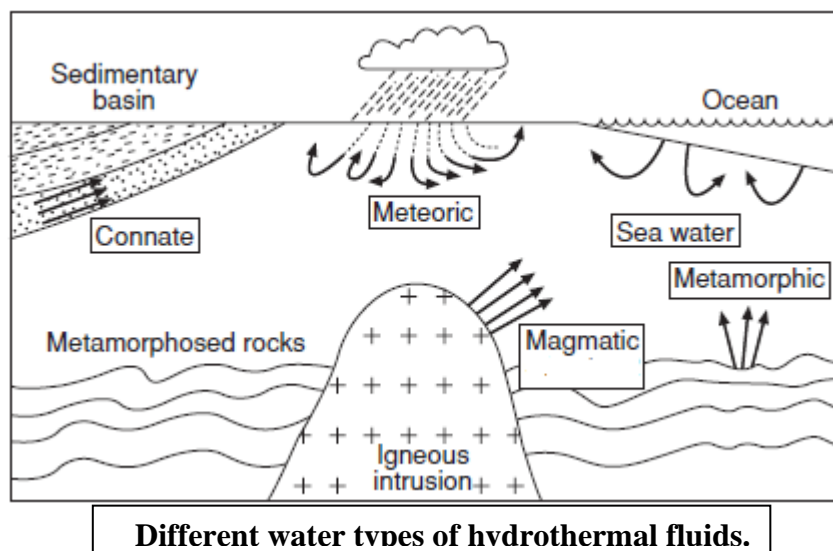
B-Source of Metals

- The ultimate source of all ore metals is the mantle.
- The immediate sources of the dissolved metals of hydrothermal fluids are:

1-Magmas, which tend to concentrate certain constituents in the fluids that separate as a consequence of magmatic crystallization.

2-Crustal rocks-for example,subducted oceanic crust, with which the hydrothermal fluids interact.

► Crustal rocks contain ore metals only at trace levels, predominantly as solid solutions components of silicate minerals-for example, Pb in potassium feldspars, Cu & Zn in micas, Cr &Ni in olivines and pyroxenes, Ti in amphiboles, etc.

► Solution leaching of metals held in solid solution can take place only during destruction of thehost minerals by dissolution (mineral-solution disequilibrium-for example, the fluid destruction of K-feldspars and basalt Ferromagnesium minerals) or during alteration of the host minerals by metamorphism (mineral-mineral disequilibrium-for example, alteration of illite into chlorite and muscovite at temperature 200 °C in the presence of water, resulting in extracting about 1,638 ppm of trace metals held in illite into the pore solutions.).

► The metal extraction from crustal rocks by hydrothermal fluids depends mainly on: a) temperatures; b) fluid: rock ratio, which controls the fluid pH-for example, the reaction of seawater with basalt at water: basalt ratio >50 leads to maintain the pH of solution at lower values "acidic conditions" due to depletion of Mg into smectite, leading to significant leaching of Na, K, Ca, Mn, Fe, Cu, Zn and Ni.

C-Fluid Movement and Circulation

► In order to be effective as a mineralizing agent, hydrothermal fluids need to circulate through the Earth's crust. The main reason for this is that they need to interact with large volumes of rock in order to dissolve and transport the metals required to form hydrothermal ore deposits.

► Fluids can move through the Earth's crust in response to the imposed hydraulic pressure under gravity effect in an uplifted area "Gravity-driven flow"

(a) Gravity driven — Maximum flow rate: 1–10 m yr^{-1}
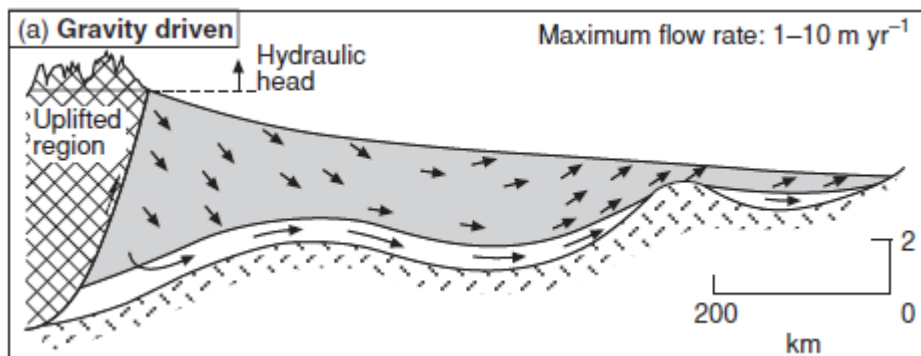
► Fluids can also move in thrust and fold belts as response to rock compaction "Orogeny-driven flow".

(b) Orogeny driven — Maximum flow rate: 0.1–1 m yr^{-1}
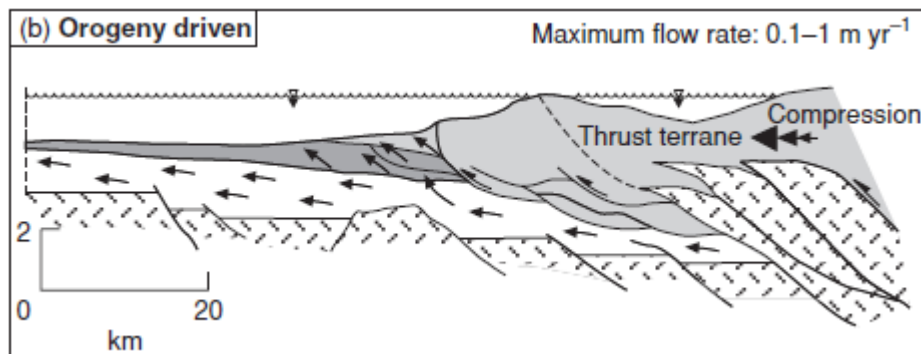
► Convection is another flowing mechanism caused by heating water. Seawater penetrates into the crust where it acquires heat from still-hot lavas or from high-level intrusions. The less-dense warm fluids then ascend to the surface along fractures, resulting in volcanogenic massive sulfide and Fe-Mn oxides mud "Thermally driven flow".

(c) Thermally driven
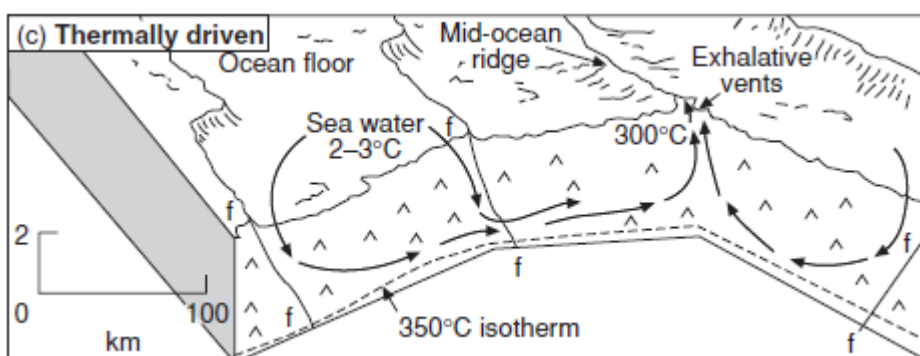
► The same scenario can be observed for igneous intrusions, where the surrounding groundwater is heated up and circulates along with the exsolved fluids through the country rocks, resulting in economic deposits of Au, Cu, U, etc.
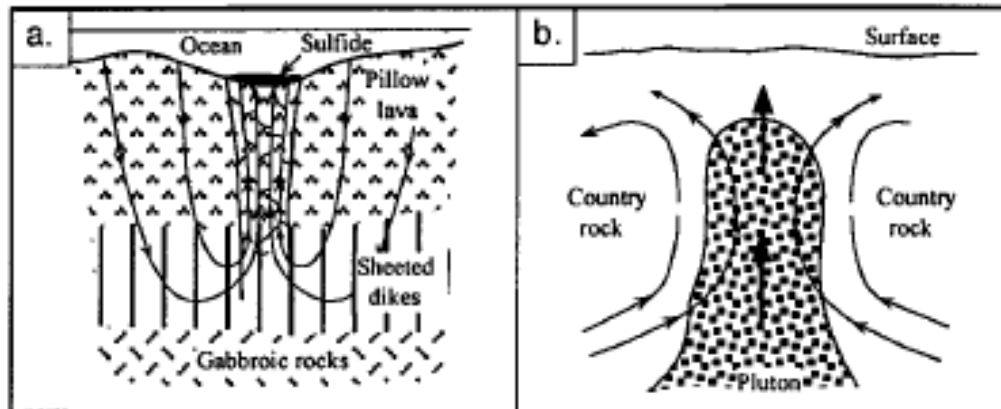
D-Dissolution and Transportation of Metals

