University of Cairo
Faculty of African Postgraduate Studies
Department of Natural Resources
Ph.D. Program (Earth Resources)

GEOLOGY OF MINERAL RESOURCES IN AFRICA

“FIRST TERM 2025/2026”

Class:	Faculty of Higher African Studies
Time:	Tuesdays 3:00 - 6:00 pm
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INTRODUCTION:

Earth is a very small part of a vast universe, but it is our home. It provides the resources that support our modern society and the ingredients necessary to maintain life. Therefore, knowledge and understanding of our planet is critical to our social well being and indeed, vital to our survival.

Our mineral supplies come from mineral deposits that are concentrations of elements or minerals formed by geologic processes. Mineral deposits have two geologic characteristics that make them a real challenge to modern civilization. First almost all of them are nonrenewable resources; they form by geologic processes that are much slower than the rate at which we exploit them. Second, mineral deposits have a place value. We cannot decide where to extract them until they are found. Consumption of minerals is growing faster than the population that is growing faster than at any time in history. Modern civilization and growing population make the search for mineral deposits ever more challenging as the demand increases and the number of high-grade deposits decreases.

Africa plays a dominant role as a source of strategic metals such as chromium, cobalt, manganese and platinum. It ranks first in the production of diamond, gold and uranium. Africa holds large resources of mineral deposits that need geologists to discover and leaders to properly use.

OBJECTIVES:

This course is intended to serve a useful information resource for professional geologists and non-geologists. It should also provide students with a critical understanding of selected mineral deposits: how are they formed and distributed in space and time?, what are the main characteristics of the mineral deposits?, how can we discover new deposits?, distribution of mineral deposits in Africa, production and reserves of mineral resources in Africa.

REQUIRMENTS AND TEXTBOOKS:

This course of mineral deposits requires a general background in geology. All of you had at least one course in geology. We will use several textbooks and lecture notes.

GRADING:

Mid Term Exam	**10%**
Activities	**10%**
Oral Exam	**10%**
Final Exam	**70%**

- **LECTURE TOPICS**
- Introduction
- Mineral deposits: Classification of mineral deposits
- Magmatic deposits I: Mafic complexes, ophiolites and massive sulfides
- Magmatic deposits II: Kimberlites, carbonatites, pegmatites and greisens
- Hydrothermal deposits (porphyry deposits)
- Hydrothermal deposits (epithermal deposits)
- **Nov. 18, 2025 MID TERM EXAM**
- Metamorphic deposits
- Sedimentary mineral deposits, residual, supergene enrichment, placer I
- Sedimentary mineral deposits, residual, supergene enrichment, placer II
- Research paper presentations
- **Dec. 23, 2025 ORAL EXAM**

Research Paper

You are asked to prepare a brief research paper on mineral resources in Africa. Each student can choose an African country to discuss the mineral deposits in it, in terms of:

a. Types
b. Genesis
c. Distribution
d. Production
e. Reserves

SUGGESTED FORMAT -- will not apply to all topics

Text (not to exceed 10 typewritten pages, 1.5 line-spaced pages).

Introduction – importance of mineral (usage), mineralogy, brief history, etc.

Significant aspects of the regional and/or local geology -- stratigraphy, structure, igneous activity, tectonic development, etc.

Mineral Resources – origin, genesis, production, reserve, etc.

Conclusions -- your major findings

References

Illustrations -- essential to have some illustrations; sources must be indicated.

FOR ALL RESEARCH PROJECTS

(1) A research topic must be selected before Nov. 22th.
(2) The paper is **due on Dec 26th**, late papers will **not** be accepted.
(3) All referenced material must be properly cited.
(4) All submitted material must be typed and in a reasonable font type and size (12).
(5) All work submitted must be your own.

You will be graded on your introduction of the topic, correct grammar, spelling, and format, presentation of technical information, development of the topic, and selection and effective use of appropriate references and illustrations.

MINERAL RESOURCES

Life on Earth requires the use of resources. The term ***resources*** covers everything we use, including such basic assets as air, soil, timber, and water; fuel resources like coal, oil and gas; and ***mineral resources***, such as sand and gravel. These natural resources may be renewable or non-renewable. ***Renewable resources*** are replenished constantly (wind, soil), on short-term time scales measured in months (crops), or over longer intervals of several years (timber). ***Non-renewable resources*** are either lost following consumption (fossil fuels) or may be recycled to be used in other products (metals). We are all familiar with the most common mineral resources but there are a host of others that play vital roles in our society yet remain virtually unknown.

In this course we use the term mineral resources to include non-food, non-fuel resources such as metals (e.g. aluminum, palladium) and industrial minerals (e.g. gypsum, phosphate).

Mineral resources become concentrated in Earth's crust as a result of specific geologic processes associated with the formation of rocks. ***Exploration*** for minerals requires that geologists recognize the tell-tale evidence that signals the presence of useful mineral deposits.

What Is an Ore?

An ore is a naturally occurring solid material containing a useful commodity that can be extracted at a profit.

What Is an Ore Deposit?

An ore deposit is defined as an accumulation of a useful commodity that is present in high-enough concentration and in sufficient quantity to be extractable at a profit.

Factors that Influence Whether a Deposit Can Be Mined:

1. Tenor and tonnage.
2. Nature of the ore (type, grain size, texture, hardness, …).
3. Location of the deposit.
4. The geological situation (surface, in depth, ...).
5. Technical, economic and political factors.
6. global and local economic and political situation.

Reserves represent the relatively small proportion of resources that are accessible near Earth's surface. Reserves represent the volume of mineral resources that can be economically extracted from Earth's crust using current mining technology. The volume of reserves will always be less than the volume of resources. Many ***metallic*** ores formed as a result of igneous or metamorphic processes associated with plate tectonics. Consequently, metallic deposits are often concentrated near current or former plate boundaries.

Reserves continue to increase despite growing demand due to:

1. New sources of minerals that continue to be discovered as geological understanding of resource concentration improves;
2. Price increases that make previously sparsely distributed ores relatively economical to produce; and
3. Technological improvements in mining processes that have resulted in more efficient mining operations. World reserves of gold increased by approximately a third in the last thirty years, primarily as a result of improved extraction techniques. Future concerns over resources are less likely to focus on access to suitable reserves and are more likely to be concerned with the interaction between mineral extraction, refining, and the degradation of the environment.

Development of mineral resources depends on more than just the presence of a mineral deposit. Determining if a mining operation will be economically viable depends upon geological factors (the quality and quantity of the ore body), mining costs, and the market price of the commodity being mined. Many mineral resources that would have ended up in a dump just a few decades ago are now recycled. Recycling reduces the need to mine the original resources, thus extending the life of the resource base, and provides additional benefits such as energy savings, and pollution reduction.

Geology of Mineral Resources

A **mineral deposit** (ore deposit) is defined as a rock body that contains one or more elements (or minerals) having potential economic value. Mineral deposits can be classified into two main categories: **metallic** and **nonmetallic**. The term ***metal*** is used to describe elements that are used for their metallic properties (conductivity and strength). The most important elements are iron, copper, aluminum, lead, zinc, gold, and silver. They are extracted from metallic deposits. ***Nonmetallic*** (industrial) mineral deposits contain minerals useful on account of their specific physical or chemical properties. They are used for construction or for industrial use, but they are not used in processing for metals. Some of these deposits are: 1. Sand and gravel in constructions, 2. building stones (limestone, sandstone, granite, marble,..), 3. Rock salt (halite), 4. Gypsum that is used to make plaster and wallboard, 5. Clay that is used to make ceramics, and 6. fertilizers (phosphate, nitrate, and potassium).

Non-economic minerals (e.g. quartz, feldspar, and calcite) found in association with ore minerals are known as ***gangue*** (pronounced "gang") and are considered waste. The average concentration of minerals in the crust is insufficient to form an ore. Various geological processes concentrate minerals within the crust. The concentration factor (CF) is the increase in the concentration of a mineral required to generate an ore. The concentration factor necessary to generate an economic mineral deposit can be determined by dividing the economic concentration by the average concentration of the mineral in the crust. For example copper makes up 55 ppm (parts per million) (0.0055%) of Earth's crust. Copper ores from the Bingham Canyon mine, Utah, are composed of 0.6% copper (6000 ppm), equivalent to a concentration factor of 109 (6000/55). In contrast, copper ores from the Escondida mine, Chile, range in concentration from 0.2-1% (2000-10,000 ppm), equivalent to concentration factors of 36-181. Relatively rare minerals have large CF values (e.g. gold, CF = >2000), whereas more common elements have low CF values (e.g. silicon, CF = 2).

Distribution of Mineral Resources

Mineral resources (especially metallic minerals) are associated with specific types of geological settings. Most metallic ores form directly or indirectly as a result of igneous activity that is associated with convergent and divergent plate boundaries. Submarine divergent boundaries are effectively inaccessible for mineral extraction so most mineral explorations are focused on current or ancient convergent boundaries or, less commonly, continental rift zones, and the earliest stage in the formation of a divergent boundary. Convergent plate boundaries are usually associated with mineralization. It should come as no surprise that many mines are located at high elevations in mountainous terrain formed as a result of plate convergence.

We are familiar with the distribution of recently active convergent plate boundaries but we must also recognize that there are numerous ancient zones of plate convergence that are no longer located close to a present day boundary. For example, mines in the Appalachian Mountains contain mineral deposits formed when Africa and North America collided approximately 300 million years ago. Nations such as South Africa earn substantial revenues from the export of mineral resources located in ancient igneous rocks formed over a billion years ago. *South Africa has the world's greatest reserves of gold (50 mines) and is a leading producer of diamonds (60 mines) and platinum-group metals (Fig. 1). Mining alone generates 8% of South Africa's gross domestic product (GDP).*

Global Distribution of Mineral Resources

The availability of mineral resources is often directly correlated to land area: large countries generally have more minerals than small countries. Large nations such as China, Russia, Canada, Brazil and the U.S. are among the world leaders in the production of a wide variety of mineral resources. Smaller nations may benefit from localized deposits of individual minerals. For example, Morocco is the world's foremost exporter of phosphate rock, used in fertilizers. For many governments the issue is not one of mineral distribution but of mineral supply. In such cases it is relatively unimportant where the mineral is located as long as it can be imported inexpensively. Prices increase and problems arise when the required mineral is unavailable.

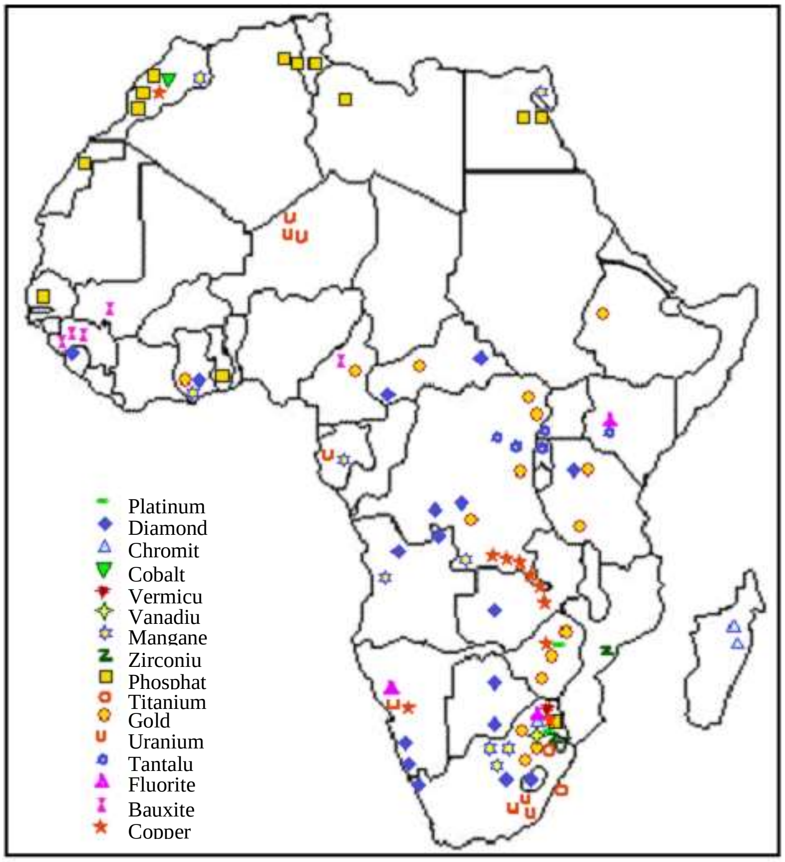


Figure 1 Distribution of strategic mineral commodities in Africa 2011-2002 (Sharaky, 2011).

Future concerns over resources are less likely to focus on access to suitable reserves of key minerals and are more likely to be concerned with the interaction between mineral extraction, production, and the environment. The environmental impact of mining is dependent upon the type of mined minerals or metals, the environment surrounding the mine, the mining techniques employed, and the methods used to minimize the impact of mining on the environment. Modern mines are regulated to:

1. protect the landscape - some types of surface mines have to return the land surface to its original shape after mining. Road building and construction inevitably alters natural landscape during the mining process.
2. protect wildlife - native vegetation has to be reintroduced after mining, companies must not harm surrounding ecosystems. Aquatic ecosystems can be harmed by polluted run-off or groundwater flow that is contaminated by metals, even in low concentrations.
3. protect people - regulations seek to prevent pollution as a result of mining.

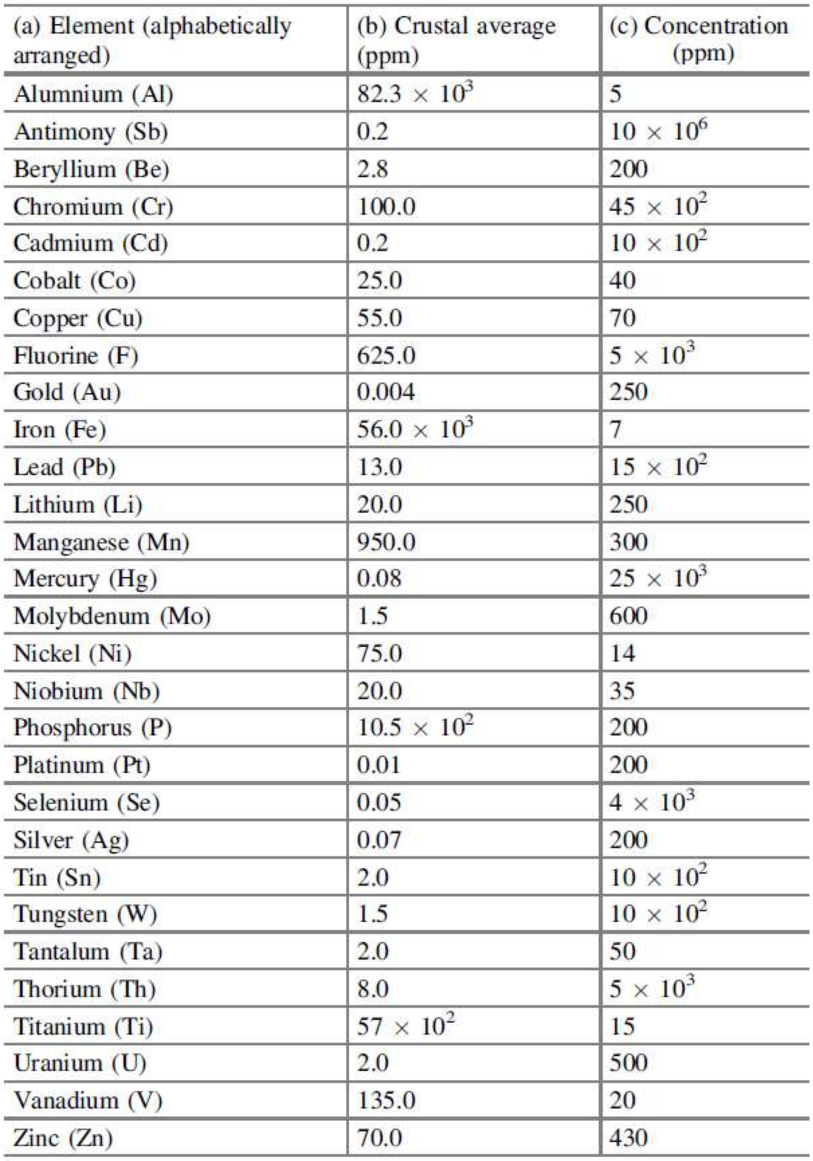
Water reacts with metallic ores to form an acid-rich runoff termed acid mine drainage. Acid mine drainage forms naturally in places where metal-rich rocks are exposed at the surface and can be exaggerated by the effects of mining which exposes large volumes of waste rock to the effects of weathering. The acidity of mine waters can be reduced artificially by adding crushed lime or naturally if the waters flow through carbonate rocks (e.g. limestone). Abandoned mines throughout the west are potential sources of pollution. In addition, drainage within mines can pollute groundwater systems. Pit lakes, formed when a former open pit mine site fills with water, can discharge acid mine waters to local aquifers. Groundwater withdrawals to prevent flooding of an active mine can lower water levels in aquifers or change the direction of groundwater flow. Water pumped out of the mine into local streams can cause higher than normal flows, altering local ecosystems.

