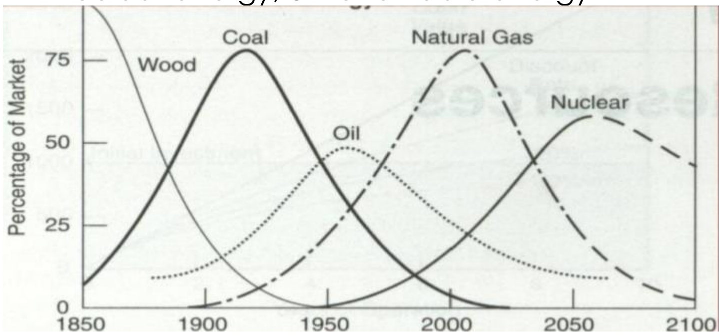
EARTH'S RESOURCES & THE ENVIRONMENTS

SHAAS N HAMDAN

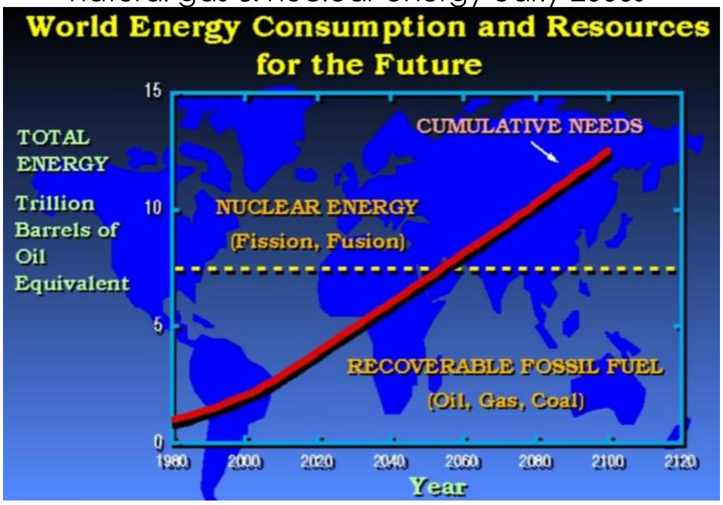
CHAPTER SEVEN
ENERGY RESOURCE

- **Main types of Energy Resources:** Fossil Fuels, Nuclear energy, & Renewable energy



World Energy Resources

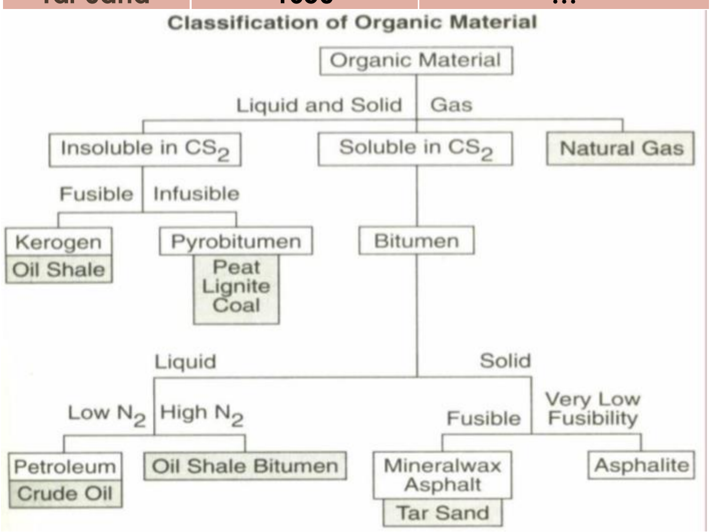
Minerals: 1800s, coal: mid-1900s, oil: late 1900s, natural gas & nuclear energy early 2000s



Fossil Fuel

- **Fossil Fuel:** is a full that made by organic matter of plant & animal, preserved in rocks as a result of geologic processes, & ***Include*** coal, oil, natural gas, shale & heavy oil, tar sand

Full Types	Reserves (ppb)	Period of time (Yr)
Oil	1012	44
Natural Gas	750	67
Coal	3745	223
Oil Shale	1500-3400	…
Tar Sand	1650	…