► Solubility is defined as the "upper limit to the amount of dissolved metal that a hydrothermal fluid can transport.

► The amount of dissolved solids in hydrothermal solutions varies from approximately $< 1\%$ to $> 50\%$ by weight.

► The major components of hydrothermal solutions are represented by Cl, Na, K, and Ca, while the minor components include Zn, Pb, Sr, SO_4, Fe, Mn, Cu, Au, etc.

► According, it is not necessary for a hydrothermal solution to load high concentration of valuable metals in order to for ore deposits. This is ascribed to the hydrothermal deposition in restricted places on the Earth's surface; thereby the precious metals will be concentrated at *a specific time and deposition rate*.

► The most common ore-forming metals including Pb, Zn, W, Cu, Mo, and Hg occur dominantly as sulfides and sulfo-salts, which are extremely insoluble in aqueous solutions.

► So, metals can be dissolved from their host minerals/rocks by ligands-bearing hydrothermal solutions.

► Ligands (e.g. Cl^-, SO_4^{-2}, CO_3^{-2}, NH_3, HS^-,etc) are negatively charged ions or neutral molecules, which can form complexes with metals by covalent bonding via sharing the electron pair of ligand, leading to promote the hydrothermal dissolution of precious metals.

► A complex ion is a ''charged species in which a metal ion is joined by co-ordinatecovalent bonds to neutral molecules and/or negative ions. For example, in the complex $Cu(NH3)_4^{+2}$, where one Cu^{+2} ions combines with four neutral NH_3 molecules, each of the NH_3 contributes a pair of unshared electrons to form a covalent bond with the Cu^{+2} ions.
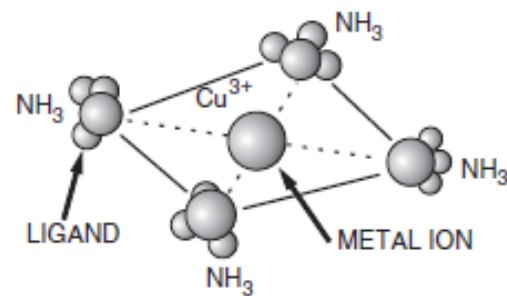
► According to Lewis theory, metals are considered acids, which can accept an electron pair, whereas ligands are bases capable of donate an electron pair to the bond. So, metal dissolution and transportation processes are a result of chemical interaction between acids and bases, resulting in different complexes.

► For example, the solubility of a mineral such as galena (PbS) in pure water, even at high temperatures, is extremely small at200 °C <u>(47.4 ppb). If 5.5 wt%NaCl were added to this solution, however, thesolubility of Pb at the same temperature wouldincrease significantly to 1038 ppm.</u>

► The dissolved metals-based complexes are more stable than the dissolved ions; this means that the aqueous complexes are kept in ionized state for longer period than the simple ions.

E-Precipitation of Dissolved Metals

• Once a metal is in solution, however, it then needs to be extracted from that fluidand concentrated in a portion of the Earth's crust that is sufficiently

restricted and accessible to makean economically viable ore body. It is obvious thata wide range of precipitation mechanisms are likelyto be effective since any mechanism that will*destabilize a metal–ligand complex* and, therefore,reduce the metal solubility, will cause it to be depositedin the host rock through which the hydrothermalsolution is passing.

- At shallow crustal levels ore deposition will take place by open space filling, whereas deeper down where porosity is restricted, replacement of existing minerals tends to occur.

Factors Controlling Metals Precipitation from Hydrothermal Solutions

1-Temperature

- *Decrease in temperature* is the factor that is regarded as the most obvious way of promoting the precipitation of metals from hydrothermal fluids. This occurs once the hydrothermal solutions are brought from high-temperature zones at depths to the surficial low-temperature areas.

- Temperature decrease is particularly effective for destabilizing metal–chloride complexes because their solubilities are much more sensitive to temperature changes than are those of equivalent sulfide complexes.
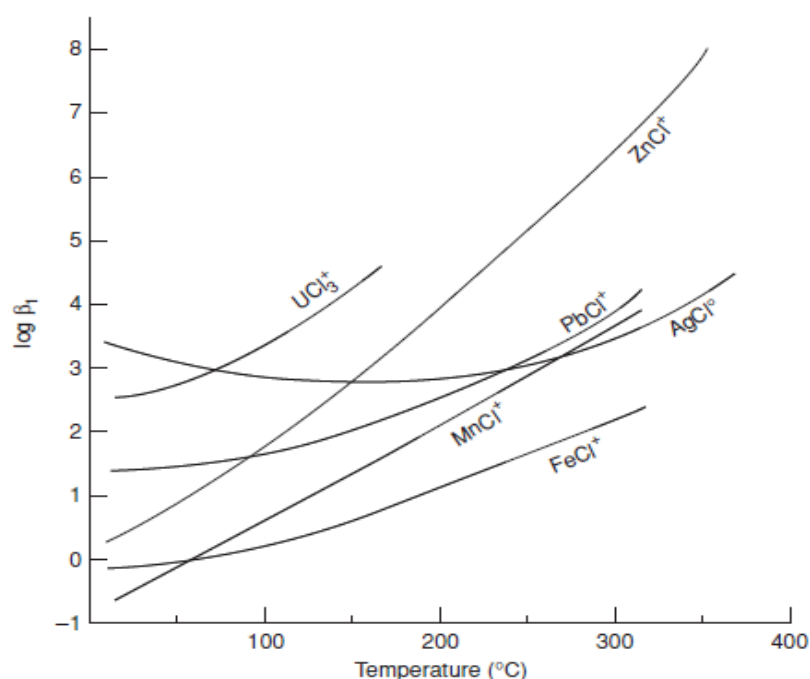
- The mechanism of temperature decreasing is more effective in the near surface environment than the deep-seated regimes where the cooling is slow and ineffectual.