Ore Grades or Concentration of elements in unit mass:

1 part per million (ppm) = 1000 part per billion (ppb)
1 ppm = 1 gram per ton (g/t)
100 ppm = 0.01%
1,000 ppm = 0.1%
10,000 ppm = 1%
1 kilogram (kg) = 32.151 ounces (troy)
I pound (lb) = 16 ounces (oz)
1 ounce (oz) = 28.349 grams

Typical Concentration Factors

Element	***Average Abundance (%)***	***Grade (%) Factor***	***Concentration Factor***
Aluminum	8.0	30.0	3.8
Iron	5.0	25.0	5
Copper	0.005	0.4	80
Nickel	0.007	0.5	71
Zinc	0.007	4.0	571
Manganese	0.09	35.0	389
Tin	0.0002	0.5	2500
Chromium	0.01	30.0	3000
Lead	0.001	4.0	4000
Gold	0.0000004	0.00001	25



(a) Element (alphabetically arranged)	(b) Crustal average (ppm)	(c) Concentration (ppm)
Alumnium (Al)	82.3×10^3	5
Antimony (Sb)	0.2	10×10^6
Beryllium (Be)	2.8	200
Chromium (Cr)	100.0	45×10^2
Cadmium (Cd)	0.2	10×10^2
Cobalt (Co)	25.0	40
Copper (Cu)	55.0	70
Fluorine (F)	625.0	5×10^3
Gold (Au)	0.004	250
Iron (Fe)	56.0×10^3	7
Lead (Pb)	13.0	15×10^2
Lithium (Li)	20.0	250
Manganese (Mn)	950.0	300
Mercury (Hg)	0.08	25×10^3
Molybdenum (Mo)	1.5	600
Nickel (Ni)	75.0	14
Niobium (Nb)	20.0	35
Phosphorus (P)	10.5×10^2	200
Platinum (Pt)	0.01	200
Selenium (Se)	0.05	4×10^3
Silver (Ag)	0.07	200
Tin (Sn)	2.0	10×10^2
Tungsten (W)	1.5	10×10^2
Tantalum (Ta)	2.0	50
Thorium (Th)	8.0	5×10^3
Titanium (Ti)	57×10^2	15
Uranium (U)	2.0	500
Vanadium (V)	135.0	20
Zinc (Zn)	70.0	430

Table 1.2 Properties and uses of a selection of substances (elements and minerals)

Type	Useful substance	Uses and properties
Alkali metals	Cesium (Cs)	Radioactive source (atomic clocks, medicine)
	Lithium (Li)	Batteries
	Potassium (K)	Pharmaceutical Industry
	Rubidium (Rb)	Photovoltaic cells, safety glass
	Sodium (Na)	Pharmaceuticals, cosmetics, pesticides
Alkali earths	Barium (Ba)	Trapping of residual gases in cathode ray tubes
	Beryllium (Be)	Alloys
	Calcium (Ca)	Alloys
	Magnesium (Mg)	Chemical and pharmaceutical industries, light alloys
	Radium (Ra)	Luminescence (watches)
	Strontium (Sr)	Varnishes, ceramic glazes
Base metals	Cadmium (Cd)	Batteries, alloys
	Cobalt (Co)	Alloys, catalyst in the chemical and petroleum industry
	Copper (Cu)	Electrical conductors, alloys
	Lead (Pb)	Car batteries, plumbing[a], crystal (glass), ammunition[a]
	Molybdenum (Mo)	Alloy (hardened steel), catalyst (oil industry)
	Nickel (Ni)	Alloys (stainless steel), batteries, electric guitar strings
	Tin (Sn)	Bronze (copper and tin), coating of tin cans[a], electronics (solder), coins
	Zinc (Zn)	Galvanizing (protection of steel against corrosion by depositing a thin layer of Zn), brass (copper-zinc alloy)
Construction metals	Iron (Fe)	construction – cars, buildings, bridges
	Aluminium	aircraft, electric cables
	Chromium (Cr)	Alloy (stainless steel), protective coating on steel
	Manganese (Mn)	Alloys, batteries, fertilizer
	Vanadium (V)	Additive in steel, catalyst
Other metals	Bismuth (Bi)	Fuses, glass, ceramics, pharmaceutical and cosmetic industries
	Hafnium (Hf)	Filament in light bulbs, nuclear reactors, alloys, processors
	Mercury (Hg)	Pharmaceutical industry, cathode fluorescent lamps, dental fillings[a], batteries, thermometers[a]
	Niobium (Nb)	Alloys, superconducting magnets
	Scandium (Sc)	Alloys (especially aluminum), metal halide lamp
	Tantalum (Ta)	Electronic capacitors
	Technetium (Tc)	Medical Imaging
	Thallium (Tl)	Low temperature thermometers, infrared detectors
	Titanium (Ti)	Pigments, high-technology alloys
	Tungsten (W)	Tungsten carbide – abrasive
	Yttrium (Y)	TV screens, lasers (YAG), superconducting alloys
	Zirconium (Zr)	High-technology alloys
Precious metals	Gold (Au)	Jewelry, coins, gold
	Indium (In)	Photovoltaic cells, infrared detectors, nuclear medicine
	Iridium (Ir)	Alloys (hardening of platinum alloys), mirror finish on ski goggles
	Osmium (Os)	Alloys, pen nibs, pacemakers
	Palladium (Pd)	Electronics (cell phones, computers . . .), catalysts, hydrogen sensors, jewelry

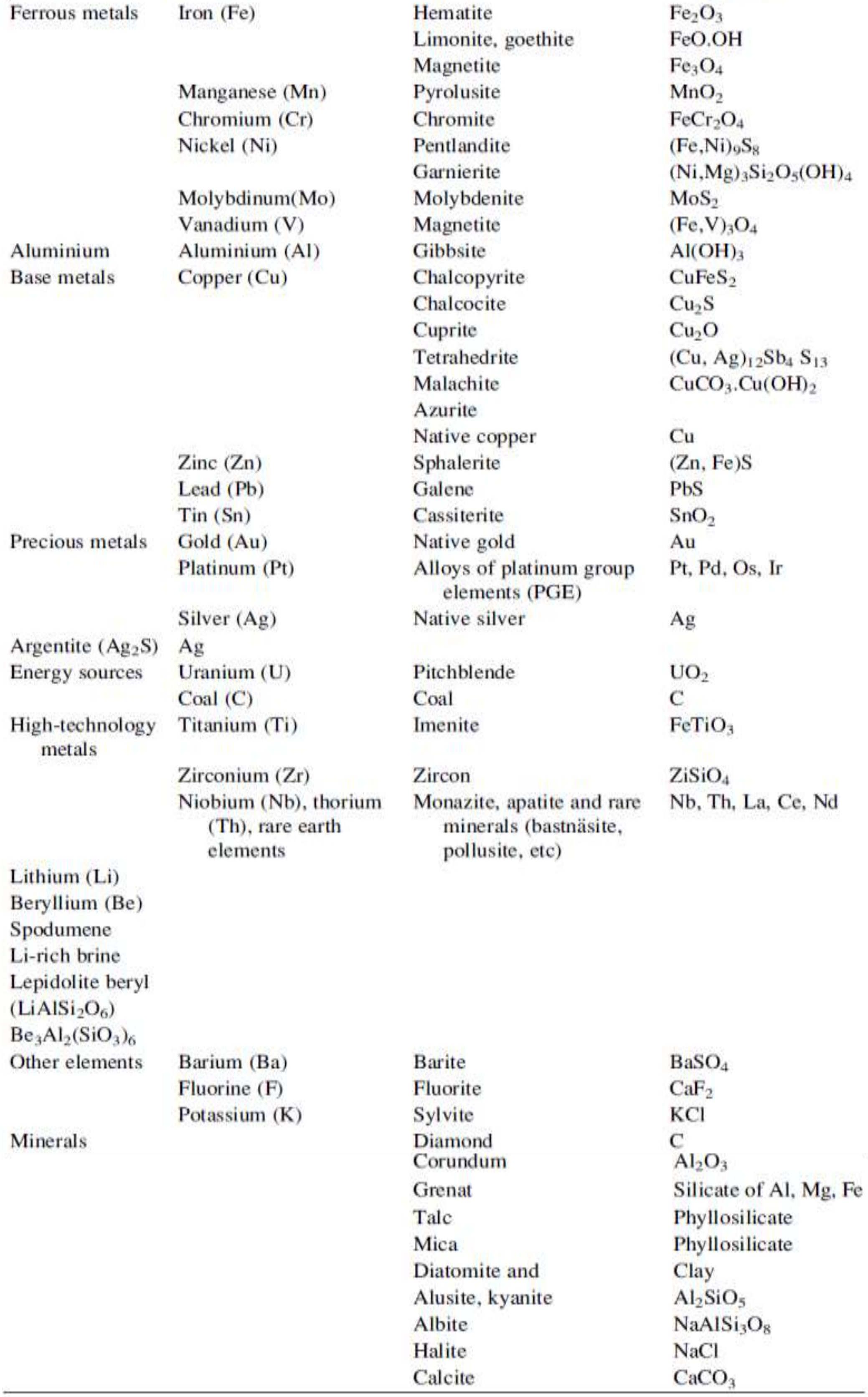
(continued)

Table 1.2 (continued)

Type	Useful substance	Uses and properties
	Platinum (Pt)	Electronics (cell phones, computers . . .), catalysts, hydrogen sensors, jewelry
	Rhenium (Re)	Alloys
	Rhodium (Rh)	Catalysts, X-ray tubes, mirrors, jewelry
	Ruthenium (Ru)	Alloys, hard drives, superconductors
	Silver (Ag)	Jewelry, silverware, photography[a]
Minerals	Diamond	Jewelry, abrasives (hardness, attractiveness)
	Corundum	Abrasives (hardness)
	Talc	Lubricant (softness)
	Pumice	Abrasives (hardness)
	Asbestos	Insulator (low thermal conductivity)[a]
	Mica	Insulator (low thermal conductivity)[a]
	Diatomite	Filters
	Barite	Drilling mud (high density)
	Andalusite	Ceramics (resistance to high temperature)
	Kyanite	Ceramics (resistance to high temperature)
	Halite	Food additive, de-icer (lowers freezing temperature of water)
	Calcite	Cement

[a] Use now restricted because of toxicity of substance or substitution

Classifications Based on the Use of the Metal or Ore Mineral



Class	Element	Mineral	Composition
Ferrous metals	Iron (Fe)	Hematite	Fe_2O_3
		Limonite, goethite	FeO.OH
		Magnetite	Fe_3O_4
	Manganese (Mn)	Pyrolusite	MnO_2
	Chromium (Cr)	Chromite	$FeCr_2O_4$
	Nickel (Ni)	Pentlandite	$(Fe,Ni)_9S_8$
		Garnierite	$(Ni,Mg)_3Si_2O_5(OH)_4$
	Molybdinum(Mo)	Molybdenite	MoS_2
	Vanadium (V)	Magnetite	$(Fe,V)_3O_4$
Aluminium	Aluminium (Al)	Gibbsite	$Al(OH)_3$
Base metals	Copper (Cu)	Chalcopyrite	$CuFeS_2$
		Chalcocite	Cu_2S
		Cuprite	Cu_2O
		Tetrahedrite	$(Cu, Ag)_{12}Sb_4 S_{13}$
		Malachite	$CuCO_3.Cu(OH)_2$
		Azurite	
		Native copper	Cu
	Zinc (Zn)	Sphalerite	(Zn, Fe)S
	Lead (Pb)	Galene	PbS
	Tin (Sn)	Cassiterite	SnO_2
Precious metals	Gold (Au)	Native gold	Au
	Platinum (Pt)	Alloys of platinum group elements (PGE)	Pt, Pd, Os, Ir
	Silver (Ag)	Native silver	Ag
Argentite (Ag_2S)	Ag		
Energy sources	Uranium (U)	Pitchblende	UO_2
	Coal (C)	Coal	C
High-technology metals	Titanium (Ti)	Imenite	$FeTiO_3$
	Zirconium (Zr)	Zircon	$ZiSiO_4$
	Niobium (Nb), thorium (Th), rare earth elements	Monazite, apatite and rare minerals (bastnäsite, pollusite, etc)	Nb, Th, La, Ce, Nd
Lithium (Li)			
Beryllium (Be)			
Spodumene			
Li-rich brine			
Lepidolite beryl			
($LiAlSi_2O_6$)			
$Be_3Al_2(SiO_3)_6$			
Other elements	Barium (Ba)	Barite	$BaSO_4$
	Fluorine (F)	Fluorite	CaF_2
	Potassium (K)	Sylvite	KCl
Minerals		Diamond	C
		Corundum	Al_2O_3
		Grenat	Silicate of Al, Mg, Fe
		Talc	Phyllosilicate
		Mica	Phyllosilicate
		Diatomite and	Clay
		Alusite, kyanite	Al_2SiO_5
		Albite	$NaAlSi_3O_8$
		Halite	NaCl
		Calcite	$CaCO_3$

Classifications Based on the Type of Mineral

Sulfides and sulfosalts

- Covellite – CuS
- Chalcocite - Cu_2S
- Chalcopyrite - $CuFeS_2$
- Bornite – $Cu_8\ FeS_4$
- Tetrahedrite – $(Cu, Ag)_{12}Sb_4\ S_{13}$
- Galena - PbS
- Sphalerite – $(Zn,Fe)S$
- Cinnabar - HgS
- Cobaltite - $(Co, Fe)AsS$
- Molybdenite: -MoS_2
- Pentlandite: $(Fe, Ni)_9S_8$
- Millerite – NiS
- Realgar – AsS
- Stibnite – Sb_2S_3
- Sperrylite – $PtAs_2$
- Laurite – RuS_2

Oxides and hydroxides

- Bauxite
  - Gibbsite - $Al(OH)_3$
  - Boehmite - (γ-$AlO(OH)$)
  - Diaspore - (α-$AlO(OH)$)
- Cassiterite - SnO_2
- Cuprite – Cu_2O
- Chromite - $(Fe, Mg)Cr_2O_4$
- Columbite -tantalite or coltan
  - $(Fe, Mn)(Nb, Ta)_2O_6$

- Hematite - Fe_2O_3
- Ilmenite - $FeTiO_3$
- Magnetite - Fe_3O_4
- Pyrolusite -MnO_2
- Rutile – TiO_2
- Uraninite (pitchblende) - UO_2