Coal

sedimentary rock made by plant remain (lignin, altered cellulose, terrestrial vascular plants)

- is the past fuel, & the potential fuel of future
- **Petrographucaly**: consist of macerals grains
- **Macerals:** Vitrinite (wood), Intertinite (fungal), Exinite (algae), & Liptinite (spores)
- **Coalification**: Break down of hydrocarbon to carbon by P-T & release of Gases & H2O
- **Environment of Deposition:**
  1. Swamps in flood plains
  2. Coastal barrier island system
  3. Deltas of rivers
  4. Poorly drained regions under glacier
- **What is required? (for deposition)**
  1. Stable sedimentary conditions in large area & long time
  2. Abundant & continuous supply of organic matter
- **Coal Seams (layers)**: Thickness of seam 1/10 original material thickness (usually <100 cm)
- **Coal Distribution**: Related to plate tectonics,
  - ➢ Non in pre-Silurian
  - ➢ Abundant in Carboniferous & Permian & Jurassic-Tertiary period

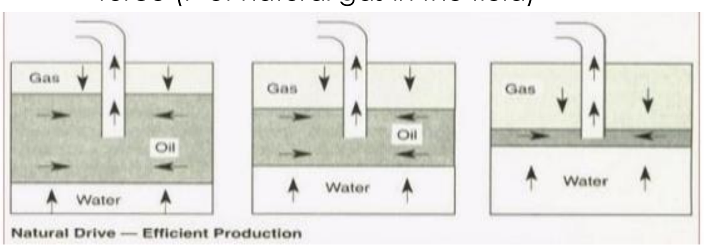
Coal Production & Environmental Impacts (EI)	
Open Pit	**Include:** Strip & Contour Mining **EI:** reclamation & Groundwater quality (increase in pH)
Underground	**Include**: Room-pillar, & Long wall (LW) (continuous mining) **EI:** Black lung disease, Fires & explosions (due to CH_4), & Subsidence (LW are designed to collapse within few months)
Coal Burning	**EI:** air-hydro pollutions (SOx, NOx)

Crude Oil & Natural Gas

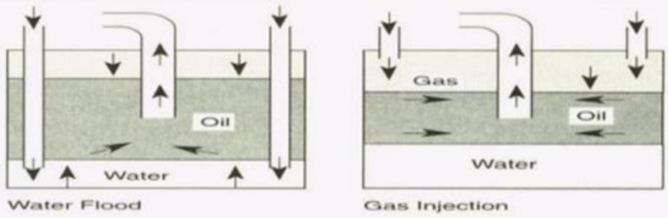
The most expensive basic commodity, & Ruling the global economy since late 20th century

- **Origin of Oil & Natural Gas**:
  1. Short (CH_4, C_2H_6, C_3H_8) or long chains (C_{4-30}) hydrocarbons (algae & plants)
  2. Fats & lipids → burial, O^{-2} → Kerogen (insoluble form of organic matter) → T, P (catagenesis) → crude oil generation (50-60°C, oil window) → gas (100°C)
- **Source rock**: shale, mudstone, & chalk
- **Cap rock:** low permeability (gypsum, salt, shale, mudstone)
- **Reservoir rock:** high porosity & permeability (sandstone, dolomite, fossiliferous lime.)
- **Geological Traps:**
  1. **structural**: anticline, faults, salt domes
  2. **stratigraphic**: lense, pinching out, reef, & unconformity
- **Environmental Impact of Oil-Gas Production**
  1. Subsidence & Collapse
  2. Gas & Water spills (brine water, Radium)
  3. Reclamation (plug, cement) remove surface installation

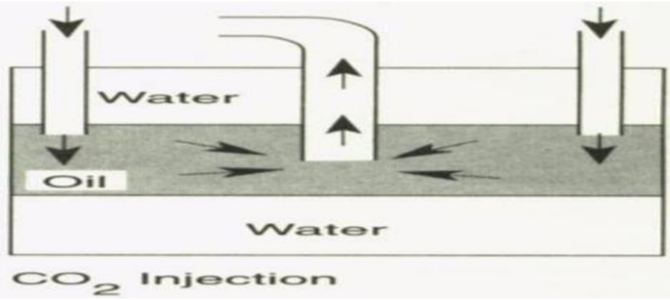
- **Oil & Gas Production**
  1. **Primary Production** by exploiting natural drive force (P of natural gas in the field)