- For example, the ocean floor undoubtedly represents the prime example of where a dramatic reduction in the temperature of ore-forming fluids plays the dominant role in controlling metal deposition. Volcanogenic massive sulfide deposits typically form at siteswhere hot (up to 350 °C) brines with very high metal contents are vented onto the ocean floor as black smokers.Precipitation of base metals (mainly Cu and Zntransported as chloride complexesand, in certain cases, precious metals (Au transportedas a gold–bisulfide complexis virtually instantaneous as the ore fluids mixwith an essentially infinite volume of very cold(2–4 °C) sea water. In this environment it is thevery rapid cooling through virtually 350 °C thatcauses a highly efficient precipitation of metal inthe immediate vicinity of the exhalative vent.
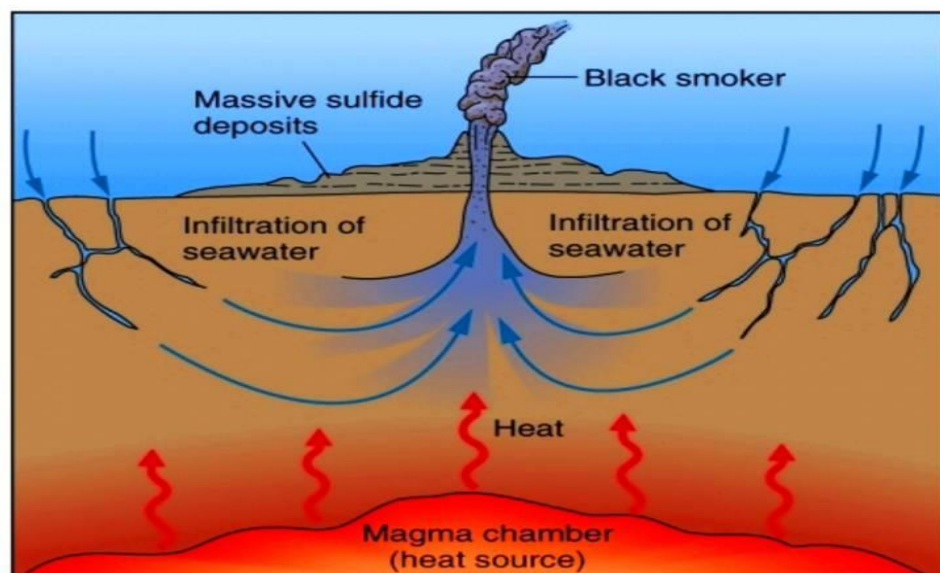
2-Vapour Pressure and Boiling

- Dissolving a gas into liquid will evolve heat "exothermic reaction", while dissolving a solid in liquid will need heat "endothermic reaction". So, an

increase in temperature will lead to destabilize the gas solubility, and this is compensated by an increase in pressure.

$$solid + solvent \leftrightarrow solution \qquad gas + liquid \leftrightarrow solution$$
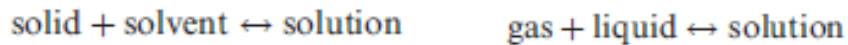
- The increased pressure is responsible for maintaining the hydrothermal volatiles (CO_2 & HS) tightly miscible with water. In this case, boiling does not occur because of the imposed pressure above the hydrothermal fluid is greater than vapor pressure. Once the imposed pressure is equal to vapor pressure, the hydrothermal solution begins to boil, resulting in release variable volatile amounts such as CO_2 and HS, with which metals formed ion complexes. The net result will be metals precipitation and formation of hydrothermal ore deposits.

3-Changes in pH

- *pH changing*. At depth, temperature gradients across the structures within which fluids are moving tend to be minimal and metal precipitation will be neither efficient nor well constrained to a particular trap zone. *Deposition of metals in such a case is achieved more effectively by changing the properties or composition of the hydrothermal fluid*. If ore solution occurs by metal–chloride complexing then precipitation could occur **very efficiently by increasing the pH of the ore fluid**. An example is provided by the reaction of an acidic ore solution with a carbonate host rock and where precipitation is promoted by digestion and replacement of the host.
- Two coupled reactions illustrate the process in terms of calcite dissolution by an originally acidic, Zn^{2+}–chloride-bearing ore solution, and subsequent sphalerite precipitation caused by increase of pH in the fluid as hydrogen ions are consumed:

$$CaCO_{3(SOLID)} + 2H^+ \Leftrightarrow Ca^{2+} + H_2CO_{3(AQUEOUS)}$$

$$ZnCl_n^{2-n} + H_2S_{(AQUEOUS)} \Leftrightarrow ZnS_{(SOLID)} + 2H^+ + nCl$$
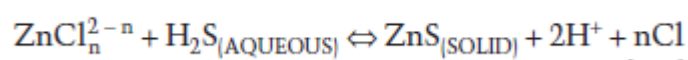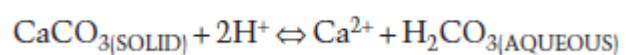
- On controversy to metal-chloride complexes, oxidation of the ore fluid is effective in decreasing the solubilities of metal–sulfide complexes. Oxidation (or loss of electrons) causes a decrease in the pH and also the total sulfide concentration, thereby promoting metal precipitation, as shown in reaction:

$$Zn(HS)_3^- + 4O_{2(AQUEOUS)} \Leftrightarrow ZnS_{(SOLID)} + 3H^+ + 2SO_4^{2-}$$
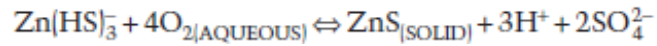
4-Fluid Mixing

- The mixing of two fluids is widely regarded as another important mechanism for reducing solubility in ore-forming solutions and promoting metal precipitation.

- This is particularly the case when a relatively hot, metal-charged ore fluid mingles with a cooler, more dilute solution. Mixing of the two fluids would result in cooling of the hotter with modification of the prevailing ore fluid properties and destabilization of existing metal–ligand complexes.

- It is showed that magmatic fluids venting directly from a volcano without any mixing or dilution below the surface are less conducive to the formation of economically viable deposits since ground preparation (or alteration) is minimized and the resultant ore accumulations at the surface have a low preservation potential. By contrast, systems characterized by mixing of magmatic waters with a meteoric water carapace 1–2 km below the surface will more likely be associated with the formation of economically viable mineralization. This is because mixing of a hot, saline, metal-charged magmatic fluid with a cooler, more dilute meteoric water promotes acid leaching of the host rocks, increases their permeability, and forces the fluids to condense and precipitate their dissolved metal solute.

Fluid mixing. Oxidizing meteoric water. Hotter, magmatic fluid. Ore precipitation. Ore leaching.

Your Comments

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Ore Deposits-Endogenetic Forming Processes: Hydrothermal Alteration and Metasomatism

1-What is the hydrothermal alteration????

- The hydrothermal alteration refers to phase changes by adding/or removal of substances from the country rocks through which hydrothermal solutions passed.