Oxysalts

- Calcite – $CaCO_3$
- Rhodochrosite – $MnCO_3$
- Smithsonite – $ZnCO_3$
- Malachite – $Cu_2(OH)_2CO_3$
- Barite - $BaSO_4$
- Gypsum – $CaSO_4\ .2H_2O$
- Scheelite - $CaWO_4$
- Wolframite - $(Fe, Mn)WO_4$
- Apatite – $Ca_8\ (PO_4)_3\ (F,Cl, OH)$

Halides

- Halite – $NaCl$
- Sylvite – KCl
- Fluorite – CaF_2

Metals and native elements

- Gold – Au
- Silver – Ag
- Platinum-group metals – Pt, Pd, Ru
- Copper - Cu
- Carbon – C (diamond, graphite)

Silicates

- Beryl - $Be_3\ Al_2\ (SiO_3)_6$
- Garnet – $Fe_3\ Al_2\ (SiO_4)_3$
- Garnierite – mixture of the Ni-Mg-hydrosilicates
- Kaolinite – $Al_4\ Si_4\ O_8\ (OH)_8$
- Sillimanite – $Al_2\ SiO_8$
- Spodumene – $LiAlSi_2\ O_6$
- Talc – $Mg_3\ Si_4\ O_8\ (OH)_2$
- Zircon – $ZrSiO_4$

Table 2.7 Major ore-importing and ore-exporting countries from http://minerals.usgs.gov/minerals/pubs/

	Country	Value ($)
(a) Importers		
1.	China	85,280,550
2.	Japan	28,365,440
3.	Germany	9,307,674
4.	Korea	6,623,871
5.	India	5,250,223
6.	United Kingdom	4,679,500
7.	USA	4,487,631
8.	Belgium	3,183,008
9.	Netherlands	3,081,213
10.	Italy	2,912,043
11.	Finland	2,896,519
12.	Canada	2,775,180
13.	France	2,630,696
14.	Russia	2,307,253
15.	Spain	2,217,288
(b) Exporters		
1.	Australia	34,546,550
2.	Brazil	18,726,620
3.	Chile	14,888,160
4.	Peru	7,273,738
5.	South Africa	7,268,294
6.	India	6,519,472
7.	USA	6,487,638
8.	Canada	6,053,128
9.	Indonesia	4,295,629
10.	Sweden	2,628,527
11.	Kazakhstan	2,412,308
12.	Russia	2,374,813
13.	Ukraine	2,153,611
14.	Iran	1,579,345
15.	Congo	1,555,942

Classification of Mineral Deposits Based on the Ore-Forming Process

A. Magmatic ore deposits:

Some mineral deposits, particularly those containing nickel, chromium and platinum, form by the separation of the metal sulfide or oxides in the molten form, within an igneous melt before it crystallizes. These are known as magmatic deposits.

1. ***Layered intrusion, Magmatic segregation, or crystal settling:*** It occurs when minerals that crystallize in the magma move downward in the magma chamber because they are denser than the magma, e.g. Bushveld Igneous Complex (BIC), South Africa.
2. ***Pegmatites*** are coarsely crystalline igneous rocks formed in the late stage of magma cooling. They include such elements as beryllium along with several gem minerals such as tourmaline.
3. ***Greisen*** is fluorine-enriched pegmatite that has an assemblage of quartz and muscovite with fluorite, topaz, and tourmaline. It is associated with highly fractionated magma enriched in volatiles Cl, B, and F, and metallic elements tin, tungsten, molybdenum, and uranium.
4. ***Kimberlites*** are sources of diamond. They are dikes or pipes of mafic rocks.
5. ***Carbonatites*** are carbonate-rich rocks. They are relatively enriched in niobium (Nb) rare earth elements (REE), phosphors (P), fluorine (F), thorium (Th), barium (Ba), strontium (Sr) and zirconium (Zr).
6. ***Ophiolites (oceanic deposits)*** are rock assemblage containing ultramafic, mafic (gabbro and basalt) capped by sediments, e.g. iron and chromite deposits.
7. ***Massive sulfide deposits*** are formed by discharge of hydrothermal solutions into sea floor to form massive sulfide layers. They are major supplies of copper, lead, zinc, and by-product gold and silver.

B. Hydrothermal ore deposits:

Hydrothermal solution is the most important source of metallic ore deposits. It is a hot water carrying valuable metals that are deposited in the surrounding rocks.

1. ***Porphyry copper-molybdenum deposits***: Porphyry systems generally occur at convergent plate margins (subduction zones) and in rift-related setting. They supply large quantities of copper, molybdenum, and gold.
2. ***Epithermal deposits*** consist of gold-bearing veins, veinlets, and disseminations, which formed from hydrothermal solutions cooler than 300°C that circulated through relatively shallow depths (<1km).

a. ***High sulfidation deposits*** contain sulfide minerals with a high sulfur/metal ratio, e.g. Summitville, Colorado.

b. ***Low sulfidation*** deposits, e.g. Boulder County, Colorado.

1. Base metal zone (e.g. copper, lead, and zinc)
2. Bonanza zone (e.g. silver)
3. High-level zone (e.g. mercury and antimony)
4. Hot spring zone (e.g. mercury)

C. Metamorphic ore deposits:

1. ***Skarn*** is a mineral assemblage formed as a result of metasomatic and hydrothermal processes acting mainly on carbonate sedimentary rocks (limestone).
2. ***Metamorphic veins***

D. Sedimentary ore deposits:

1. ***Banded iron formation (BIF)*** is chemical sediment, thin or laminated containing 15% or more iron of sedimentary origin.
2. Phosphate uranium deposits.
3. Sediment-hosted copper-lead-zinc deposits
4. ***Placer deposits: Placer deposits*** are formed by the mechanical concentration of resistant minerals, which are released by weathering. The main commodities derived from placer deposits are tin, gold, platinum, zircon, and diamond.

MAGMATIC ORE DEPOSITS

Ore deposits associated with magmatic transport systems are classified as magmatic deposits in which metals are transported by and precipitated directly from a magma.

SOURCE OF METALS:

In general, the magmas that we will consider in this class of deposits are generated by partial melting in the mantle. Magma compositions are generally ultramafic to mafic (dark igneous rocks with high iron and magnesium content).

The composition of magmas varies due to:

1. Differentiation of magma.
2. Partial melting of silicate rocks leads to more silica-rich (more felsic) magmas.
3. Percentage of partial melt generated.
4. Parent rock composition.
5. Mixing of two magmas.
6. Changing in depth at which magma is generated.
7. Volatile content of the melt.

1. LAYERED INTRUSIONS (MAGMATIC SEGREGATION)

Layered intrusion or magmatic segregation deposits form as a direct result of igneous differentiation. During the crystallization of magma, usually mafic or ultramafic, heavy, metal-rich liquids settle and accumulate at specific sites, often at the base leading to layered intrusions. Layering is especially conspicuous in mafic rocks containing chromite, magnetite, platinum and ilmenite.

General geologic characteristics of the layered mafic intrusive complexes:

1. Large, circular to oval-shaped, platter-like intrusions (several hundred kilometers in diameter and less than 10 kilometers in thickness).
2. Composed of crystallized mafic rock (gabbro in composition).
3. Characterized by very regular layering of minerals.
4. Mostly Precambrian (are Proterozoic) in age.
5. They appear to be intruded into stable cratons (immobile).
6. The layers result from the settling out of crystals during crystallization based on density contrast. Minerals with higher melting points crystallize early during crystallization. If more than one mineral is crystallizing simultaneously, the more dense minerals settle more rapidly.

Distribution: Only eight known layered igneous complexes in the world, and of these only three have significant chromium. Two of those have been mined for chromium and platinium: Bushveld Igneous Complex, South Africa and the Great Dyke, Zimbabwe

Form: In cross section most layered complexes appear as an inverted funnel or steep-sided cone (Fig. 2). The complexes are immense in size often covering thousands of square kilometers. All are layered grading from ultramafic rocks at the base to mafic or intermediate rocks near the top of the complex. Some also are associated with late stage granitic intrusives which cut the complex.

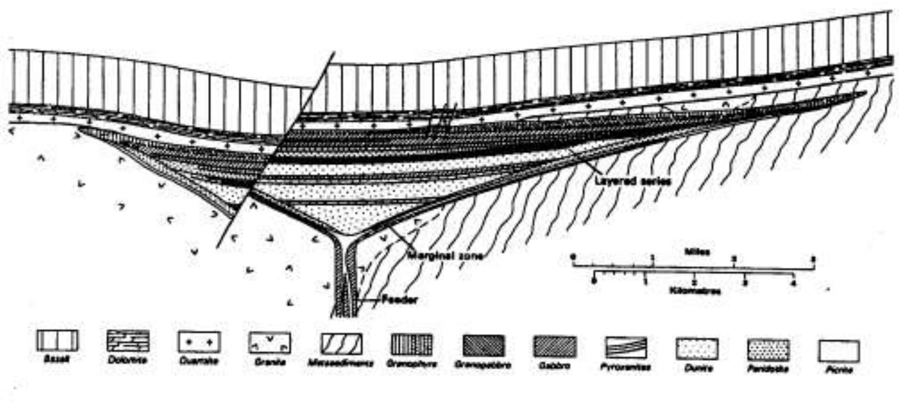


Figure 2. **Cross Section of a Typical Layered Mafic Igneous (LIM) Complex.**

Metals mined from layered mafic intrusive complexes (LMIC):

A. Base metals: Copper (Cu), iron (Fe) and nickel (Ni) in sulfides.
B. Platinum Group Elements (PGEs) in sulfides.
C. Chromium (Cr) in chromite.
D. Titanium (Ti) and Vanadium (V) in anorthosites (calcium plagioclase).

A. Base Metals (Cu, Fe, Ni):

Common ore minerals in base metal sulfide deposits are: Ni from pentlandite (Fe,Ni)S, Cu from chalcopyrite ($CuFeS_2$). (Associated sulfide/oxide mineralogy: pyrrhotite $Fe_{(1-x)}S_x$, pyrite (FeS_2), cubanite ($Cu_2S \cdot Fe_4S_5$), magnetite (Fe_3O_4). More than 10.5 million tons of nickel, representing almost 20% of the West's nickel reserves, are located in South Africa's Bushveld Igneous Complex where the nickel bearing horizons occur over a total length of some 250 kilometers.

Genesis of sulfide metals:

Upon cooling, the sulfur-rich liquid produces an immiscible sulfide phase (droplets of sulfide liquid in silicate liquid, like oil in water) from which minerals such as pyrrhotite (FeS), pentlandite $(Fe,Ni)_9S_8$, and chalcopyrite ($CuFeS_2$) crystallize. Typical magmatic Ni-Cu deposits tend to occur in embayments at or near the base of their intrusive hosts.

a. Immiscible liquids: Magmas enriched in sulfur separate into two immiscible liquids, a silicate liquid (about 99% of the magma) and a sulfide liquid (1% of the liquid). Separation occurs at more than 1000°C.

b. Scavenging of metals by sulfide melt: Some metals (base, Pt-group, and precious) present in the silicate liquid preferentially diffuse into the sulfide liquid.

c. Sulfide liquid sinks: Once formed, the sulfide liquid droplets coalesce and sink to the floor of the magma chamber based on density contrast.

B. Platinum Group Elements (PGE's):

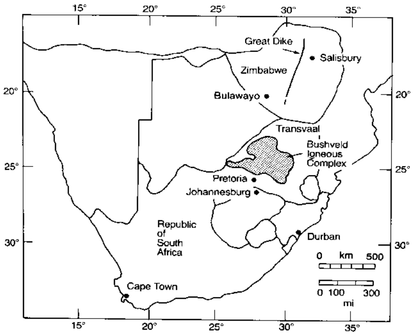
Platinum may be counted as one of the precious metals since it is more costly than gold. It is one of a group of metals called platinum group elements (PGE) consisting of iridium (Ir), osmium (Os), palladium (Pd), platinum (Pt), rhodium (Rh), and ruthenium (Ru). Geologically, platinum is found in thin layers of sulfides that are found in mafic igneous rocks. These kinds of rocks are common in ***Bushveld Igneous Complex*** (BIC), South Africa and ***Great Dyke***, Zimbabwe.

Characteristics of the PGE's:

1. Common ore minerals of PGEs are braggite (Pt,Pd,Ni)S , cooperite (Pt,Pd)S, laurite RuS_2 and a Pt-Fe alloy in base-metal sulfides.
2. PGE mineralization generally but not always restricted to layers.
3. PGE mineralization found in very different places/levels in different intrusions.
4. Not all intrusions contain ore grade PGE mineralization.

Bushveld Igneous Complex (BIC), South Africa:

The Bushveld Igneous Complex (BIC), which extends for 400 kilometers in the Northern Province Fig. 3), South Africa contains the world's largest known deposits of PGE's. It is a large igneous intrusion through the earth's crust, which was tilted and eroded new outcrops to surface around to form edge of a great geological basin. It is also the richest in terms of mineral deposits. In addition to deposits of platinum group elements, chromite, Ni-Cu sulfide, and Ti and V are present. 7 shallow overlapping conical intrusions that coalesced into three larger magma chambers forming total body of 8 x 240 x 400 km (Fig. 3). It is believed that all sections of the system were formed at the same time (2 billion years ago) and are remarkably similar. Vast quantities of molten rock from the earth's mantle were brought to surface through long vertical cracks in the earth's crust creating the geological intrusion known as the BIC. The effects of these injections of molten rock over time, combined with the crystallization of different minerals at different temperatures, resulted in the formation of a structure rather like a layered cake consisting of distinct mineral strata, including three PGE-bearing reefs:



gure 9-4. Locality map of the BIC and the Great Dike. (*After* Willemse, 1969b)

Figure. 3. Bushveld Igneous Complex (BIC), South Africa and Great Dike, Zimbabwe.

1. **Merensky Reef:** A 1 m-thick horizon traceable over 250 km. that averages about 2% PGE-bearing sulfides. The Merensky Reef has been the source of most of South Africa's PGE. Tonnage and grade are 2160 million tons (Mt) at 8.1 g/ton of PGEs plus Au.
2. **Platreef:** Up to 200 m-thick zone traceable up to 60 km. Disseminated sulfide minerals are present sporadically. The deposit contains 3700 Mt at 8.7 g/ton combined PGEs plus Au.
3. **UG2**: A 0.8 m-thick chromite horizon that contains a few percent PGE-bearing sulfides (high in Rh). PGEs are also present as alloys in the chromite ($FeCr_2O_4$). Tonnage and grade: 1,700 Mt of 7.3 g/ton combined PGEs plus Au.

Great Dyke, Zimbabwe:

Great Dyke, Zimbabwe (530 km long, 6 km wide, Fig. 4) and made up of 4 coalescing, narrow, funnel-shaped layered mafic intrusions). Main sulfide zone extends along strike. Tonnage and grade are 1,679 million tons at 5 g/ton combined PGEs plus 0.7 g/t Au. Hartley and Ngezi are two of several platinum-bearing deposits hosted in the Great Dike. The mineralization occurs in a 1.0–1.5 m-thick sulfide-rich band 15–40 m below the base of the upper mafic layer.

Fig. 4. Great Dyke, Zimbabwe

C. Chromium (Cr) deposits:

Chromite occurs only in the lower portions of the complexes interbedded with the ultramafics. Chromite deposits are the product of the separation of solid phases from a liquid and their accumulation into chromite-rich layers. The processes involved in the formation of chromite layers are fractional crystallization and gravity settling. Chromite crystallizes into mineral grains within the silicate liquid and, because they are heavier than the liquid, they sink to form a cummulate layer at the base of the intrusive.