2. **Secondary production**: increase oil recovery (latter stage), by gas injection & water flooding



3. **Tertiary Production**: (Enhanced Oil Recovery, EOR) CO_2 Injection, Combustion of oil-Gas on margins of a field, & Injection of alkaline solution to reduce viscosity



Heavy Oil (HO) & Tar Sand

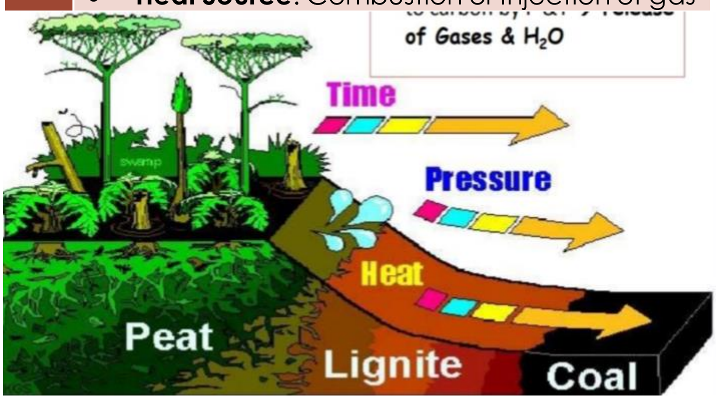
HO: Oil not flow in normal reservoir conditions
- For economic production it will require tertiary recovery

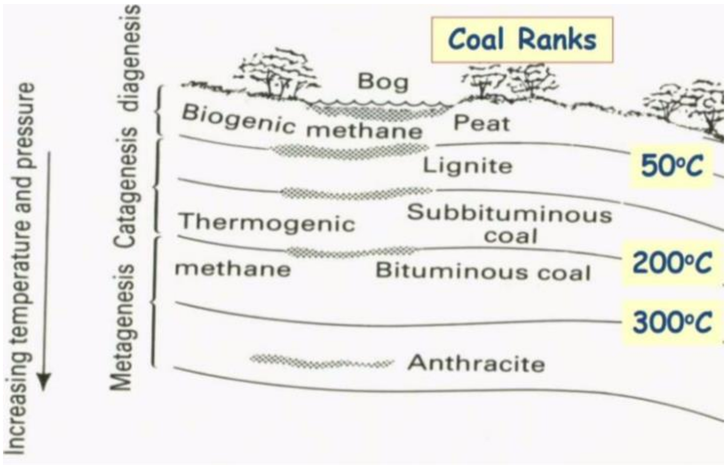
Tar Sand: Oil that will not flow at all even if using tertiary recovery
- Found in all types of rocks but large accumulation in sandstone
- can be mined & physically separated

Specifications of H.O & Tar Sand:
1. can't be converted to gasoline easily
2. yield a large fraction of heavy products
3. have high Sulfur & Nitrogen compounds
4. contain high metal Con. (Ni, V, Cr)