- For example, The hydrothermal removal of substances can be represented by release of silica and potassium from K-feldspar, which first altered to muscovite and then kaolinite via the action of reducing hydrothermal solutions as follows:

$$\tfrac{3}{2}KAlSi_3O_8 + H^+ \Leftrightarrow \tfrac{1}{2}KAl_3Si_3O_{10}(OH)_2 + 3SiO_2 + K^+ \qquad \textbf{3.6}$$
$$\text{(k-fel)} \qquad\qquad\qquad \text{(musc)} \qquad\quad \text{(qtz)}$$

$$KAl_3Si_3O_{10}(OH)_2 + H^+ + \tfrac{3}{2}H_2O \Leftarrow \tfrac{3}{2}Al_2Si_2O_5(OH)_4 + K^+ \qquad \textbf{3.7}$$
$$\text{(musc)} \qquad\qquad\qquad\qquad \text{(kaol)}$$
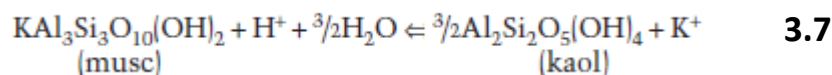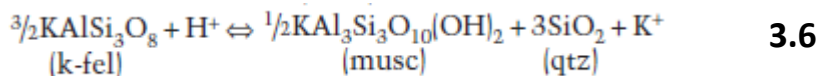
- The hydrolysis of K-feldspar to muscovite in terms of this reaction requires nothing more than the presence of H+ ions in an aqueous solution. No new ingredients need to be added to the system "isochemical". If the reaction proceeds to the right, H+ ions are consumed and the fluid will become more basic, and will continue to do so until the K-feldspar is used up. The reaction will also produce quartz as part of the alteration assemblage, as well as K^+ ions dissolved in the aqueous solution. If the products of reaction [3.6] are permitted to further react with H^+ ions in solution such that the system undergoes an increase in fluid/rock ratio, then muscovite would react to form kaolinite.

- Note that K-feldspar may be accompanied with plagioclase feldspar in the same rock. Plagioclase feldspar under the same conditions can be altered to pyrophyllite and quartz. <u>So, it is not necessary for the hydrothermal alteration to produce one mineral phase, but it generally results in mineral assemblages represented here by kaolinite and pyrophyllite.</u>

$$2NaAlSi_3O_8 + 2H^+ \Leftrightarrow Al_2Si_4O_{10}(OH)_2 + 2SiO_2 + Na^+$$
$$\text{(plag)} \qquad\qquad \text{(pyroph)} \qquad \text{(qtz)} \qquad [3.8]$$
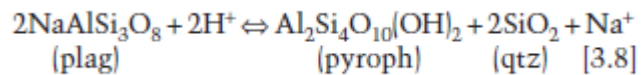
- The hydrothermal alteration by adding substances is represented by silicification of country rocks, as an example.

2-What arethe phase changes caused by hydrothermal alteration????

2-1-Physical changes in rocks through which fluids pass:

- The altered rocks are ***more porous and permeable than fresh rocks*** due to the penetrative power of hydrothermal solutions and subsequent dissolution and fracturing of the altered rocks.
- ***Changes in color*** are common during hydrothermal alteration and areaccordingly one of the most useful indications of the process. These color changes appear as changing the rock color to white color shades due to formation of sericite, quartz, kaolinite, carbonate, potassium feldspar, and alunite. This is called bleaching process. Also, color changes are reported as green-greenish grey colors imparted on the altered rocks as a result of formation of chlorite and epidote.
- ***Changes in rock texture***, particularly grain size, for example the alteration of feldspar phenocrysts "e.g. 4cm in length" bysericite or kaolinite "e.g. 0.01 mm in diameter" leads to a reduction of the phenocrysts size.

2-2-Mineral changes in rocks through which fluids pass:

The formation of mineral assemblages during the hydrothermal alteration is controlled by five factors:

Temperature; Pressure; Rock composition; Fluid composition; Fluid/rock ratio.

The most common mineral assemblages associated with hydrothermal solution can be summarized as follows:

- *Clay minerals* include kaolinite, illite, and smectite. These minerals are formed on alteration of feldspars under relatively low temperature conditions (e.g. telethermal conditions).

- _**Biotite is**_ a rock-forming mineral and an alteration product under hypothermal conditions (300-500 ^{o}C).

- *Feldspars* (albite and K-feldspar) are rock-forming minerals and alteration products under hypothermal conditions (300-500 ^{o}C).

- *Sericite* is the mostcharacteristic mineral of hydrothermally altered rocks. In igneous rocks it commonly replaces feldspars in the early stage but as the process continues it replaces the ferromagnesian minerals (pyroxene, hornblende, and biotite).

- *Chlorite* is an abundant mineral in hydrothermally altered rocks. It was commonly formed at an early stage through the alteration of biotite, hornblende, and pyroxene.

2-3-Chemical changes in rocks through which fluids pass:

Hydrothermal solutions have obviously introduced a variety of substances intoalteredrocks. Those of most importance include water, silica, sulfur, carbon dioxide, potassium, sodium, calcium, magnesium, boron, fluorine, chlorine, lithium, phosphorous, and the common metals that are deposited mainly as sulfides and oxides. We mean by chemical changes here the increased or decreased content of specific elements in the altered rocks compared with the fresh ones. ***This mainly depends on the chemical composition of the penetrative solution***. Such changes can be determined by quantitative chemical analysis (e.g. XRF, ICP-OES, and ICP-MS) of the altered and fresh rock types. For example:

- Increasing the silica content of limestone and dolomite as a consequence of silicification.
- Potassium is commonly added mainly in the alteration of igneous and metamorphic rocks but it is removed in examples of argillic alteration.
- Sodium is largely eliminated during alteration, and in few cases it is added for the albitization processes.
- Calcium/or lime is generally lost during the hydrothermal alteration of limestone where it is replaced by silica, magnesium and iron.
- Magnesium is eliminated during the alteration of igneous rocks, but it can increase during chloritization.
- Carbon dioxide is present in negligible amounts in fresh igneous rocks, so its content considerably increases on hydrothermal alteration of such rocks.

3-Hydrothermal Alteration Zones

There are nine alteration zones are associated with the movement of hydrothermal solutions through the Earth's crust:

Potassic Alteration Zone

- It typically represents the highest temperature form of alteration (500–600 °C) associated with porphyry Cu-type deposits, forming in the core of the system and usually within the granite intrusion itself.
- Potassic (or K-silicate) alteration is characterized by the formation of new K-feldspar and/or biotite, usually together with minor sericite, chlorite, and quartz.
- Accessory amounts of magnetite/ hematite and anhydrite may occur associated with the potassic alteration assemblage.

Phyllic "sericitic" Alteration Zone

- This alteration style is very common in a variety of hydrothermal ore deposits and typically forms over a wide temperature range by hydrolysis of feldspars to form sericite (fine-grained white mica), with minor associated quartz, chlorite, and pyrite.

$$3/2KAlSi_3O_8 + H^+ \Leftrightarrow 1/2KAl_3Si_3O_{10}(OH)_2 + 3SiO_2 + K^+$$
$$\text{(k-fel)} \qquad\qquad \text{(musc)} \qquad \text{(qtz)}$$
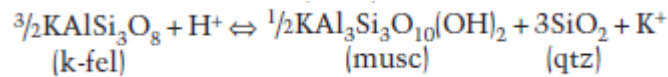
- Phyllic alteration is associated with porphyry Cu deposits, but also with mesothermal "200-300C" precious metal ores and volcanogenic massive sulfide deposits in felsic rocks.

Propylitic Alteration Zone

- It comprises mainly chlorite and epidote, together with lesser quantities of clinozoisite, calcite, zoisite, and albite.
- It is a mild form of alteration representing low to intermediate temperatures (200–350 °C) and low fluid/rock ratios.
- It characterizes the margins of porphyry Cu deposits as well as epithermal precious metal ores.