Types of chromite deposits:

1. Stratiform, sheet-like layers vary from 1 cm to 2 m in thickness with a lateral extent of tens to hundreds of kilometers in mafic layered intrusions. Chromite layers contain 25 to 95% chromite ($FeCr_2O_4$) with Cr/Fe ratios between 1.3 and 2.5. The ultramafic and mafic layers include rocks such as dunite (olivine-rich), peridotite, pyroxenite and a variety of others, less commonly gabbroic rocks.

2. Podiform, irregular to lenticular (lens-like or pod-like--hence the name podiform) bodies that occur in ultramafic rocks, which formed by magmatic segregation processes similar to those described for stratiform chromite deposits, but the magma chambers are smaller (minimagma chambers, 0.5 to 1 km in extent) and far more tectonically active with frequent intrusion of new and more primitive basaltic magmas into chamber. The rocks associated with podiform chromites are generally referred to as "Alpine-type" peridotites and they are usually found along major fault zones within mountain belts.

Typical chromium deposits in Africa are Bushveld, South Africa and Great Dyke and Selukwe, Zimbabwe.

D. Titanium (Ti) and Vanadium (V) in anorthosites:

Anorthosites are primary sources for titanium. Nearly all large igneous deposits of titanium are associated with anorthosite massives. The source of most placers of titanium minerals can be traced to the weathering of anorthosite massive. Anorthosite is a rock composed of 90% plagioclase ($NaAlSi_3O_8$-$CaAl_2Si_2O_8$). This rock is found in two distinct settings: the mafic layered intrusions and the large anorthosite massives (hundreds of km^3). All are Proterozoic in age: 1.3 ± 0.2 Ga.

Origin of anorthosite massive:

It may be a result of an incipient and aborted continental rifting event. The anorthosite may represent the material that remains after partial melting of intermediate composition rocks in the lower crust.

Titanium deposits in anorthosites

Ti ore minerals are: rutile (TiO_2), ilmenite ($FeTiO_3$) originated from mafic layered intrusions. Fe-Ti oxide minerals are denser than silicate minerals and may concentrate by segregation through crystal settling (gravity settling). Fe-Ti mineralization in the form of ilmenite, hematite, magnetite and rutile occurs at the gabbro/anorthosite contact. Genesis is not well understood, but thought to be related to buoyant blockage of magma at the crust-mantle boundary and subsequent partial melting and fractionation.

2. PEGMATITES

Pegmatites are coarsely crystalline intermediate to felsic igneous rocks formed in the late stage of magma at **very slow** cooling. They are mined for tin, high purity quartz, potassium feldspar, albite, kaolinite, white mica, gem beryl, gem tourmaline, tantalite, columbite, apatite, cassiterite, uraninite and other minor minerals. Gem-quality cassiterite is very rare.

Distribution: Pegmatites occur in rocks of all ages, from the Archean to the Cenozoic, but Phanerozic (last 600 million years) occurrences are far less numerous.

Form: Pegmatites are generally dike-like in both plan view and cross section. Most are small with lengths rarely exceeding 500 meters and widths of less than 100 meters. A few "giants" have lengths of more than two kilometers, but these are rare.

Setting: Pegmatites can occur in association with both mafic and felsic intrusive igneous rocks, but the latter predominate. Economic pegmatites are restricted to those associated with felsic intrusives. Temperature of formation varies from magmatic (700°C) to low-temperature hydrothermal (150°C).

A second type of pegmatite is often found in high-grade metamorphic shield terrains, where there are no intrusives in close proximity. These are small in size and mineralogically simple, often consisting only of quartz and minor mica. They are thought to represent pockets of partial melting.

Bikita Pegmatite, Zimbabwe

The Bikita mining district is located in east central Zimbabwe.

Regional Geology: The Victoria Schist Belt which hosts the pegmatites is 80 km long by 10 km wide trending NE-SW. The belt takes the form of a complexly folded. The major unit within the belt is the Archean Bularwayan Supergroup consisting of a lower sedimentary group of pelitic schist, banded iron formation and carbonates and an upper volcanic group of pillow lavas and schists. Most of the larger pegmatites occur in the upper volcanic group. The entire belt is surrounded massive granitic plutons age dated at 2.6 Ga.

Geology of the Bikita Field: Fifteen pegmatites have been discovered. Host rocks are chloritic schists of the volcanic group. A local, central dome that has exposed the underlying sedimentary group, appears to be the major structural feature. Zoning is well developed. Important minerals include albite, microcline, quartz, lepidolite (Li mica), spodumene (emerald, Li), petalite (Li), beryl (Be) and pollucite (gem Cs) .

The Bikita pegmatite in SE Zimbabwe has been mined periodically since tin was discovered in 1910, and mining of petalite (for lithium) started in the 1940s. The main product currently exported by Bikita Minerals is a graded petalite concentrate which is produced on site at the mine and chiefly sold for glass and ceramics. Tantalite concentrates have also been produced at the mine.

Bikita is 1,700 m long, varies in width from 30 to 70 m, and dips 15 to 45 degrees. Minerals hosted in the pegmatite include petalite, lepidolite, spodumene, pollucite, beryl, eucryptite, amblygonite, and bikitaite. The Bikita pegmatite is poorly dated, but is probably Neoarchean. As of 2021, Bikita is the only mine in Africa producing lithium, and currently that lithium is not used in battery supply chains. However, the Bikita mine area does contain spodumene pegmatites, which may contribute to the battery supply chain in the future.

Kenticha pegmatite district, Adola Belt Ethiopia: These Cambrian pegmatites have been mined since the early 1990s, with an emphasis on the significantly weathered regolith. The pegmatites intrude greenschist to lower amphibolite facies schists and serpentinites. The pegmatites range from tens of meters to one kilometer in length.

Tin (Cassiterite SnO_2)

Cassiterite (SnO_2) is the only commercial ore of tin. Across Africa, deposits range in age from Archaean in Zimbabwe and Palaeoproterozoic in South Africa, to Mesozoic and Pleistocene in Nigeria. In South Africa, tin was mined from the Rooiberg area of the Bushveld Complex at least 500 years ago.

Lithium deposits

Lithium is a soft, silver-white metal within the alkali metal group on the periodic table. Lithium concentrations in the Earth's upper crust is 24 ppm. In igneous rocks, the abundance is typically 28–30 ppm, but in sedimentary rocks, it can be as high as 53–60 ppm. Mines and salt lakes generally are believed to contain a total of 14×10^6 tons of Li. The Li concentration in seawater is quite low (0.1–0.20 ppm), but the total amount of Li is estimated to be ≈ 230×10^9 tons.

Lithium usages:

Lithium deposition is currently being considered as the most serious safety concern for Li-ion cells. Some of the common uses of lithium include (i) rechargeable battery for electric vehicles, mobile phones, laptops, and cameras; (ii) alloys with aluminum and magnesium to improve their strength and make them lighter; (iii) glass and ceramics (lithium oxide); (iv) high temperature lubricant (lithium stearate); (v) medical drugs to treat depression (lithium carbonate), and (vi) storage of hydrogen used as fuel (lithium hydride).

Geology of Lithium:

Lithium is mined from three different deposit types: lithium brine deposits, pegmatite lithium deposits and sedimentary lithium deposits. Lithium in pegmatites is most commonly found in the mineral spodumene, but also may be present in other minerals such as petalite, lepidolite, amblygonite and eucryptite.

1. **Lithium-cesium-tantalum (LCT) pegmatites** are extremely coarse-grained granitic rocks from crystallized magma below the Earth’s crust. They form small but mineralogically spectacular igneous bodies. Pegmatite lithium deposits, also known as hard-rock lithium deposits, can contain extractable amounts of a number of elements, including lithium, tin, tantalum and niobium. These rocks account for about one-fourth of the world’s lithium production, one-tenth of the beryllium, most of the tantalum, and all of the cesium.
2. **Sedimentary rock deposits** account for about 8 percent of known global lithium resources, and are found in clay deposits and lacustrine evaporites.
3. **Brines**: Lithium carbonate is now produced from continental brines in Latin America. Lithium brine deposits represent about 66% of global lithium resources and are found mainly in the salt flats of Chile, Argentina, China and Tibet.

Properties and Characteristics of Lithium

High Energy Density:

Lithium has a high energy density, which means it can store a significant amount of energy in a small and lightweight package. This property makes lithium ideal for battery applications, where high energy density is essential for portable electronics, electric vehicles, and energy storage systems.

Low Density:

Lithium is a lightweight metal with a low density, which makes it attractive for various applications where weight reduction is critical, such as aerospace and automotive industries. Lithium’s low density contributes to the overall lightweight and high-performance characteristics of lithium-based products.

Low Melting and Boiling Points:

Lithium has a low melting point of 180.54°C (356.97°F) and a low boiling point of 1,342°C (2,448°F). This property makes lithium relatively easy to process and extract from its ores using conventional metallurgical methods.

Abundance in Earth’s Crust:

Lithium is found in small amounts in the Earth’s crust. Lithium ore deposits are typically associated with granite, pegmatites, and other geological formations.

Lithium minerals:

The most important ore mineral for lithium batteries is spodumene (LiAlSi2O6), for which cracking and refining processes are well established. Other lithium ore minerals include petalite(LiAlSi4O10), lepidolite (K(Li,Al)3(Al,Si,Rb)4O10(F,OH)2), and amblygonite.

Other important minerals found in pegmatites include pollucite (mined for caesium), columbite-tantalite (tantalum) and cassiterite (tin).

Occurrence of Lithium (Li)

Lithium (Li) ore occurs naturally in various geological settings around the world. The continent of Africa has significant natural lithium resources, which may provide an opportunity for many African countries to contribute to meeting increased demand whilst also supporting economic growth. Many African countries (most notably Zimbabwe, Namibia, Ghana, Democratic Republic of Congo and Mali) have lithium resources and the potential for lithium mines.

The Bikita pegmatite in SE Zimbabwe has been mined periodically since tin was discovered in 1910, and mining of petalite (for lithium) started in the 1940s. The main product currently exported by Bikita Minerals is a graded petalite concentrate which is produced on site at the mine and chiefly sold for glass and ceramics. Tantalite concentrates have also been produced at the mine. As of 2021, Bikita is the only mine in Africa producing lithium. The Bikita mine area does contain spodumene pegmatites, which may contribute to the battery supply chain in the future.

Spodumene, a lithium aluminum silicate mineral (LiAlSi2O6) in the pyroxene family, an important ore of lithium and a source of ceramic materials. It is ordinarily found in lithium-bearing granite pegmatites. When brilliant and glassy, clear spodumene is valued as a semiprecious gem.

Usage:

Lithium (Li) ore plays a critical role in various industries and applications due to its unique properties. It is used as rechargeable batteries - Electronics - Glass and Ceramics - Pharmaceutical Industry.

Lithium is also used in various other applications, such as in the production of lubricants, greases, and alloys. Lithium is also used in the production of aluminum and magnesium alloys, which are used in aerospace, automotive, and other high-performance applications.

Production:

In 2021, it was estimated that Chile had reserves of lithium amounting to 9.2 million metric tons, the largest worldwide. That same year, the United States had total lithium reserves of approximately 750 thousand metric tons.

Like Brazil, **Zimbabwe** has seen its lithium output increase dramatically. The African nation’s production has remained flat in the past few years, producing 1,200 MT of the battery metal. China's Sinomine Resource Group (SZSE:002738) recently acquired the country's only lithium producer, which allegedly holds the world’s largest-known lithium deposit at over 11 million MT. The company has plans to invest US$200 million into expanding the mine's production capacity by another 2 million MT per year; the investment will also allow to mine to produce lithium spodumene.

Since former President Robert Mugabe’s resignation after 37 years, there has been great speculation as to the country’s potential in the lithium market. Winston Chitando, Zimbabwe’s new mining minister, said he believes the country has “the potential to actually account for 20 percent of global lithium demand when all known lithium resources are being exploited.” Total reserves in Zimbabwe stand at 220,000 MT, as per the US Geological Survey.

3. OPHIOLITES

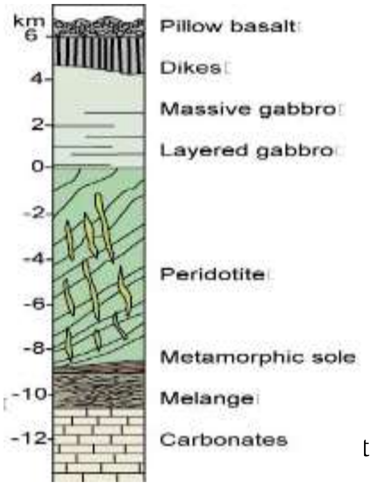


Figure 5. Ophiolite structure.

Ophiolites are pieces of oceanic plate that have been thrusted (obducted) onto the edge of continental plates. They provide models for processes at mid-ocean ridges. Ophiolites are characterized by a classic sequence of rocks: stratified igneous rock complex composed of upper basalt and dikes, middle gabbro member and lower peridotite member found in association with sedimentary rocks (Fig. 5). Some large complexes measure more than 10 km thick, 100 km wide and 500 km long. The term "ophiolite" means "snake stone" in Greek. Basalt and gabbro are commonly altered to patchy green rocks, and peridotite is mostly changed into black, greasy serpentinite. Ophiolites have been found in Cyprus, New Guinea, Newfoundland, California, and Oman. The Samail ophiolite in southeastern Oman has probably formed in Cretaceous. Late Proterozoic (750 Ma) ophiolites are distributed in the Pan-African orogenic belt (Fig. 6). The main economic importance of ophiolite is producing ***chromium*** and sometimes ***copper***.

4. MASSIVE SULFIDE DEPOSITS

A. Volcanic-hosted massive sulfide (VMS) deposits

Volcanic-associated Massive Sulfide (VMS) deposits occur in *submarine* volcanic rocks of all ages. They are important sources of *copper*, *zinc* and *lead* in addition to silver and gold. These deposits formed as massive (over 60% sulfide) lens-like accumulations on or near the sea floor in association with volcanic activity.

Classification:

A. Felsic volcanic hosted - Cu-Pb-Zn-Ag-Au

B. Mafic volcanic hosted - Cu (-Zn, -Au)

C. Mixed volcanic/sedimentary - Cu-Zn (-Au)

Sources of fluids:

1. Circulating sea water 2. Magmatic water

African distribution: Namibia (Cu and Zn)

Genetic Model: VMS deposits are generally accepted to have formed at or near discharge vents of hydrothermal systems on the sea floor. Most models of the hydrothermal system accept a seawater convection cell driven by the heat of a cooling subvolcanic igneous body with metals being leached from surrounding rocks through which the hydrothermal fluids circulate. Discharge is focused along fault or fracture systems. Sedimentary structures in the massive component of the deposits may result from mechanical reworking and downslope transportation of sulfide ores after initial deposition. Underlying alteration and stringer mineralization are formed as a result of interaction of hot discharging fluids with the footwall rocks. "Black smokers" are modern day analogues to fossil VMS deposits (Fig. 7). They have been observed over the past several years forming in deep submarine trenches off the Pacific Coast of North America.

B. Sedimentary Massive Sulfide:

Sedimentary Massive Sulfides are formed by hydrothermal emanations on or near the sea floor in association with the deposition of sedimentary rocks.

A. Lead-zinc-silver (Pb-Zn-Ag) B. Barium (Ba)

5. KIMPERLITES AND CARBONATITES:

Kimberlites and carbonatites are two closely related alkali rocks of mafic affinity. Since they share a number of characteristics, they can be considered as a single entity. Kimberlites are potassic, ultramafic rocks (<35% SiO_2) dominated by olivine and other mantle phases often including diamond. Carbonatites are granular rocks consisting primarily of calcite, dolomite, ankerite or other carbonates with subordinate apatite, magnetite and alkali-rich silicates and exhibiting features of an intrusive igneous rock. Both are characterized by the presence of carbon, the former as diamond and the latter in carbonates. Diamonds, unlike commodities such as gold, do not have a set value. They can be worth from a few $/carat to thousands of $/carat depending on their quality (evaluated on the size, color and clarity of the stone).