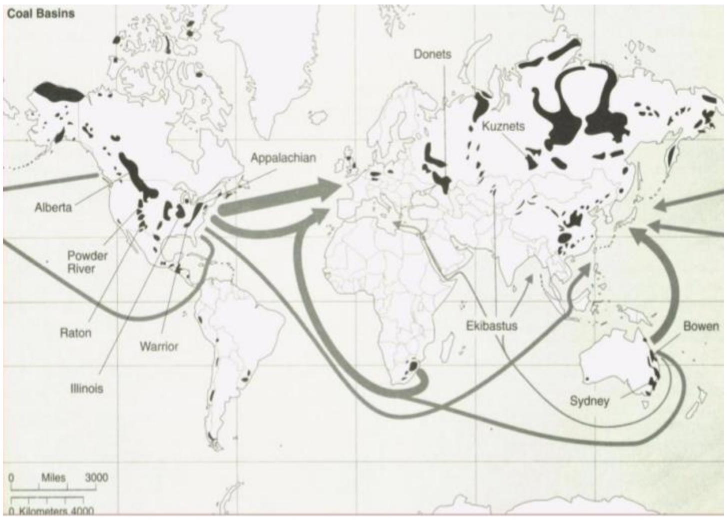
Oil Shale

- **Oil Shale (Bituminous Lime)**: Shale which can be processed to obtain oil, & source rock which was not being able to give its oil
- **Problems**:
  1. Flocculation in oil prices
  2. Technical & Environmental problems
  3. Huge water consumption (2-5 times volume of oil)
- **Environmental Problems**: From 1ton, gases emitted 20-40ppmSO_2, 140-200ppmNOx, 150ppmCO, 14ppmCO_2, & Particulate 50%
- **Oil Recovery (Pyrolysis)**: It is a process that releases hydrocarbons & gases or solids by Crushing (pulverizing) or Heating (500-1000°)
- **Heat Source**: Combustion or Injection of gas