Argillic Alteration Zone

- This alteration style is commonly subdivided into intermediate and advanced categories depending on the intensity of host mineral breakdown.
- Intermediate argillic alteration affects mainly plagioclase feldspars and is characterized by the formation of clay minerals kaolinite and the smectite group (mainly montmorillonite). It typically forms below about 250 °C by H^+ metasomatism and occurs on the fringes of porphyry systems.
- Advanced argillic alteration represents an extreme form of base leaching where rocks have been stripped of alkali elements by very acidic fluids active in high fluid/rock ratio environments. It is characterized by kaolinite, pyrophyllite, or

dickite (depending on the temperature) and alunite together with lesser quartz, topaz, and tourmaline.

- It is commonly associated with near surface, epithermal precious metal deposits where alteration is associated with boiling fluids and condensation of volatile-rich vapors to form extremely acidic solutions.

Silication Alteration Zone

- Silication is the conversion of a carbonate mineral or rock into a silicate mineral or rock and necessarily involves introduction of additional components into the system.
- It is the main process which accompanies the prograde stage in the formation of polymetallicskarn deposits which develop when a fertile, acidic, magmatic fluid infiltrates a carbonate host rock.
- Carbonate rocks are a particularly efficient host for metal deposition from hydrothermal solutions because of their ability to neutralize acidic fluids and their "reactivity," which enhances permeability and fluid flow.

$$3CaMg(CO_3)_2 + 4SiO_2 + 6H^+ + 4H_2O \Rightarrow Mg_3Si_4O_{10}(OH)_2 + 6H_2CO_3 + 3Ca^{2+}$$
$$\text{(dol)} \qquad\qquad\qquad\qquad\qquad \text{(talc)}$$
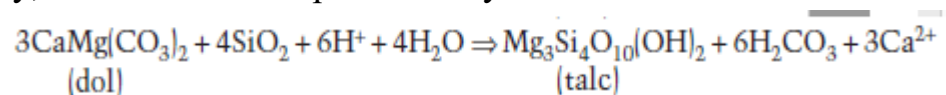
Silicification Alteration Zone

- Silicification should not be confused with Silication.
- It refers specifically to the formation of new quartz or amorphous silica minerals in a rock during alteration.
- Minor silicification develops in the alteration halos associated with many different ore deposit types and is usually a by-product of hydrolysis reactions where Si is locally derived.

$$\tfrac{3}{2}KAlSi_3O_8 + H^+ \Leftrightarrow \tfrac{1}{2}KAl_3Si_3O_{10}(OH)_2 + 3SiO_2 + K^+$$
$$\text{(k-fel)} \qquad\qquad \text{(musc)} \qquad\qquad \text{(qtz)}$$

$$2NaAlSi_3O_8 + 2H^+ \Leftrightarrow Al_2Si_4O_{10}(OH)_2 + 2SiO_2 + Na^+$$
$$\text{(plag)} \qquad\qquad \text{(pyroph)} \qquad \text{(qtz)} \quad [3.8]$$
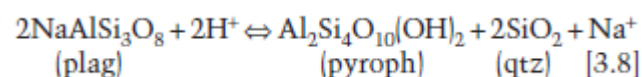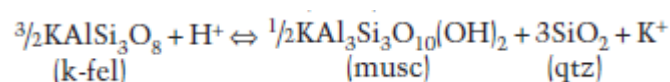
- The majority of fractures through which hydrothermal fluids have passed are at leas partially filled with quartz to form veins. The Si in these settings is usually derived by leaching of the country rocks through which the fluids are circulating.
- This alteration type is a chracteristic zone in the epithermal ore deposits "50-200C"e.g. Au, Ag, and Hg).

Carbonatization Alteration Zone

- Carbonatization refers to the formation of carbonate minerals (calcite, dolomite, magnesite, siderite, etc.) during alteration of a rock and is promoted by fluids characterized by high partial pressures of carbon dioxide (PCO2) and neutral to alkaline pH.
- It forms when reaction occurs between a low salinity, CO2-rich fluid and its host rock. The carbonate mineral that forms is a function of the composition of the host rock.

Greisenization Alteration Zone

- Greisens represent an alteration assemblage comprising mainly quartz, muscovite, and topaz, with lesser tourmaline and fluorite, usually forming adjacent to quartz–cassiterite–wolframite veins.

Hematitization Alteration Zone

- Alteration that is associated with oxidizing fluids often results in the formation of minerals with a high Fe^{3+}/Fe^{2+} ratio and, in particular, hematite with associated K-feldspar, sericite, chlorite, and epidote.
- In the magmatic-hydrothermal environment, occurrences such as the granitoid-hosted, Olympic Dam-type Cu–Au–Fe–U deposit in South Australia are characterized by this style of alteration.

- This style of alteration appears to be related to redox processes where highly saline, oxidizing fluids come into contact with a more reduced host rock environment, or mix with more reduced fluids.
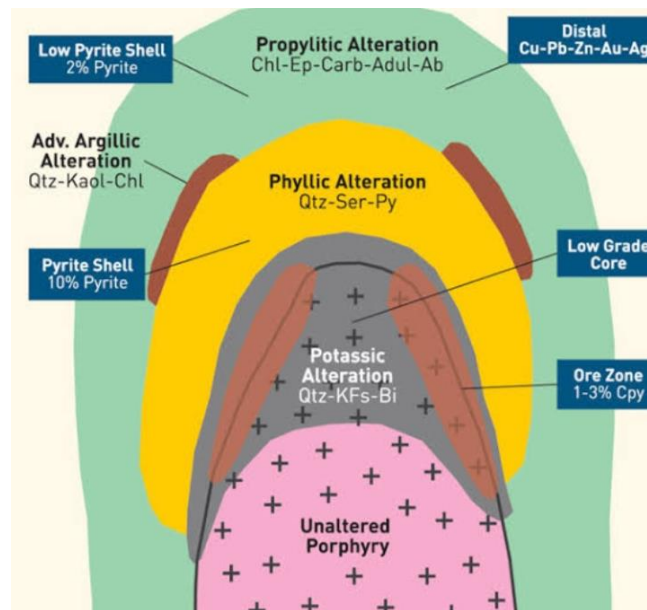
4-Metasomatism

- The current definition of metasomatism is "a metamorphic process by which the chemical composition of a rock or rock portion is altered in a pervasive manner and which involves the introduction and/or removal of chemical components as a result of the interaction of the rock with aqueous fluids (solutions).

- During metasomatism, the interacted rock body remains in a solid state.This means that the rock volume is unchanged.

- Metasomatism is a special kind ofhydrothermal alterations generated byfluids advection through the Earth's crust without changes in rock body form. For example, the Metasomatic deposits "skarn" result from the contact between hot granitic intrusion and limestone. Also, serpentinization of oceanic floor is included.

Fayalite+water--------- magnetite+ aqueous silica+hydrogen

$3Fe_2SiO_4+2H_2O$--------$2Fe_3O_4+ SiO_2$ "aqu."+H

Forsterite+aqueoussilica+water--------serpentine

$$3Mg_2SiO_4 + SiO_4 + H_2O \text{-------} 2Mg_3Si_2O_5(OH)_4.$$
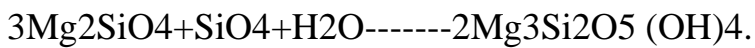
An important example of the regional metasomatism is the formation of spilite rock from metasomatized ocean floor basalt as following:

Tensile cracking during cooling and contraction of submarine lavas and feeder dikes, coupled with active extensional rifting, promotes deep propagation of fractures in the oceanic crust. Cracks allow seawater to circulate through the hot rock, promoting hydrating mineral reactions that partially to completely replace primary anhydrous magmatic phases. Heated seawater expands and buoys upward out of the cracks, carrying ions leached from the rock and dissolved in the hot brine. Sulfides and other solids precipitate in the cold seawater as this solution exits from seafloor hot springs, creating particle-laden "black smokers" at vents along the ridge. Basaltic rocks are metasomatized to varying degrees by addition of Na and water. Less mobile Ti, Al, and Mg may increase in concentration in the protolith as a consequence of loss of substantial Ca. Relict basaltic fabrics are preserved in these **spilites**, whose metasomatic mineral composition is dominantly sodicplagioclase+chlorite+ quartz.