Distribution: Kimberlites and carbonatites occur in continental settings and range in age from late Proterozoic to Recent. The greatest concentration, however, is in rocks of Mesozoic age. Both carbonatites and kimberlites have been found in all continents, but the largest concentration is along the East African Rift System. The type area for kimberlites is Kimberley, South Africa, which yielded more than 200 million carats (1 g = 5 carats). Kimberlites are dikes or pipes of mantle-derived mafic igneous rocks, commonly including primary diamond. Secondary diamond deposits are formed from kimberlites by weathering and transportation. Carbonatites are relatively enriched in Nb, rare earth elements (REE), P, Cu, F, Th, Ti, Ba, Sr, and Zr. The most important mineral products are calcite for cement and apatite for phosphatic fertilizer. The Palabora carbonatite in South Africa contains 300 million tons of copper ore (chalcopyrite) grading 0.69% Cu, in addition to economic deposits of apatite (phosphate). It consists of large, irregularly, elongate body of micaceous pyroxenite (<1 x 2.5 km). The age is of the Palabora complex is essentially the same as that of the Bushveld Igneous Complex, BIC (>2,000 Ma).

Ore Deposits: Only mineral in the kimberlites is ***diamond*** that averages less than 0.0000025% (25 ppb) (of a typical diamond-bearing Kimberlite. Diamonds are graded into gem quality and industrial based on size and clarity. Most diamonds fall into the industrial category (>90%) and many diamond pipes produce only industrial diamonds.

The principal minerals in carbonatites are calcite and dolomite, which are rarely recovered. Barite is also quite common and occasionally recovered, but in general ***apatite*** (phosphates), ***magnetite***, ***rare earth elements*** (Bastnaesite-(REE)(CO_3)F and Monazite-(REE)PO_4), and ***uranium*** and ***thorium*** bearing minerals and ***sulfides*** are the mined commodities.

Africa is the richest continent for diamond mining, accounting for 61% of world production in 2002, and more than 60% of the global reserve. The major sources are in the south with lesser concentrations in the west-central part of the continent. The major producing countries are Botswana (41% of African production), D.R. Congo (8.2%), South Africa (18%), Angola (21%) and Namibia (11.5%).

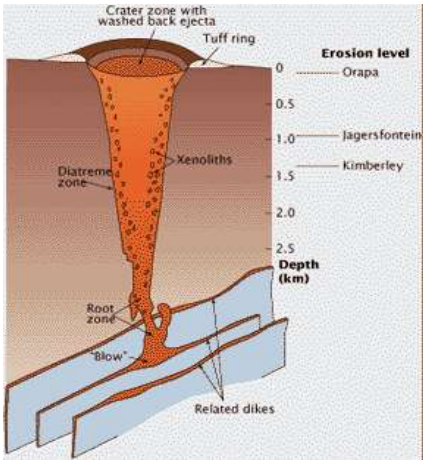


Fig. 8. A kimberlite pipe.

Origin: Kimberlites and carbonatites appear to share several genetic characteristics: (1) associated with continental rifts, (2) similar ages, (3) proximity to alkali-rich rocks, (4) high partial pressure of CO_2. Kimberlites are of obvious mantle origin, due to the presence of diamond, which requires the extreme pressures of the mantle, as well as other mantle phases. Kimberlite magma rises through Earth's crust in networks of cracks or dikes. The pipes only form near Earth's surface. The cross-section of a kimberlite (Fig. 8) shows the carrot-shaped "pipe" filled with volcanic rock, mantle fragments, and some embedded diamonds. The rock is called kimberlite after the city of ***Kimberley***, South Africa, where the pipes were first discovered in the 1870s. The root zone starts in fissures, where gases are released from the rising magma and drive the eruption; they blow out the fragment-laden kimberlite to form the volcano's tuff ring and fill the pipe. Another rock that provides diamonds is ***lamproite***. The volcano that carries diamond to the surface emanates from deep cracks and fissures called dikes. It develops its carrot shape near the surface, when gases separate from the magma, perhaps accompanied by the boiling of ground water, and a violent supersonic eruption follows. The volcanic cone formed above the kimberlite pipe is very small but the magma originates at depths at least 3 times as great.

Cu-Fe-U-phosphate mined at Palabora, South Africa

Palabora carbonatite contains 315 Mt of copper ore averaging 0.7% Cu, largely as chalcopyrite with lesser bornite and chalcocite. The copper orebody is hosted in a carbonatite pipe. Magnetite is mined for iron. Apatite (phosphate) is mined as a byproduct for fertilizer. Carbonatite is pipe-shaped, 2000 x 4000 m in plan view and is surrounded by igneous silicate rocks that are genetically related to but were intruded before the carbonatite. Magnetite/apatite mineral segregations are associated with the silicate rocks and surround the carbonatite.

HYDROTHERMAL ORE DEPOSITS I

1. PORPHYRY Cu and Mo

Hydrothermal ore deposits are the largest class of metallic mineral deposits. These deposits form from precipitation of metal-bearing minerals from hydrothermal fluids (hot aqueous fluid).

Porphyry: Typical porphyry copper deposits are cylindrical, stock-like composite masses having elongate outcrops 1.5 x 2 km in diameter with an outer shell of medium to coarse grained equigranular rock and a core of similar composition that is porphyritic. They are subvolcanic (5-1 km below the surface). Upon cooling at shallow depths, fine grain minerals crystallize around older coarse minerals (phenocrysts) to form porphyritic texture. With more crystallization, the volume increases and then the internal pressure increases. At a later stage, solidified shell (carapace) is formed around the porphyry due to rapid cooling. It prevents volatiles from escaping the magma to the wallrock. So that the internal vapor pressure increases and forms confined pressure that increase with cooling until it exceeds the lithostatic pressure (weight of the rocks), resulting in fracturing and brecciation of the carapace and the wallrock surrounding the porphyry. This process (crystallization, increasing volatiles, explosion, fracturing, and brecciation) can be repeated several times to form stockwork veins and breccia pipes above the stock. Molybdenum is deposited first followed by copper based on their solubilities.

HYDROTHERMAL FLUID: A ***hydrothermal fluid*** is defined as a hot (50- >500°C), aqueous solution (hydro = water; thermal = hot). Precipitation from aqueous fluid has one of the most important mechanisms of ore formation. The principle ingredient of hydrothermal solutions is water. Pure water, however, can not dissolve metals. Hydrothermal solutions are always brines, containing dissolved salts such as NaCl, KCl, $CaSO_4$ and $CaCl_2$. The range in salinity varies from that of seawater (around 3.5 wt %) to about ten times the salinity of seawater. Such brines are capable of dissolving small amounts of elements such as Au, Ag, Cu, Pb and Zn. High temperatures increase the effectiveness of the brines to dissolve metals. These elements are deposited to form the mineral deposits and gangue minerals in response to a change in the solution, very often a sharp decrease in temperature. An example of this process would be if you dissolved as much table salt as possible in boiling water.

ORIGIN OF HYDROTHERMAL SOLUTIONS:

The waters of hydrothermal solutions can be derived from magmatic sources, meteoric (ground water) sources and seawater. Some hydrothermal solutions may also be produced by regional metamorphism. During wet partial melting, the water that causes the melting is released when the magma solidifies. This water carries with it soluble constituents such as NaCl, as well as elements such as Au, Ag, Cu, Pb, Zn, Hg, and Mo that do not easily enter into the common minerals (e.g. quartz, feldspar) by ionic substitution. Meteoric and seawater can also form hydrothermal solutions if they are heated sufficiently and a convection system is generated. The source of this heat is magmatic intrusions, so magma is a key ingredient in the generation of hydrothermal mineral deposits. Hydrothermal mineral deposits are thus associated with convergent and divergent plate boundaries.

ROLE OF WATER:

a. Water depolymerizes the melt and reduces its viscosity (breaks oxygen bridges).
b. Water transports elements.
c. Water increases diffusion rate.
d. Water decreases crystallization temperatures.
e. Water exsolves and expands in the magma, causing explosive subvolcanism.

FLUID CONSTITUENTS: In addition to water, other volatile constituents that may be present in the magmas include H_2S, CO_2, SO_2, HCL, B, F, H_2.

METAL SOURCE FOR HYDROTHERMAL ORE DEPOSITS:

1. Magmas from which the hydrothermal fluid separates. Magmas contained dissolved water. As a magma cools and begins to crystallize, the water in the magma can become oversaturated and separate into a separate aqueous fluid phase. Metals that were

originally in the magma preferentially concentrate in this separated hydrothermal or aqueous fluid phase.

2. Rocks that have been in contact with a hydrothermal fluid. Hydrothermal fluids are capable of altering wall-rock that they permeate. During this process, metals in minerals can be leached and dissolved by the hydrothermal fluid phase.

TRANSPORT AND DEPOSITION OF METALS FROM HYDROTHERMAL FLUIDS.

Hot brines can hold in solution greater concentrations of metals than cold brines. As a hydrothermal solution moves upwards, it cools and the dissolved minerals precipitate out of solution. For a hot aqueous fluid to transport a metal, it must be "somewhat" soluble as a metal ion or metal complex. Relative to shallow crustal or surface conditions, metal ion or complex solubility general increases with the following:

1. Increased temperature (T).
2. Increased pressure (P).
3. Changes in the composition of the aqueous fluid, e.g. increased salinity will stabilize some metal-chloride complexes.
4. Increased acidity (pH). Many metals are more soluble in acidic fluids.
5. Change the effective oxygen or sulfur "pressure" (fugacity) of the fluid. An example: Decreased oxygen fugacity will increase the solubility of iron.

To be effective in generating sufficient mineralization to form ore bodies, the process must be continuous over a large period of time, so a convection cell is required to maintain a constant precipitation.

If the upward movement of the hydrothermal solution is slow, the precipitation of the minerals would be spread over a wide area and may not be sufficiently concentrated to form an ore body. Sudden cooling, caused by rapid movement of the fluid into porous layers such as volcanic tephra or into open fractures such as veins and brecciated rocks, leads to rapid cooling and the rapid precipitation of minerals over a limited region.

Boiling, rapid pressure decrease, reactions with adjacent rock types, and mixing with seawater can also cause rapid precipitation and the concentration of mineral deposits.

Minerals precipitate from hydrothermal fluids when they become oversaturated. Saturation is achieved by changes in pressure, temperature or composition of the hydrothermal fluid. If the solubility of the metal decreases abruptly, then the metal will precipitate as a metal-bearing mineral in sufficient concentration to form a mineral deposit or an ore deposit. Factors that can abruptly decrease metal solubility include:

1. Pressure decrease can trigger mineral precipitation from fluid.
    a. Fluid overpressure exceeds rock strength; fracturing occurs.
    b. Boiling of the fluid.
    c. Seismic activity.
    d. System changes from lithostatic (rock mass) to hydrostatic (water mass) pressure.
2. Temperature decrease can trigger mineral precipitation from fluid.
    a. Natural cooling of the system near the surface.
    b. Mixing of fluid with groundwater or seawater.
3. A change in fluid composition can trigger mineral precipitation.
    a. Boiling of the fluid as it approaches the surface (ions partition between gas and fluid phase).
    b. Reaction of the fluid with wall-rock (the fluid partially dissolves the wall-rock which changes the composition of the fluid).
    c. Mixing of fluid with groundwater or seawater.
    d. Precipitation of minerals from the fluid.

Hydrothermal solutions in the Red Sea:

In 1964, oceanographers discovered a series of hot, dense brines at the bottom of the Red Sea. The higher density of the brines (i.e. increased salinity) means that they remain at the bottom of the sea, despite being hot. The sediments at the bottom of these pools contain ore minerals such as chalcopyrite, sphalerite and galena. The Red Sea is a stratabound mineral deposit in the making.

PORPHYRY DEPOSITS

Definition: The term porphyry deposits means mineral deposits with widely dispersed metal mineralization (copper or molybdenum) in intermediate to felsic porphyritic rocks (coarse-grained crystals and half fine-grained crystals and/or glass that commonly is present in igneous rocks that have been intruded to shallow levels in the crust). The term also refers to large, relatively low-grade, epigenetic (metals deposited in pre-existing rocks), intrusion-related copper or molybdenum deposits mined using bulk-mining techniques. Porphyry copper deposits provide more than 50% of the worlds copper from over 100 producing mines. Their close relatives the porphyry molybdenum deposits produce 70% of the world's molybdenum.

PORPHYRY TYPES:

(i) Cu (-Au) (ii) Mo (-W) (iii) Cu-Mo

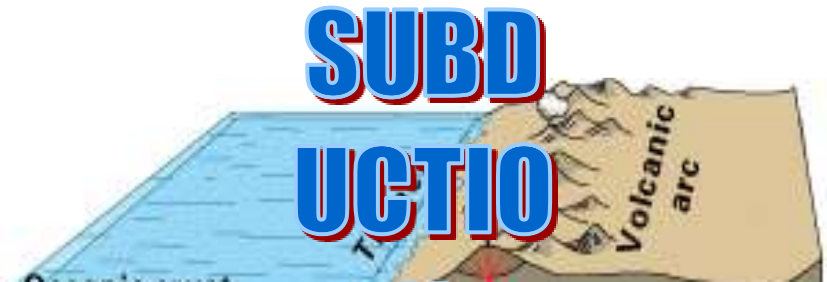
The major products from porphyry copper deposits are copper and molybdenum or copper and gold. Geologically, the deposits occur close to or in granitic intrusive rocks that are porphyritic in texture. There are usually several episodes of intrusive activity, so expect swarms of dykes and intrusive breccias. The country rocks can be any kind of rock, and often there are wide zones of closely fractured and altered rock surrounding the intrusions.

CHARACTERISTICS OF PORPHYRY DEPOSITS:

a. Mined metals: Copper (Cu), Molybdenum (Mo) and/or gold (Au).
b. Spatially and genetically related to porphyry intrusions.
c. Mineralizing intrusion is emplaced at shallow levels (less than 4 km).
d. Intrusions range in composition from intermediate to felsic.
e. Any rock type that the intrusion intrudes can host the mineralization.
f. Intrusions and surrounding rocks are intensely fractured.
g. Epigenetic large-scale ore deposit.
h. Low-grade (0.8 to 2.5% copper and 0.25% MoS_2 (= 0.15% Mo). Common by-products are Cu, Mo, Au, Ag, Sn, and W.

DISTRIBUTION AND AGE OF PORPHYRY DEPOSITS:

Porphyry-type deposits occur mainly along linear volcano-plutonic arcs related to subduction process (Figs. 9 and 10). Porphyry copper provinces seem to coincide, worldwide, with orogenic belts. This remarkable association is clearest in Circum-Pacific Mesozoic to Cenozoic deposits but is also apparent in North American, Australian and Soviet Paleozoic deposits within the orogenic belts. Porphyry deposits occur in two main settings within the orogenic belts; in **island arcs** and at **continental margins**. Deposits of Cenozoic and, to a lesser extent, Mesozoic age predominate. Those of Paleozoic porphyries are uncommon and only a few Precambrian deposits with characteristics similar to porphyry coppers have been described. Most porphyry copper deposits are Mesozoic to Cenozoic age and occur in association with volcanic mountain chains at or near destructive plate margins. Erosion removes older deposits.