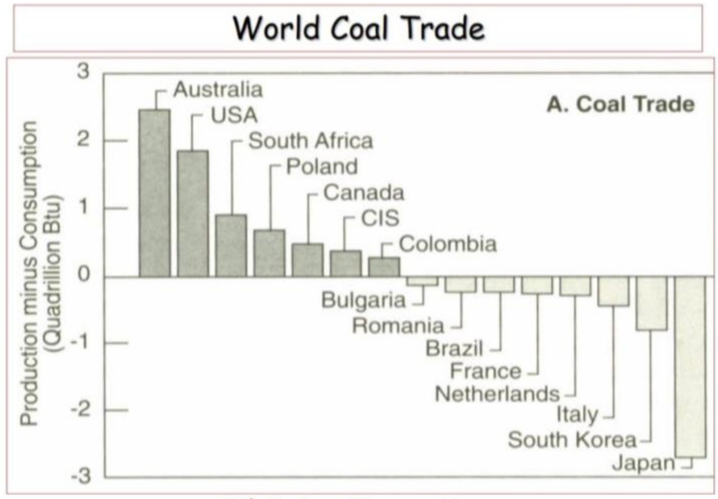




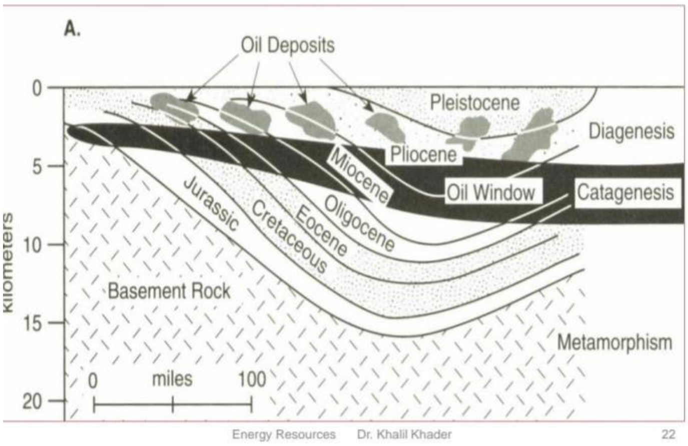
Coalification

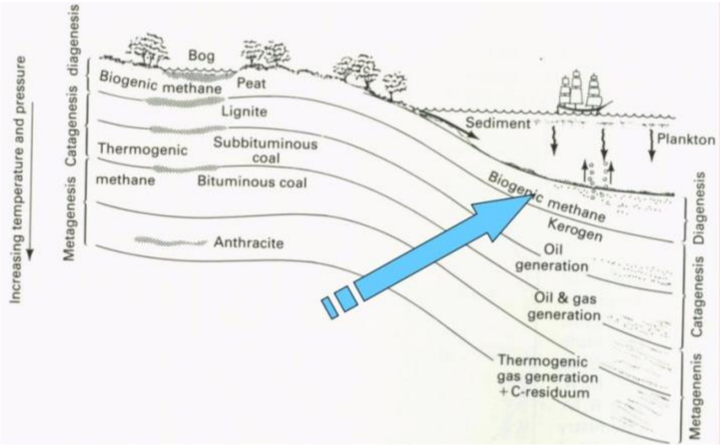


Coal Distribution

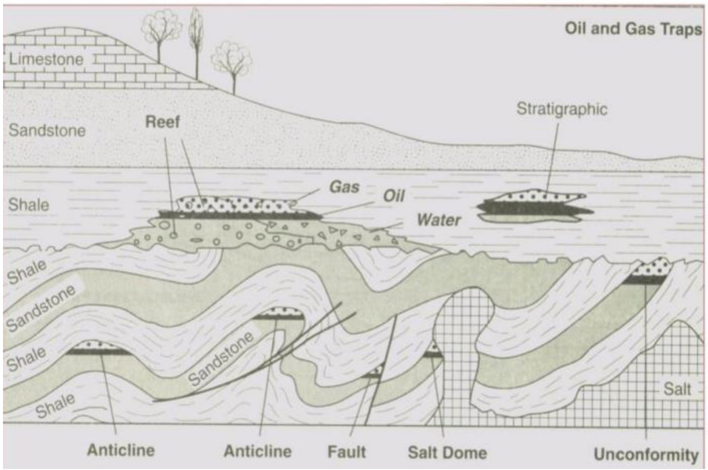


Oil & Gas Formation

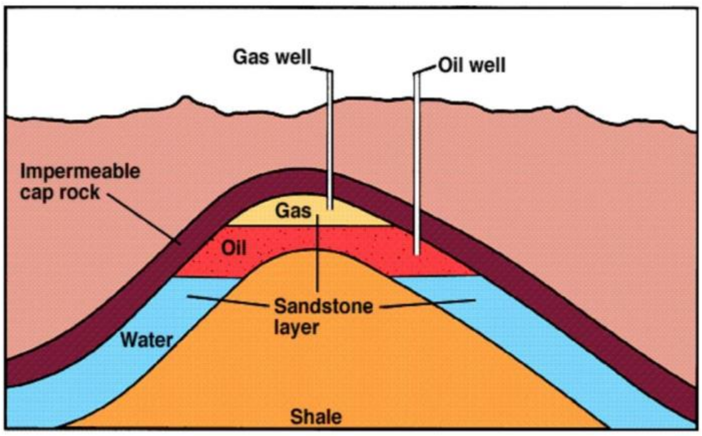




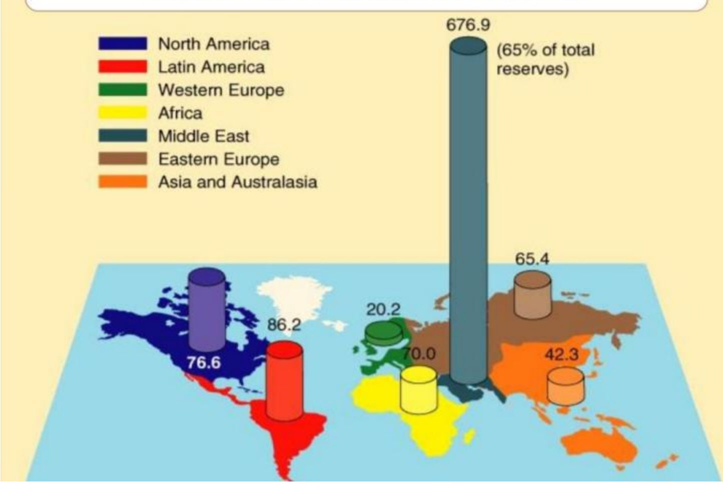
Geology of Oil and Gas



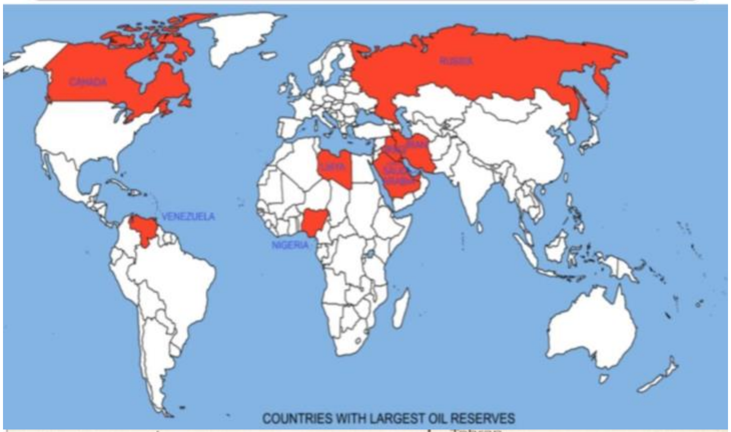
Crude Oil and Natural Gas Pool

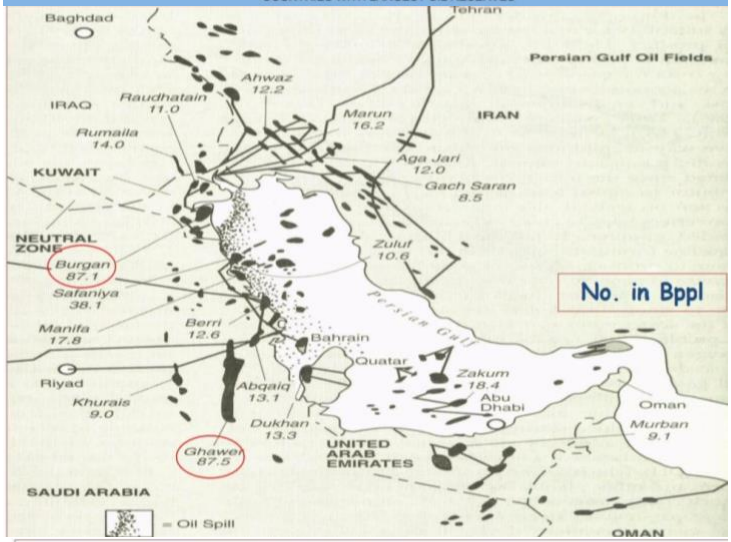


Oil & Gas World Reserves

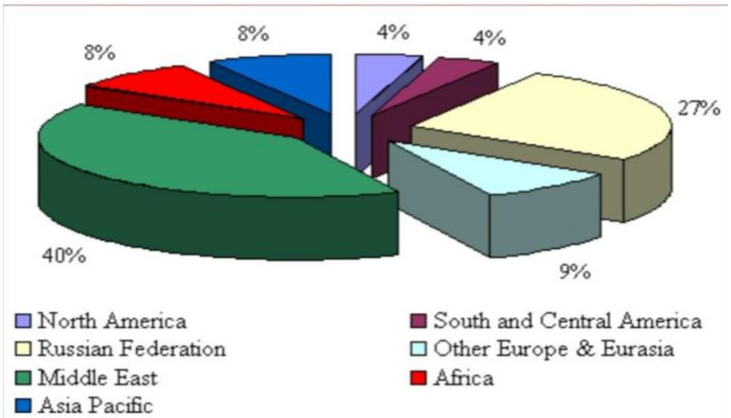


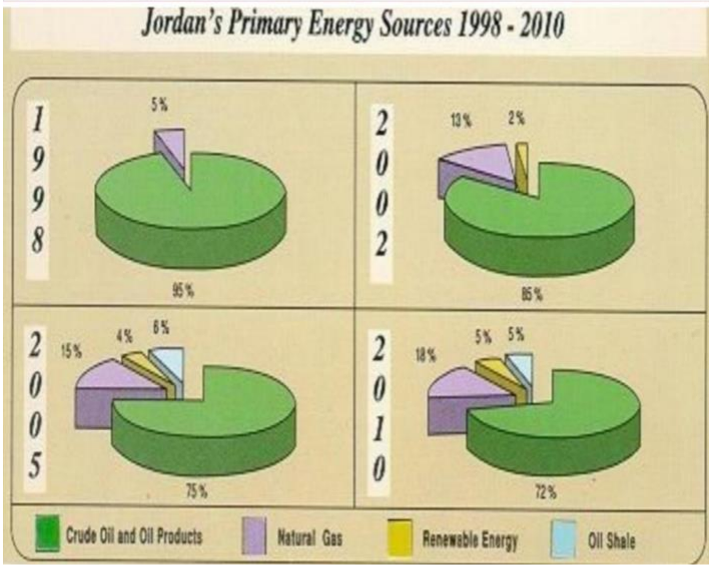
Largest Oil Reserves





Natural Gas Reserve





Oil Shale Conversion

- Oil shale mined & processed to generate oil similar to oil pumped from oil wells