- Metasomatic reaction commonly takes place under the surface.

- The difference between metamorphism and metasomatism is that the chemical composition of whole rock is constant during the metamorphism, while there is a noticeable change in the rock composition during metasomatism. Specifically, the nonvolatile components remain constant, while the volatile components, in particular water, change during metamorphism.

- Eventually, the metasomatic fluids are hot brine solutions of high alkalinity. This is the main cause why these solutions do not give rise to dissolution and volume changes. Also, it is worth to mention here that the silicate minerals are insoluble under alkaline conditions.

Your Comments

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Lecture#6

Ore Deposits-Exogenetic Forming Processes

In addition to the endogenetic processes, mineral resources can be formed by a number of surficial geological processes:

- *Chemical weathering of the pre-existing minerals.*

- *Evaporation followed by precipitation.*

- *Direct crystallization from seawater.*

- *Microbe-induced precipitation.*

All these processes are called exogentic mineral-forming processes. Many different metals are enriched in the surficial environment, the most important ofwhichinclude Al, Ni, Mn, Fe, Cu, Au, Pt, and U.

1-Chemical weathering of the pre-existing minerals

- **Dissolution and hydration:**

Dissolution is a chemical process in which the solid naturally occurring materials are converted into a liquid phase. Certain natural materials such as halite (NaCl) and other evaporitic minerals (KCl), as well as the carbonate minerals (calcite, siderite, dolomite, etc.), tend to dissolve relatively easily and completely in normal to acidic groundwaters and precipitate again either on evaporation or under alkaline conditions. The solubility of elements is a function of its ionic potential (ionic

charge/ionic radius). Cations with ionic potential<3 are soluble under normal-acidic conditions and precipitate under alkaline conditions. Anions of ionic potential > 10 form soluble complexes that precipitate with alkalis. Ions with intermediate values (ionic potentials between 3 and 10) tend to be relatively insoluble and precipitate readily as hydroxides.

Ionic Potential and precipitation behavior of ions
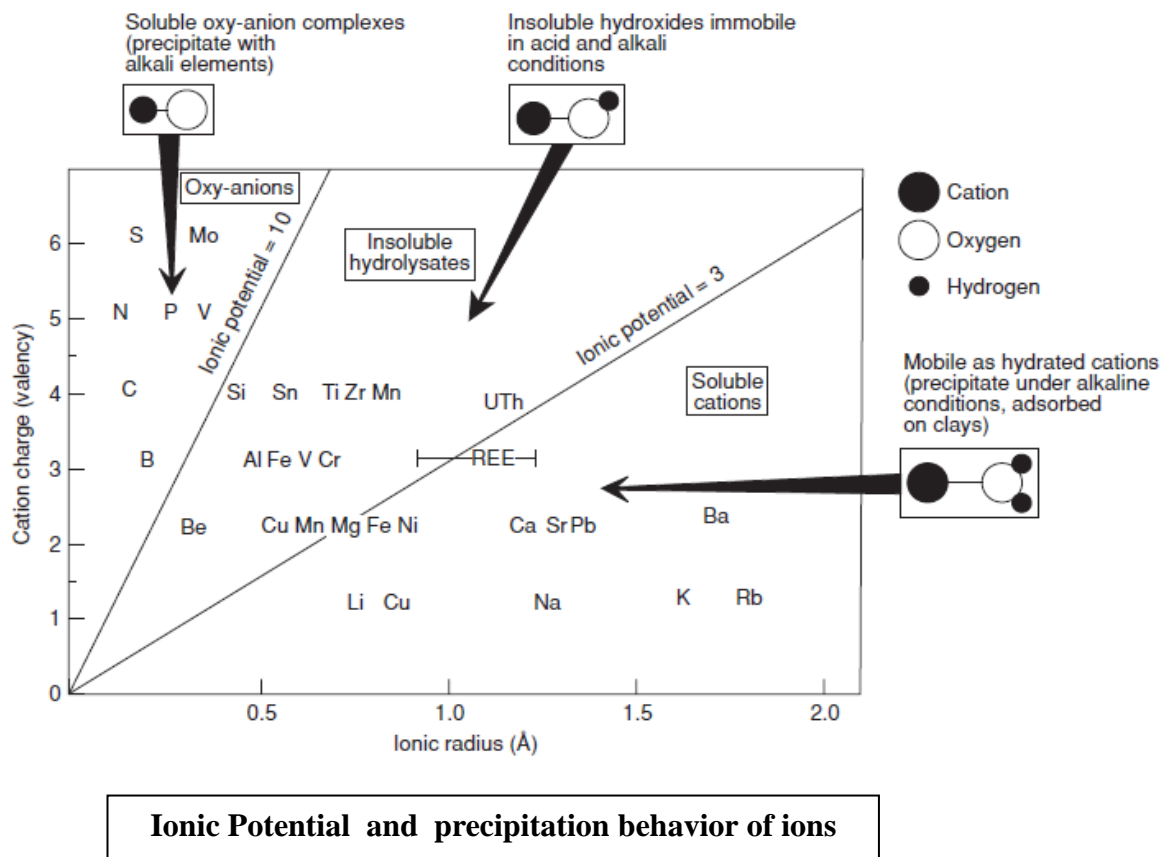
Lateritic soils as an example on the dissolution-driven mineral formation:

Over the pH range at which most groundwaters exist (5–9), silicon is more soluble than aluminum and consequently chemical weathering will tend to leach Si, leaving behind a residual concentration of immobile Al and ferric oxides/ hydroxides. This is typical of soil formation processesin tropical, high rainfall areas and yieldslateritic soil profiles, which can also contain concentrations of bauxite (aluminum ore) and Ni. Lateritic soils will not, however, form under acidic conditions (pH < 5) as Al is

more soluble than Si and the resultant soils are silica-enriched and typically depleted in Al and Fe.

What is about hydration???

On the other hand, hydration of minerals can occur directly, good examples of which include the formation of gypsum ($CaSO_4.2H_2O$) from anhydrite ($CaSO_4$), and the incorporation of water into the structure of clays such as montmorillonite.