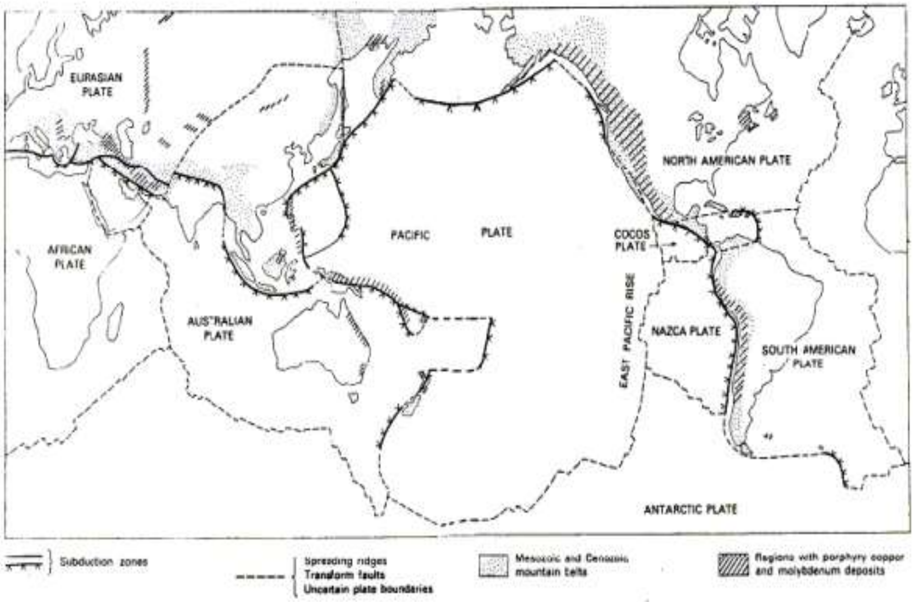


Figure 10. Porphyry copper deposits

GENESIS OF PORPHYRY DEPOSITS

Typical porphyry copper deposits are cylindrical, stock-like composite masses having elongate outcrops 1.5 x 2 km in diameter with an outer shell of medium to coarse grained equigranular rock and a core of similar composition that is porphyritic. They are subvolcanic (5-1 km below the surface).

Upon cooling at shallow depths, fine grain minerals crystallize around older coarse minerals (phenocrysts) to form porphyritic texture. With more crystallization, the volume increases and then the internal pressure increases. At a later stage, solidified shell (carapace) is formed around the porphyry due to rapid cooling, which prevents volatiles from escaping the magma to the wallrock. So that the internal vapor pressure increases and forms confined pressure that increase with cooling until it exceeds the lithostatic pressure (weight of the rocks), resulting in fracturing and brecciation of the carapace and the wallrock surrounding the porphyry (Fig. 11). This process (crystallization, increasing volatiles, explosion, fracturing, and brecciation) can be repeated several times to form stockwork veins and breccia pipes above the stock. Molybdenum is deposited first followed by copper based on their solubilities.

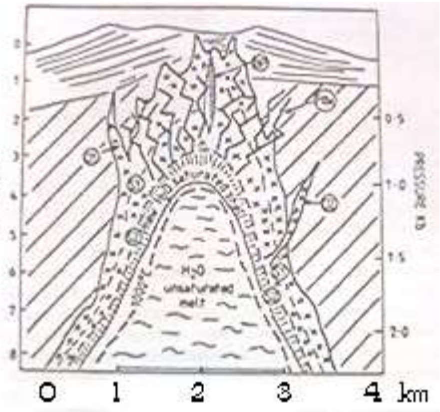


Figure 11. Formation of porphyry.

ALTERATION: Alteration is a change in the mineralogy of the country rock as a result of a chemical reaction with hydrothermal solutions. For example, mafic minerals such as hornblende or biotite may alter to chlorite and feldspars may alter to clay. An alteration zone describes rocks which have been altered to a specific group of secondary or alteration minerals. Strong 4 alteration zones develop in and around the mineralizing intrusion (Fig. 12) that contains abundant felsic minerals (quartz, plagioclase and K-spar), lesser mafic minerals (hornblende, biotite or both), and minor oxide minerals (magnetite, ilmenite):

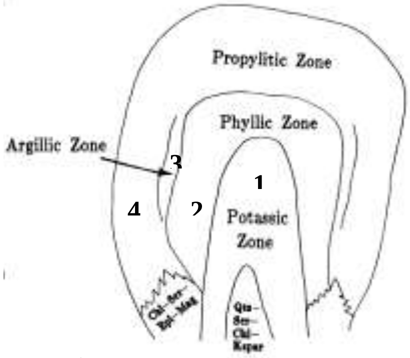


Figure 12

Hydrothermal Alteration Zoning Patterns for the Lowell–Guilbert Model of Porphyry Copper Deposit.

1. **Potassic alteration**: This is the hottest zone and is most commonly the zone that contains primary copper ore. As the name implies, minerals that contain potassium are stable (secondary K-feldspar, biotite). Other typical minerals include intermediate plagioclase and anhydrite.

2. **Phyllic or sericitic** alteration (sericite is a fine-grained white mica similar to muscovite). Moderately intense alteration zone. This zone is largely quartz, sericite and pyrite. All other minerals have been altered to these three minerals.
3. **Argillic alteration** (argillic refers to clay or clay minerals). Transitional between propylitic and sericitic alteration zones. This is the zone of alteration of feldspars (plagioclase and K-spar) to clay minerals (kaolinite) and chlorite.
4. **Propylitic alteration**. Weakest alteration zone. Quartz and K-feldspar are stable. Plagioclase and mafic minerals are altered to "green" minerals (chlorite, epidote, carbonate minerals and clay minerals).

MINERALIZATION: Original sulfide minerals in these deposits are pyrite, chalcopyrite, bornite and molybdenite. Gold is often in native found as tiny blobs along borders of sulfide crystals.

HYDROTHERMAL ORE DEPOSITS II

EPITHERMAL VEINS AND BRECCIAS

GENESIS OF EPITHERMAL DEPOSITS

Epithermal: As hot (hydrothermal) fluids rise towards the surface from cooling intrusive rocks (magma charged with water, various acids, and metals in small amounts) through fractures, faults, brecciated rocks, porous layers and other channels (i.e. like a plumbing system), they cool or react chemically with the country rock. Some form ore deposits if the fluids are directed through a structure where the temperature, pressure and other chemical conditions are favorable for the precipitation and deposition of ore minerals. The fluids also react with the rocks they are passing through to produce an alteration zone with distinctive, new minerals.

The presence of intrusive rocks and alteration associated with them provide important guides to prospecting ground for seasoned prospectors. Deposits are often controlled by the physical characteristics of the country rocks. The igneous rocks and quartzites fracture readily while the "softer" rocks do not tend to hold open spaces.

A. EPITHERMAL DEPOSITS

Epithermal deposits are products of magma-related hydrothermal activity at shallow depths (within 1 to 2 km) and low temperatures (100-300°C). Most deposits are in the form of siliceous (quartz) vein fillings and dissemination. Open space fillings are common and include vugs and drusy cavities.

TYPES OF EPITHERMAL VEINS:

Epithermal vein deposits include most gold mines, many large silver mines and a few copper and lead-zinc mines. Veins commonly consist of quartz usually occurring as interlocking crystals in a variety of sizes or as finely laminated bands parallel to the walls of the vein. Minor amounts of sulfide minerals and other gangue minerals such as calcite and various clay minerals often occur; gold is rarely visible. Veins range in thickness from a few centimeters to 4 m, the average mining width being around 1.2 m. Grades of gold historically have been in the 13.7 to 17.1 g/t range with cut-off around 8.6 g/t. Gold may be associated with pyrrhotite, arsenopyrite, pyrite, chalcopyrite and with minor sulphides - the classic 'free gold'. Silver is commonly associated with galena and galena-sphalerite, tetrahedrite or other copper minerals, antimony or copper-arsenic sulphides and chalcopyrite. Many more recently developed deposits have larger tonnages and lower grades and can be mined economically. If a vein system occurs near the surface it may be possible to mine by open pit methods that would greatly reduce mining costs. As the hydrothermal solution mixes with meteoric water, it cools faster and the result is changing the chemical condition. Elements and minerals are deposited in different zones (Fig. 13) depending on physical (temperature, pressure, …) and chemical (pH, solubility, chemical composition, …) conditions.

1. **Base metal veins:** Base metal veins form close to the porphyry at relatively high temperature (300°C). They contain copper, zinc and lead.
2. **Bonanza silver veins:** Bonanza silver veins contain mainly silver.
3. **High level veins:** High level veins contain mainly mercury (Hg) and antimony (Sb).
4. **Hot springs:** Hot springs are usually surrounded by silica-rich deposits known as **sinter** or carbonate-rich deposits known as **travertine**.

TYPES OF EPITHERMAL FLUIDS:

Epithermal gold mineralization can be formed from two types of chemically distinct fluids Ä "low sulfidation" (LS) fluids, which are reduced and have a near-neutral pH (the measure of the concentration of hydrogen ions) and "high sulfidation" (HS) fluids, which are more oxidized and acidic.

1. **Low sulfidation fluid type (LS):** LS fluids are a mixture of rainwater that has percolated into the subsurface and magmatic water (derived from a molten rock source deeper in the earth) that has risen toward the surface. Gold is carried in solution and, for LS waters, is deposited when the water approaches the surface and boils.

2. High sulfidation fluid type (HS): HS fluids are mainly derived from a magmatic source and deposit gold near the surface when the solution cools or is diluted by mixing with rainwater. The gold in solution may come either directly from the magma source or it may be leached out of the host volcanic rocks as the fluids travel through them.

CHARACTERISTICS OF EPITHERMAL DEPOSITS

a. Near-surface deposits range between 100 and 1,000 m vertically.
b. Veins and veinlets host ore.
c. Deposits are commonly found in extensional tectonic settings.
d. Ore is commonly deposited as open-space filling.
e. Gold (Au) and silver (Ag) are the main economic metals with abundances of mercury (Hg), arsenic (As), antimony (Sn) and tellurium (Te).
f. Common gangue minerals are quartz, calcite, fluorite, barite, pyrite.
g. Zoning of hydrothermal alteration is generally from silicification in the core outward through illite-sericite or clay mineral alteration to propylitic alteration.
h. Grade and tonnage vary from small, high-grade to large, low-grade.

B. HYDROTHERMAL BRECCIA: Breccias are usually associated with porphyries. Such breccia bodies are referred to as ***breccia pipes*** because of their cylindrical morphology. Generally, breccias contain Molybdenite, gold, fluorite and copper.

RELATIONSHIP BETWEEN PORPHYRY, EPITHERMAL AND SUBDUCTION:

A close genetic relationship has been proved between subduction, porphyry and epithermal deposits. When an oceanic and continental plate converge, the denser oceanic plate is subducted under the continental plate. As the cold, wet, and slightly denser oceanic plate descends into the hot upper mantle (asthenosphere), melting occurs and a new magma is generated. This magma rises toward the earth's surface. If it stops below the surface (within few kilometers) it will form *porphyry*. It can extrude at the surface to form volcanoes (*volcanic arc*). As the magma forming porphyries cools, it precipitates and concentrates various metallic ores (Cu, Mo). At a late stage of cooling of the porphyries, the residual fluid enriched in water, silica, gases and valuable elements (Au, Ag, Pb, Hg, …) is channeled through fracture systems within the higher portion of the porphyry and/or within the surrounding wall rock and forms quartz veins.

EXPLORATION GUIDES FOR PORPHYRY AND EPITHERMAL DEPOSITS:

1. A suitable fracture or plumbing system must be identified, i.e. tectonic terrain.
2. Dykes and granitic rocks with porphyritic textures
3. Breccia zones with sulfides among fragments.
4. Quartz veins with sulfides
5. Alteration zones: A zone of high silica + clays + pyrite may indicate a vein system at depth, i.e. represents a good; drill target.
6. Trace element geochemistry provides pathfinders to mineralization, especially arsenic, antimony, mercury, thallium and selenium.

METAMORPHIC ORE DEPOSITS

Metamorphic processes may lead to the formation of new mineral deposits or they may modify pre-existing deposits. Fluids generated during metamorphism appear to have contributed to the formation of some vein-type hydrothermal deposits. The processes of metamorphism give rise to some of the World's major deposits of tungsten, some important copper occurrences, Molybdenum (Mo), lead (Pb), tin (Sn), zinc (Zn), and precious metals. Metamorphic industrial minerals or rocks include graphite, garnet, kyanite, sillimnite, asbestos, talc, mica and gems. Most of gold deposits in Egypt are related to metamorphism.
Metasomatism: Where the mineralogical and chemical changes occur in rocks because of interaction with fluids from an external source, the process is called ***metasomatism***. It leads to the formation of ore deposit type known as "**skarn**".

SKARNS

Skarn refers to a specific rock that contains calc-silicate minerals, commonly garnet and pyroxene, that formed by reaction of fluids with existing minerals. Commonly, economic skarn forms when a significant volume of hydrothermal fluid derived from a magma encounters and reacts with carbonate rocks. There are many definitions and usages of the word "skarn". Skarns can form during contact metamorphism and from a variety of metasomatic processes involving fluids of magmatic, metamorphic, meteoric, and/or marine origin. They are found adjacent to plutons, along faults and major shear zones, in shallow geothermal systems, on the bottom of the seafloor, and at lower crustal depths in deeply buried metamorphic terrains. The term ***sharn*** has been used to include a variety of calc-silicate rocks rich in calcium (Ca), iron (Fe), magnesium (Mg), aluminum (Al) and manganese (Mn) that formed by replacement of originally carbonate-rich rocks.

Distribution: Skarns occur on all continents, but are restricted in both age and petrology of the host. No skarn deposits older than Paleozoic have been mined, and nearly all are of Mesozoic age. This has implications about the depth of emplacement of the typical skarn deposit. Further, skarn deposits occur only in felsic rocks, indicating magmatic water must be an important and necessary constituent of the ore-forming process.

Form: Skarn deposits have very irregular shapes, the irregularity a consequence of the erratic replacements of the host rocks. The ability to replace host rocks is a function of their permeability and porosity as well as bulk chemistry and lithology. Most skarn ore bodies are small, rarely producing more than 10 million tons. Some giants have produced 60 million tons, but they are dwarfed in tonnage by the porphyry systems that often lie in close proximity.

Setting : Most minable skarn deposits occur in carbonate rocks, since carbonates are the most easily replaced and/or metamorphosed. However, some skarns in sandstones and shales have been productive. The new mineral assemblages that form during the metasomatic process are indicative of the addition of **Fe, Mg. Ca, Mn and Si,** the latter probably the most important. Due to this process a new suite of rocks is formed termed calc-silicates.

Genesis: Although the actual mineralogy of skarns and the zoning of the deposits can be quite complex, the genetic model is rather straightforward. Emplacement of a water-rich pluton results in contact metasomatism of the surrounding rocks. As the fluids cool, metals replace the calc-silicate assemblages. Perhaps the only remaining question is the exact point in time when the minerals are precipitated. Some evidence seems to suggest they are deposited after a period of dehydration followed by rehydration that would seem to imply a much larger role for meteoric fluids than stable isotopes indicate.

CLASSIFICATION OF SKARNS:

Skarns can be subdivided according to several criteria.

1. Based on the replaced rocks: Exoskarn and endoskarn are common terms used to indicate a sedimentary or igneous protolith, respectively (Fig. 14).
    a. **Exoskarns**: Altered rock that was originally part of the surrounding carbonate rock:
        i. Magnesian skarn: skarn that replaces dolomite.
        ii. Calcic skarn: skarn that replaces limestone.
    b. **Endoskarns:** Altered rocks that were originally part of a pluton (intrusive rocks).