- Extracting oil from oil shale more complex than conventional oil recovery & more expensive
- The oil substances in oil shale are solid & cannot be pumped directly out of the ground. But must be mined & then heated to a high temperature (a process called retorting)

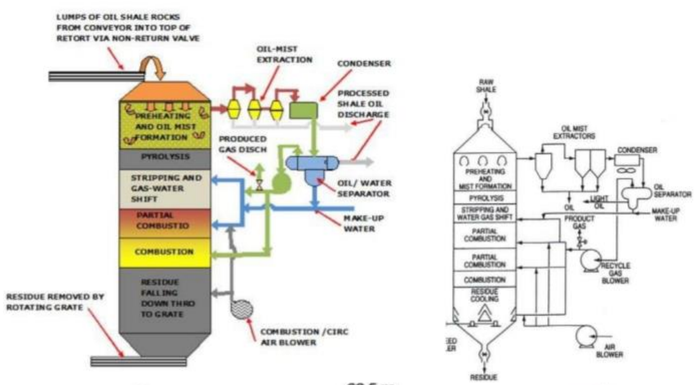
Vertical surface Retorts

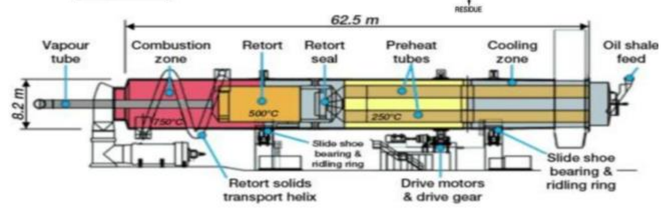
- Is a vertical shaft retorts, used with increasing success & efficiency in Scotland
- **The Gas Combustion Retort (GCR):** is one of the most successful vertical retorts, achieves high retorting & thermal efficiencies. require no cooling water, an important feature in semi-arid regions (A variation called Petro-Six is operating in Brazil)