- ## Hydrolysis:

Hydrolysis is defined as a chemical reaction in which one or both of the O–H bonds in the water molecule are broken. Such reactions are important in weathering. One example occurs during the breakdown of aluminosilicate minerals such as feldspar, and also the liberation of silicon as silicic acid into solution, as shown by the reaction:

$$Si^{4+} + 4H_2O \Leftrightarrow H_4SiO_4 + 4H^+$$
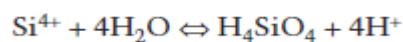
Another example relates to the hydrolysate elements such as Fe and Al that are relatively soluble in acidic solutions, but will precipitate as a result of hydrolysis. The hydrolysis of aluminum, yielding an aluminum hydroxide precipitate, is illustrated by reaction:

$$Al^{3+} + 3H_2O \Leftrightarrow Al(OH)_3 + 3H^+$$
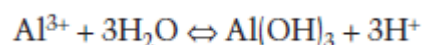
- ## Oxidation-reduction:

Oxidation (and reduction) refers essentially to chemical processes that involve the transfer of electrons. In the surficial environment oxygen, present in either water or the air, is the most common oxidizing agent. The element most commonly oxidized in the surficial environment is probably iron, which is converted from the ferrous (Fe^{2+}) to the ferric (Fe^{3+}) valence state by oxidation (loss of electrons). An example of the role of oxidation in chemical weathering is provided by the relative instability of biotite compared to muscovite. Biotite has the formula $K^+[(Mg^{2+}, Fe^{2+})_3(Si_3Al)O10(OH)_2]^-$ and is much more easily weathered than muscovite $K^+[(Al_2)(Si_3Al)O_{10}(OH)_2]^-$ because of the ease with which the ferrous iron can be

oxidized to ferric iron. Weathering and the resulting oxidation of Fe in biotite leads to a charge imbalance that destabilizes the mineral, a process that is less likely to happen in muscovite since it contains no iron in its lattice. The presence of iron in minerals such as olivine and the orthopyroxenes is one of the main reasons why they are so unstable in the weathering zone.

Besides mineral destabilization, the oxidation process can result in mineral formation. As such example, the oxidation –hydration processes of the glauconite deposits at El-Bahariya Oasis have participated in the formation of El-Gedida iron deposits. This was occurred by the oxidation of ferrous iron in glauconite structure and leaching different proportions of the other elements (e.g. Si, Al, Mn, Ca, Mg…..etc) under oxidized, acidic humid conditions.

Oxidation-reduction reactions can also lead to form ore minerals (e.g. Cu minerals) through what ***so-called super-gene enrichment*** in which the primary Cu minerals (e.g. chalcopyrite) are oxidized and leached downward by the action of oxidized, acidic groundwater, and then the soluble cuprous and sulfate ions are reduced and precipitated below the water table as secondary Cu minerals (e.g. chalcocite, covellite, and bornite). The residual layer in the upper weathering profile is enriched in iron oxyhydroxides (e.g. hematite and goethite) and called ***gossan***.

$$4CuFeS_2 + 17O_2 + 10H_2O \Rightarrow$$
chalcopyrite
$$4Fe(OH)_3 + 4Cu^{2+} + 8SO_4^{2-} + 8H^+$$
goethite

$$2FeS_2 + 2H_2O + 7O_2 \Leftrightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+$$

$$2Fe^{2+} + 3H_2O + O_2 \Leftrightarrow 2FeOOH + 4H^+$$
goethite
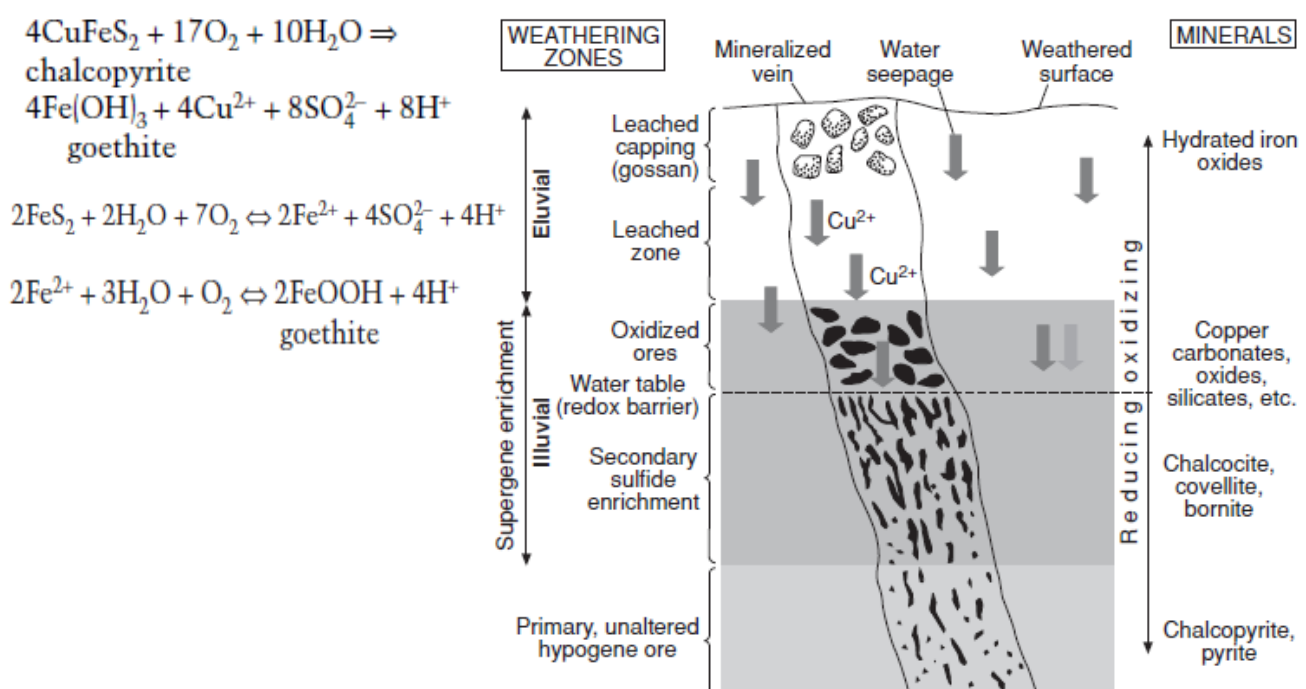
Chemical Precipitation of Minerals:

In addition to chemical weathering, minerals can also be crystallized by the chemical precipitation from seawater. When either sea or lake waters evaporate, salts are precipitated. These salts include <u>sodium chloride, potassium and magnesium chlorides, borax, and sodium carbonate</u>. Such salts are important economically. There is another mineral type chemically precipitated from seawater, *it is a banded iron formation (BIF)*, so called because they are finely layered alternations of cherty silica and an iron mineral, generally hematite, magnetite, or siderite. It was formed by the action between iron dissolved in seawater and oxygen released by the photosynthetic cyanobacteria (2.1 billion y. ago).

Placer Deposits:

When mineral grains of different density are moved by flowing water, the less dense grains will be most rapidly moved, and a separation of high density and low density grains can be effected. <u>Mineral deposits formed as a result of gravity separation based on density are called placer deposits.</u>For effective concentration , placer minerals must not only have a high density (greater than about 3.3 gm/cm^3 , they must also possess a high degree of chemical resistance to dissolution or reaction with surface water and be mechanically durable. The common sulfide ore minerals don't form placers, because they rapidly oxidize and break down. Ore minerals having suitable properties for forming placers are the oxides cassiterite (tin), chromite (chrome), ilmenite and rutile (titanium). In addition, native gold and platinum and diamond have been mined from placers.

zone of weathering

stream placer

zone of transport by mass-wasting

ore minerals

veins

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Your Comments

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Mineral beneficiation

1.1 Sieve analysis of ground ores:

Sieve size range (µm)	Wt	Wt%	Cumulative	Cumulative %
+250	0.02			
-250 to +180	1.32			
-180 to +125	4.23			
-125 to +90	9.44			
-90 to +63	13.10			
-63 to +45	11.56			
-45	4.87			
total				

_____

1.2 Sieve analysis of ground ores: the weight of sample is 44.542

Sieve size range (µm)	Wt passing	Wt%	Cumulative	Cumulative %
+250	44.52			
-250 to +180	43.2			
-180 to +125	38.97			
-125 to +90	29.53			
-90 to +63	16.43			
-63 to +45	4.87			
-45	0			
total				

1.3 Sieve analysis of ground ores:

Sieve size range (µm)	Wt retained	Wt%	Cumulative	Cumulative %
(1000 mm) -1 to +500	44.52			
-500 to +250	43.2			
-250 to +125	38.97			
-125 to +90	29.53			
-90 to +75	16.43			
-75	4.87			
Total				

Determine D50 in all problems.

liberation

2.Liberation degree depending upon the type of mineral interlocking.