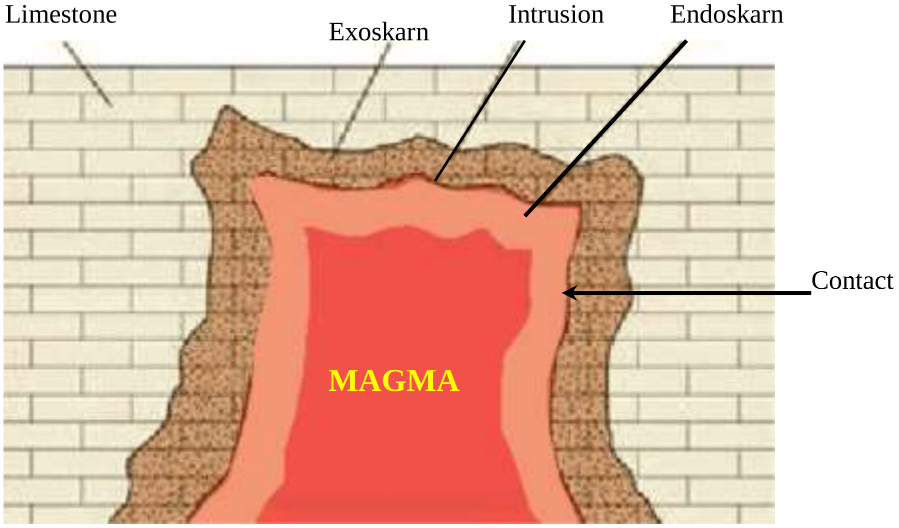


Figure 14. Skarn

2. Skarns are best classified by the dominant economic metal to Au, Cu, Fe, Mo, Sn, W, and Zn-Pb skarn deposits. Different igneous intrusions tend to put different metals into a skarn.
   a. **Gold Skarns:** Most gold skarns are associated with relatively mafic diorite - granodiorite plutons and dyke/sill complexes. Some large Fe or Cu skarns have Au in the distal zones.
   b. **Tungsten Skarns:** These are found in association with calc-alkaline plutons in major orogenic belts. They are associated with coarse grained, equigranular batholiths (with pegmatite and aplite dykes), surrounded by high temperature metamorphic aureoles. This is indicative of a deep environment.
   c. **Copper Skarns:** These are the world's most abundant type and are particularly common in orogenic zones related to subduction both in continental and oceanic settings. Most are associated with porphyritic plutons with co-genetic volcanic rocks, stockwork veining, brittle fracturing, brecciation and intense hydrothermal alteration. These features are all indicative of a relatively shallow environment. The largest copper skarns can exceed 1 billion tones and are associated with porphyry copper deposits.
   d. **Zinc Skarns** Most occur in continental settings associated either with subduction or rifting. They are also mined for lead and silver, and are high grade. They form in the distal zone to associated igneous rocks.

e. **Molybdenum Skarns** Most are associated with leucocratic (lacking ferromagnesian minerals) granites and form high grade, small deposits. other metals are also commonly associated, the most common being Mo-W-Cu skarns.

f. **Tin Skarns:** These are almost exclusively associated with high silica granites generated by partial melting of continental crust. Greisen alteration by fluorine produces a characteristic yellowish mica.

g. There are many other types of skarn. Some of the more interesting include rare earth elements and uranium. Another skarn type is related to metasomatism in regional metamorphic environments.

Variations in skarn types results from:

a. Differences in associated igneous rock types/tectonic environments.

b. Different depths of formation of the skarn.

c. Different oxidation states of the magma.

d. Different composition and petrology of the invaded wall-rock.

GENERAL CHARACTERISTICS OF SKARNS:

1. ***Distribution in space and time:*** Largely restricted to Phanerozoic age rocks.
2. ***Grade***: WO_3 0.4 to >1%, Sn 0.1 to 0.7%, Zn up to 12%
3. ***Tectonic setting***: Most associated with porphyry-type intrusives and mineralization.
4. ***Host rock***: Mostly calcareous rocks
5. Form at shallow depth in a range of temperatures from 350 to 800°C.
6. ***Mineralogy***: Mined for Magnetite (Fe), scheelite (W), chalcopyrite (Cu), cassiterite (Sn), sphalerite (Zn) and galena (Pb).
7. The main gangue minerals in the exoskarns are: garnets, pyroxenes and amphiboles.

Some economic rocks:

Quartzite: A metamorphic rock composed principally of quartz grains. It is derived by metamorphism of a quartz sandstone or chert.

Marble: A metamorphic rock derived from limestone or dolomite and often associated with Skarns.

An example of metamorphic deposits in Africa:

1. Rössing Uranium Deposits, Namibia

Figure 15. Rössing mine, Namibia

Rössing is situated 70 km northeast of the Namibian town of Swakopmund, where uranium oxide is extracted from the world's largest open cast uranium mine, for the generation of electricity across the globe. The Rössing uranium deposit occurs in a migmatite zone in metamorphosed country rocks that comprises deformed metasedimentary rocks of quartzo-feldspathic lenses to large intrusive and replacement bodies varying widely in texture, size and emplacement habit. Contact metamorphic effects are evident in metasedimentary rocks adjoining the alaskitic intrusives. The most marked effects are evident where the pegmatites have invaded the marbles of the Rössing Formation. Skarn bodies, ranging in size from a few centimeters to several meters are widespread, the majority being composed of coarse aggregates of pale green pyroxene and garnet.

The Rössing deposit is in the Damaran metamorphic belt, which is composed of 1,000 million-year-old Late Precambrian sedimentary and volcanic rocks that were intensely deformed and metamorphosed during the Damaran orogenic event 510 Ma. They contain quartzite, gneisse and marble.

The Rössing deposit, with reserves of 390 million tons of ore averaging only about 0.035% U_3U_8, occurs along the southern flank of a domal structure. Uraninite (UO_2), the dominant primary mineral, occurs as grains ranging in size from a few microns to 0.3 mm, with the majority in the 0.05 to 0.1 mm fraction Approximately 40% of the uranium and most of the economic ore occur as secondary U minerals formed by oxidation and supergene enrichment.

SEDIMENTARY MINERAL DEPOSITS

Sedimentary Mineral Deposits are the substances that are concentrated by chemical precipitation from lake or seawater. Although clastic sedimentary processes can form mineral deposits, the term sedimentary mineral deposit is restricted to chemical sedimentation, where minerals containing valuable substances are precipitated directly out of water.

Weathering is the disintegration and decomposition of rock at the earth's surface (in situ change in character). In contrast, ***erosion*** is the process where rock material is removed from one location to another by water, wind or ice. Disintegration and decomposition are the basis of the two modes of weathering, ***mechanical*** and ***chemical weathering***.

A. Mechanical weathering:

It is the physical breakdown of rocks into smaller fragments without changing in rock composition.

Agents of mechanical weathering:

1. Frost (wedging and heaving).
2. Unloading (pressure release).
3. Heat: (Thermal expansion and contraction due temperature changes.
4. Salt crystal growth.
5. Organic activity (plants and animals).

B. Chemical weathering:

It involves rock decomposition; air and water bring about chemical reactions that turn the rocks and minerals into new ones.

Processes of chemical weathering:

1. ***Solution***: solubility of minerals by liquid (water).
2. ***Oxidation***: reaction of mineral with oxygen to form oxides.
   $4Fe + 3O_2 = 2Fe_2 O_3$ (hematite)
3. ***Hydrolysis***: water dissociation into H^+ and OH^- ions, and H^+ replaces K, Na, Ca, and Mg ions to form clay minerals.
4. ***Carbonation:*** $CO_2 + H_2O = H_2CO_3$

$$H_2CO_3 + CaCO_3 = Ca^{+2} + 2HCO_3^-$$

Rate of Weathering depends mainly on:

1. ***Mineral composition and Stability***: Most stable minerals are the bottom of Bowen's Reaction Series (lower temperature). Example: quartz versus olivine. Mineral solubility in water (quartz is less soluble than halite or calcite).
2. ***Structure***: Fractures, cracks and foliation increase weathering rates.
3. ***Climate***: Temperature and rainfall (the more water at higher temperatures the faster the weathering).

4. ***Topography*** controls the amount of rock exposed to the agents of weathering. High elevated areas show faster weathering due to increasing of wind speed.
5. ***Plant and Animal Life*** can physically break up rock material underneath but plants protect the soil and slow the surface weathering.

I <u>EVAPORITE DEPOSITS</u>:

Evaporation of lake water or sea water results in the loss of water and thus concentrates dissolved substances in the remaining water. When the water becomes saturated in such dissolved substance they precipitate from the water. Deposits of ***halite*** (NaCl, table salt), ***gypsum*** ($CaSO_4.2H_2O$) has a hardness of 2 and specific gravity of 2.3. (used in plaster and wall board), ***borax*** ($Na_2B_4O_5\ (OH)_4.8H_2O$) used in soap, and ***potash*** (***sylvite***, potassium chloride), from which potassium is extracted to use in fertilizers. Halite occurs naturally in many parts of the world as the mineral halite and as mixed evaporites in salt lakes. Seawater contains an average of 3.5% (by weight) NaCl. Underground salt deposits are found in both sedimentary and domal deposits.

II <u>IRON ORE DEPOSITS IN EGYPT</u>:

The main iron ore deposit in Egypt is located in Bahariya Oasis, Western Desert. The ore is hosted by sedimentary rocks that invaded by hydrothermal solutions that deposited iron.

Genesis: The ore is epigenetic, of fresh groundwater origin, and formed in two different stages. First, during dry climatic conditions, the iron has been oxidized and leached from the sandstone of the Nubian Aquifer by upward-moving hydrothermal solutions (hot groundwater) and deposited in the overlying pre-existing Lower-Middle Eocene karstic limestone. Second, during wet pluvial periods, the iron has been leached from the glauconitic clayey beds and infiltrated downwards and deposited on the underlying primary ore. During the two stages, initial structures, variations in pH–Eh, and biological activities were the main factors controlling the deposition and characters of the ore. The iron ores in northern Bahariya are confined to the lower part of the Middle Eocene limestone (50 Ma). Structurally, the Bahariya depression is considered to be a major doubly plunging anticline with a NE–SW trend. The ore consists mainly of hematite, goethite, and pyrolusite with gangue minerals barite, kaolinite, glauconite, quartz and alunite. The iron content ranges from 28% to 55% with an average of 47.6% Fe in great reserves (270 million metric tons) of iron ore deposits.

III **PHOSPHATE DEPOSITS**:

Phosphate rock is a general term referring to rock with high concentrations of phosphate minerals, most commonly those of the apatite family with the general formula $Ca_5(PO_4,CO_3)3(F,OH,Cl)$. About 90% of phosphate mined is used to produce chemical fertilizers. Commercial deposits require relatively low alumina, iron, calcium, fluorine, chlorine, pyrite, and magnesium, and should be grindable and chemically reactive.

Phosphate deposits can be classified into three types:

1. ***Marine sedimentary phosphorites****,* where the phosphorus was chemically and biologically precipitated as apatite group minerals in regions of reducing condition of upwelling cold, nutrient rich, and shallow marine water. It forms 76% of world phosphate. The commercial phosphate rock should contain at least 20% P_2O_5. e.g. Phosphates in North Africa.
1. ***Igneous phosphate***, where the phosphorus (apatite) is a primary component of alkali carbonatite complexes eg. Palabora, South Africa. This type forms 23% of world phosphate.
2. ***Island phosphate*** (***guano accumulations)***: Island phosphates, where phosphorus is concentrated up the food chain and excreted as guano on tropical islands. Guano deposits of bird excrements originate from an interaction with underlying limestone. This type of phosphate forms 1% of world phosphates. Minor amount of guano occurs in some coastal cavities of Mozambique.

IV. **SEDIMENT-HOSTED DEPOSITS**:

Sediment-hosted copper deposits account for 27% of the world's copper reserve. They are mainly hosted by sandstone and calcareous shales.

Zambian Copper Belt: Copper belt of Katanga (Shaba) Province (Fig. 16) contains one of the greatest concentrations of high-grade copper and co-product cobalt resources in the world. Zambian Copper Belt occupies the southern part of the Lufilian arc that extends for 800 km into DR Congo and Angola with 100 km width. The major copper-cobalt bodies are hosted by sediments of the Katanga Supergroup (shale-quartzite). The ores of Zambia occur in 900-million-year-old younger Precambrian sedimentary rocks (shale, calcareous sulfide-rich) and quartzite. The primary ore minerals are chalcopyrite,

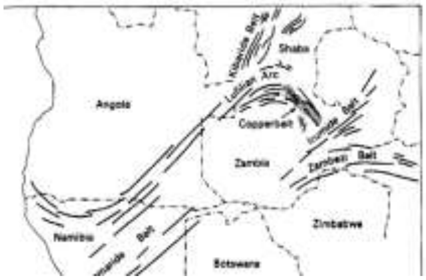


Figure 16. ***Zambian Copper Belt.***

bornite, and carrollite, which are often associated with pyrite. Secondary sulfides namely bornite and chalcocite are important below the zone of oxidation but tend to decrease down-dip. Cherty horizons are generally richest in copper and often contain uranium mineralization. Carrollite, the cobalt bearing sulfide is most commonly concentrated in the upper units of the ore horizon.

While the Central African Copper belt is best known for its strata bound Cu-Co deposits, a number of other ore deposit types are also significant: U-(Co-Co-Ni-Mo), Pb-Zn-(Cu-Ge-Ga), Cu-Au, massive barite, Cu-rich vermiculites and Au-PGE enrichments. The Ore Formation averages 30 m in thickness near the surface but thins to 20 m down dip and to as little as 6 m over granite basement highs. It is composed mainly of fine grained biotite-quartz argillite, with a basal zone that is strongly contorted, schistose, rich in carbonate and cut by quartz-dolomite-anhydrite veins. The grade of copper averages from 3 to 6% Cu from mine to mine, exceptionally to 15 or 20% Cu.

***Genesis*:**

Deposition from hydrothermal solutions derived from a lower granitic intrusion. Early theories on genesis of the stratiform Cu-Co ores focused on either the magmatic hydrothermal concept (relationship of the mineralization to 'younger granites'), the syngenetic concept or to diagenetic. However, in the 1980s, investigations began to reveal the similarity in mineralogy and fluid inclusions between the stratiform Cu-Co mineralization and the vein-type U deposits which occur in the same stratigraphic horizons, suggesting the role of metamorphic fluids as the mineralizing agent. While accepting the role of primary sedimentary and diagenetic parameters in ore localization, the relationship of the strata bound mineralization to Lufilian-age faults and folds has been noted.

V RESIDUAL MINERAL DEPOSITS:

Residual mineral deposits substances are concentrated by chemical weathering processes. During chemical weathering and original body of rock is greatly reduced in volume by the process of leaching, which removes ions from the original rock. Elements that are not leached form the rock thus occur in higher concentration in the ***residual rock***. The most important ore of Aluminum, bauxite, forms in tropical climates where high temperatures and high water throughput during chemical weathering produces highly leached lateritic soils rich in both iron and aluminum. Most bauxite deposits are relatively young because they form near the surface of the Earth and are easily removed by erosion acting over long periods of time.

A. ***A laterite*** is any strongly leached soil rich in iron, aluminum, nickel and related elements. Laterites - intense chemical weathering depletes the upper soil in silica and other soluble materials and instead concentrates iron and aluminum in the upper zones. They are common in the tropical areas - poor soils to cultivate because the minerals have all been washed out.

B. ***Bauxite*** ($Al_2O_3.H_2O$) is clay-like sediment composed mainly of alumina (~ 50% Al_2O_3) and iron oxide. Bauxite is a tropical or sub-tropical weathering product. A distinctive pisolitic texture (small equidimensional spheres) and common red-brown color distinguishes it from kaolin. It is the principle ore of aluminum. Bauxite, is an impure mixture of the aluminum oxide and hydroxide minerals gibbsite, boehmite and diaspore. Commercial grade bauxite contains more than 30% Al_2O_3. Impurities include silica, oxides and hydroxides of iron, and small amounts of titanium oxide. Bauxite is used mostly for the production of aluminum metal. Small amounts are processed for use as abrasives, refractories, and as chemicals in water treatment, antiperspirants, and as a leavening agent in bread.