Liberation products

| Free –locked particles | Locked particles |
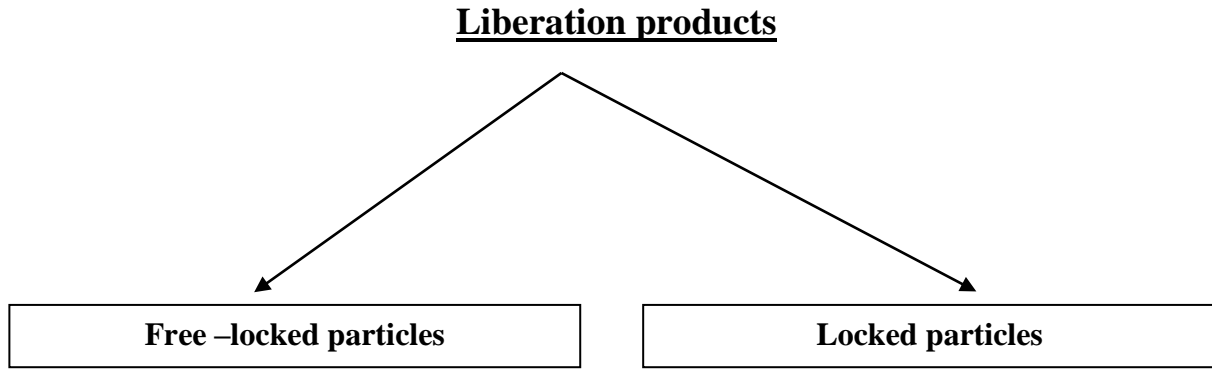
The liberation degree is expressed as % of free-locked particles in relative to the total particles.

The maximum liberation degree in fraction size (   )

The minimum liberation degree in fraction size (   )

Problem 1:

Sieve fraction "μm"	Wt "gm"	Free Glauconite#	Locked particles#
(1000 mm) -1+500	30	260	185
-500+250	45	350	240
-250+125	70	390	186
-125+75	55	205	240
-75	25	95	200

Describe the liberation of glauconite and determine the size fraction to which the whole sample have to be crushed?

Metal balance

3.Metal balance during the comminution process.

For a single feed of a given mineral processing operation (e.g. comminution, magnetic separation…….), input = output. For instance, consider 250 kg feed containing 35wt% Fe was subjected to magnetic separation. The sum of concentrate and tailing must be 250kg and the same for Fe.

Feed "input" during mineral processing
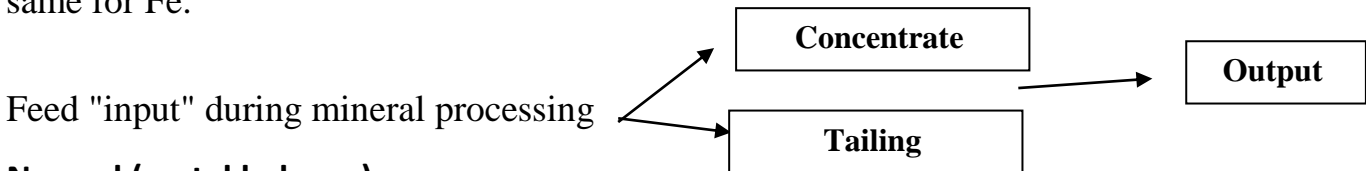
Normal (metal balance)

Abnormal (contamination or loss)

Metal balance%= wt% * metal assay in a given fraction/100.

Problem1: chemical analysis of the studied head samples of Aswan baritic iron ore.

Chemical analysis %	
Fe total	BaO
23.5	34.0

The size distribution and chemical analysis of the head sample.

Particle size in (mm)	Weight %	Fe %	BaO %
-10 +8.5	5.9	23.97	31.78
-8.5 +5	16.41	22.06	34.57
-5 +2.5	14.40	20.72	39.45
-2.5 +1	15.27	20.14	41.60
-1 +0.5	13.36	19.17	43.5
-0.5 +0.25	11.93	21.03	38.08
-0.25 +0.125	5.60	23.35	33.5
-0.125 +0.063	2.03	27.86	18.27
-0.063	15.10	36.18	12.03

Calculate metal balance for magnetic separation and write your comment about the metal balance in the chemical analysis?

the metal recovery and Separation efficiency

1.Ore grade: Average concentration of specific metal in an ore deposit.

For example, if ilmenite ore deposit contains 55wt% TiO2, the ore grade will be 55wt% of titanium metal

> Metal grade %= [wt of mineral in the concentrate*the conc. of metal in its mineral/wt of concentrate] *100

Problem 1: For example, consider 1000gm feed sample of galena and calcite was undergone flotation, resulting in 750gm concentrate of which 700gm assigned for galena and 50gm for calcite, and 250gm tailing of which 200gm of calcite and 50gm of galena. Consider that the lead "Pb" grade in a pure galena "PbS" is 86.6%. Calculate the metal grade of galena in the concentrate.

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2.Recovery: depend on mineral type.

Metallic ore: the percentage of the total metal contained in the ore that is recovered in the concentrate.

A recovery of 90% means that 90% of the metal in the ore is recovered in the concentrate and 10% is lost in the tailings.

Nonmetallic ore: the percentage of the total mineral contained in the ore that is recovered into the concentrate.

> R % = [c*C /F*100] *100
>
> C" metal assay in concentrate", C " Wt% of concentrate"
> F " metal assay in the feed sample"

Recovery depend on weight present.

There is direct relationship between ore recovery and weight percent.

There is reverse relationship between ore grade and recovery.

Problem 2: Crushed sample of phosphate rock assaying 22% P2O5 was subjected to dry, high-intensity magnetic separation at different magnetic intensities. The overall results are listed in the following table. Calculate the P2O5 recovery for the concentrate and tailing fractions and determine the best magnetic intensity.

Magnetic intensity "T"	Magnetic fraction (concentrate)		Non-Magnetic fraction (tailing)	
	Wt %	Wt% P_2O_5	Wt %	Wt% P_2O_5
3	60	28	40	13
3.4	79	26	21	6
4	85	25	15	4

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3.Separation efficiency: (S.E)

$$\text{Separation efficiency (S.E.)} = Rm - Rg$$

where $Rm = \%$ recovery of the valuable mineral,
$Rg = \%$ recovery of the gangue into the concentrate.

$$S.E = 100 * C * m (c - f)/ f * (m - f)$$

Example 1.1

A tin concentrator treats a feed containing 1% tin, and three possible combinations of concentrate grade and recovery are:

High grade   63% tin at 62% recovery
Medium grade   42% tin at 72% recovery
Low grade   21% tin at 78% recovery

Determine which of these combinations of grade and recovery produce the highest separation efficiency.

m = 78.8 % for Sn   in SnO2