Formation of bauxite: Bauxite forms by two essential chemical changes:

3. removal of silica, and 2. separation of Al from Fe.

African distribution of bauxite:

Tropical and subtropical environments (**Guinea**, **Ghana** and **Cameroon**)

Requirements: Bauxite and laterite deposits require:

1. Abundant rainfall to dissolve unwanted rock constituents.
2. High temperature to speed the dissolution reaction.
3. Sufficient high relief to drain away water.
4. Enough vegetation for mechanical weathering.
5. Sufficient length of time.

C. ***Kaolin (Kaolinite, $Al_2Si_2O_5(OH)_4$)*:** Kaolin is a sedimentary rock composed of white kaolinite clay. This aluminum-rich rock is an aluminum ore commonly used in ceramics, paints, paper, and other products. Large valuable deposits of kaolin tends to form in an acidic environment whereas bauxite tends to form in an alkaline environment. It is formed from the destruction of aluminum silicates, principally feldspars. The chemical weathering conditions that produce kaolin deposits are similar to those of bauxite. Kaolinization often occurs as an intermediate stage in the formation of laterite and bauxite. Kaolinite is a naturally occurring weathered product of granite valued for its whiteness, purity and physical and chemical properties. Crude Kaolin is a mixture of three main minerals: Kaolin, Quartz and Mica. This mixture is fed into a processing plant where the Kaolin is extracted and the waste mica and quartz returned to the quarry for backfilling. Kaolinite is widely distributed in nature. Pure deposits are mined for porcelain, both bathroom fixtures and fine China cups, and coatings on glossy paper. Most soils of the world contain kaolinite in the clay size fraction (<2µm). In weathered soils, such as tropical regions of Africa, kaolinite is usually the dominant clay mineral.

VI SUPERGENE (SECONDARY) ENRICHMENT:

Supergene enrichment is a process that causes metal enrichment during weathering of pre-existing hypogene sulfide body through local dissolution, transport and reprecipitation. It involves the release of ore metals from unstable sulfide minerals to downward percolating meteoric water and precipitation of more stable secondary oxide and sulfide minerals. A typical profile through a supergene mineral deposit consists of three zones from bottom to top (Fig. 17):

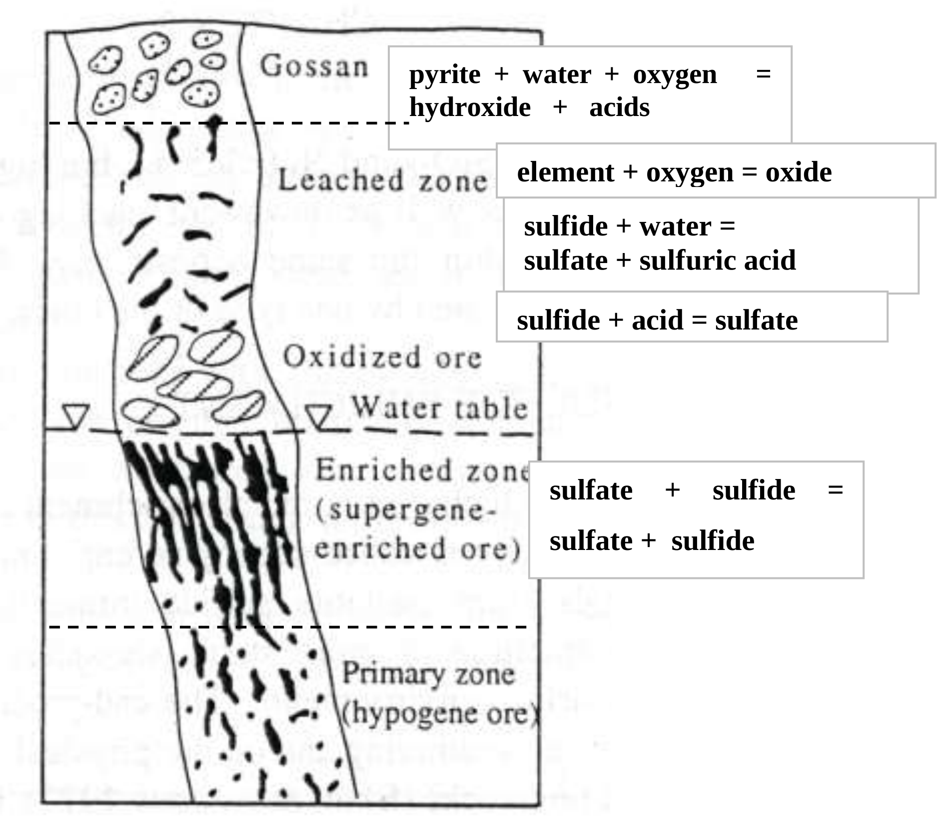


Figure 17. A typical profile through a supergene mineral deposit.

Hypogene zone or protore: Zone of metal-enrichment from "original" processes (e.g., zone of hydrothermal precipitation of Cu above porphyry).

Supergene enriched zone: Zone enriched by the precipitation of metals that were leached from the oxidized zone by groundwater, where the solution becomes more basic and reducing at and below the water table.

Oxidized zone (Leached zone): Zone that has been weathered and leached of many metals and ions that are soluble in oxidizing water above the water table. In many cases, the base of this zone is linked to the level of the water table at the time that weathering and enrichment occurred.

Gossan: Iron oxide-enriched zone at the surface that commonly caps the zone of leaching, commonly gossan is known as “iron hat”.

Chemical reactions involved in the development of oxidized zone, which is generally lies above the groundwater table, include oxidation of sulfide minerals that are unstable under oxidizing conditions, leaching of metals from hypogene sulfide minerals as soluble sulfate solutions, and precipitation of some of the metals as insoluble oxide, hydroxide, carbonate, and sulfide minerals that are stable under oxidizing conditions. The process starts with oxidation of pyrite, the most common hypogene sulfide mineral, to strong oxidizing solvents such as sulfuric acid and iron sulfate. The supergene alteration of sulfide ore body causes it to behave as a large electrochemical cell with electronic flow through the ore body and ionic flow through the surrounding groundwater system.

VII placer deposits:

The term "placer" is derived from the Spanish word for sand bank. Placer deposits, in the strictest sense, are formed in river systems, but the term is typically used to describe deposits formed in glacial and beach environments. Placer Mineral Deposits - substances are concentrated by flowing surface waters either in streams or along coastlines. When the velocity of the water slows, large minerals or minerals with a higher density are deposited. Most of the placer deposits being mined today are Cenozoic or younger and occur in unconsolidated materials. However, some ancient placers, or “***paleo-placers***”, are found in sedimentary rocks as old as Precambrian in age. In fact, some paleo-placers which are eroded become the source of present day placer deposits.

Mechanical concentration into placer deposits involves two stages:

(1) the *decomposition* or disintegration of the materials involved by chemical and mechanical weathering, and (2) their *concentration* by moving water or air. Concentration can occur

only if the valuable minerals possess the three properties: high specific gravity, chemical resistance to weathering, and durability (malleability, toughness, or hardness).

Placer minerals: The minerals concentrated in placers include two types:

(1) ***light minerals*** those with low to medium specific gravity. The most common mineral with low to medium specific gravity in placers is quartz (S.G. = 2.65).

(2) ***heavy minerals*** those with a medium to high specific gravity such as gold, platinum (S.G. = 19), cassiterite (S.G. = 7), magnetite (S.G. = 5), chromite, ilmenite, native copper, gemstones, monazite (S.G. = 5) and zircon (S.G. = 4.5).

Ages of placer deposits: All ages especially Tertiary and Quaternary.

Grade: Placer deposits have low grade but easy to produce (loose and open pit).

Classification of placer deposits: Depending on the type of the mechanical agencies, the placer deposits are classified into:

1. ***Alluvial placers*** (steam deposits, heavy minerals): Alluvial placers are those formed in present and past watercourses in gulches, creeks, rivers, flood plains and deltas. By far the most important type of placer is the ordinary alluvial gravel or stream placer.
2. ***Beach placers*** (marine): Concentrations of heavy minerals may occur in various places along the ocean and sea coasts as a result of the action of shore currents and waves, which tend to sort and distribute the materials broken down from the sea cliffs or washed into the sea by streams.
3. ***Eluvial placers*** - Also known as "***hillside*** placers." After minerals released from their original bedrock encasement through agents of rock decay and weathering, the whole weathered mass may "creep" down the hillside. The principal mechanism for the concentration of heavy minerals in eluvial placers is the winnowing action of ***gravity*** and downhill creep, the latter being essentially dependent on the angle of slope or gradient where the placers are formed on the sides of hills or mountains.
4. ***Offshore placers*** (continental shelf): Diamond deposits have been explored and mined offshore near the coastal town of Lüderitz, Namibia.
5. ***Aolian placers*** (wind): Eolian placers are localized concentrations formed by winds blowing away the fine material. Wind action is responsible for the removal of large amounts of fine detritus in the desert. The process involved has been called deflation. It is quite likely that it will be found to play an important part in the surface concentration of desert placers.
6. ***Lacustrine*** (lakes)

Witwatersrand, South Africa:

Witwatersrand is the world’s major source of gold (Archean gold) for the last century. Total production from the Witwatersrand gold fields exceeds 50,000 t of gold (50% of the global total). It is also one of the largest geochemical anomalies in the Earth’s crust, and with respect to its origin, the greatest debate in the history of economic geology.

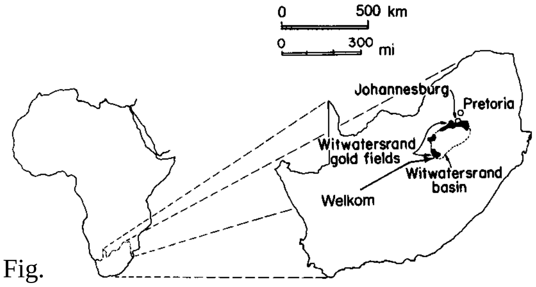


Fig.

Map of the Republic of South Africa showing the location of the Witwatersrand

Placer: Alluvial fans

Rocks: Conglomerate

Age: about 3 Ga.

Source: Archean granite,

Grade: 7 g/t gold

The gold and uranium are concentrated within numerous conglomerate units within the ancient basin. The Witwatersrand Basin is responsible for almost 40% of the world's gold resource and has therefore been very important for the economic development of South Africa. The Witwatersrand Basin is also the site of the world's deepest mine, the Western Deep Levels mine (~4,000m) in the Far West Rand goldfields, and the world's oldest and largest known impact crater, the Vredefort structure found at the centre of the basin.

Origin of Gold:

For more than a century since the discovery of the gold fields there has been continuous debate as to the nature of the gold mineralization in Witwatersrand Basin. The debate can be simplified to two end members: hydrothermal model or placer model.

1. Hydrothermal model: The hydrothermal replacement model infers that the gold has been introduced into the Witwatersrand basin in an aqueous solution after burial (with associated hydrothermal alteration), and gold migration on the scale of a few kilometers is implied. Evidences of hydrothermal are presence of secondary gold grain shapes, hydrothermal minerals and quartz veins.

2. Placer model: The placer model infers that the gold was transported into the Witwatersrand basin in detrital form and deposited in response to sedimentary sorting processes.

In favoring a modified placer model for Witwatersrand gold, he provided five main reasons against the hydrothermal introduction of gold: (1) no fluid channelways; (2) gold is insoluble; (3) no mineralogical zoning; (4) no alteration; and (5) gold is closely linked to sedimentology. Re-Os dating has suggested that gold in the Witwatersrand gold fields has an age of 3.01 Ga, which would make the gold grains older than the enclosing strata, and hence, placer in origin.

Geology of the Witwatersrand Basin:

The Witwatersrand Basin lies within Kaapvaal Craton of southern Africa. The craton formed 3.7-2.7 Ga, evolving from processes such as continental magmatic activity, the accretion of composite terrains and the formation of sedimentary basins such as the Archean Witwatersrand Basin. The Kaapvaal Craton and the Zimbabwe Craton collided approximately 3 billion years ago, forming the Limpopo Mobile Belt comprised of high-grade metamorphic rocks. The greenstone belts of the cratonic basement complex, such as the Murchison Belt to the north-east and the Amalia Belt to the west, contain regions of carbonate-gold veins and potassic granites with accessory uraninite. The greenstone belts may represent a source of the heavy minerals found in the Witwatersrand Basin.

The Witwatersrand Basin lies unconformably on the Archean cratonic basement. The basal sequence, the Dominion Group, is a sequence of thin conglomerates and thick lava flows containing only one known gold bearing zone and a uranium-rich strata. The sequence was deposited approximately 3.0 - 2.7 Ga in what is believed to be an intra-continental rift-basin associated with bimodal volcanism. The sequence now covers 15,000km^2 and is approximately 2,710 meters in depth.

After a hiatus of 100 million years, the Witwatersrand Supergroup was deposited. The Supergroup is divided into two units, the lower West Rand Group and the upper Central Rand Group. The West Rand Group was deposited at approximately 3 Ga and consists of shales, quartzites, grits and conglomerates and only one gold-rich conglomerate bed. In contrast, the Central Rand Group, deposited from approximately 3 Ga, consists of quartzites (90%), grits and shale and most importantly, numerous gold-bearing conglomerate horizons. The deposition of the Witwatersrand Supergroup ceased during the onset of an extensional regime and the extrusion of the Ventersdorp Supergroup lavas at 2.7 Ga. The Ventersdorp Supergroup is characterized by minor rift-related bimodal volcanism and interbedded coarse grained, poorly sorted alluvial fan deposits. Folding and thrusting, followed by erosion and subsidence over the entire Kaapvaal Craton occurred prior to the deposition of the Transvaal Supergroup. The deposition of the Transvaal Supergroup at 2.2 Ga, of clastic and dolomitic limestone, was followed by igneous activity related to the emplacement of the Bushveld Complex. Eventually, the Witwatersrand Basin was partially buried by the Karoo Supergroup of shallow marine, aeolian, fluvial and glacial sediments, which were deposited by the end of the Paleozoic.

***General Mine Geology*:** The unusual gold reefs of the Witwatersrand Basin are dip at 20-25° towards the centre of the basin and are found to persist over 10-100 km^2, maintaining consistent gold grades (15 grams per tone) and reef mineralogy. The auriferous reefs are commonly no more than one meter in thickness, although some of the richest reefs within the mid-fan facies are only centimeters thick. The auriferous reefs are conglomeritic units commonly overlying unconformities in the alluvial fan deposits. The conglomerate units are typically pebble-supported, mature (free of clays and silts) and tightly cemented. The spaces between the well-rounded pebbles are occupied by rounded pyrite, sand-sized grains of quartz and many other heavy minerals, such as sericite, rutile, zircon and chromite. Rare diamonds, uranite and native gold are also found in the conglomerate beds.

Ore Paragenesis and Metasomatism

The genesis of the gold-uranium deposits has been widely debated, and two opposing camps have evolved: (1)The paleoplacerists (Minter, 1976; Robb and Myres, 1995) suggest that the ore deposits were initially heavy mineral placer deposits that were modified by post depositional processes such as recrystallization and short distance fluid migration. (2) The hydrothermalists (Phillips and Myers, 1988; Barnicoat *et al.*, 1997) suggest that the gold and uranium are entirely hydrothermal in origin, precipitating in the permeable conglomerate units. It is now commonly recognized that the genesis of the gold and uranium found within the Witwatersrand Basin developed through two processes; one syn-sedimentary, the other post-depositional. Four stages of ore genesis were suggest by Feather and Koen (1975) which include the initial stage of deposition, followed by three post-depositional stages of mineral growth linked to the changing tectonic environment.