- Crushed shale moves downward by gravity, & recycled gases enter bottom & heated by retorted shale, Air is injected & mixes with the rising hot re-cycle gases
- Combustion of gases & residual carbon from spent shale heats the raw shale above the combustion zone to retorting T
- Oil vapors & gases cooled by the incoming hale leave the top of the retort as a mist

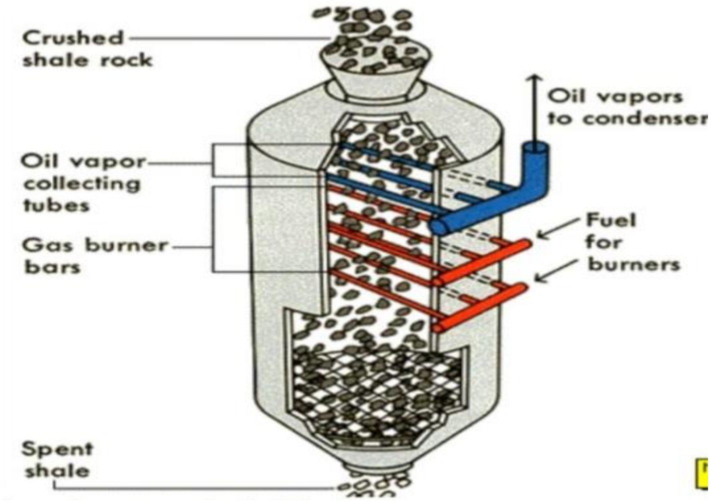
Horizontal Retorts kilns for pyrolysis

- ***JOSCO II***: preheated shale in a bed, then circulated the shale in a hot rotating drum with heated ceramic balls.
- **The ATP process** combines gas recirculation & direct & indirect heat transfer from circulated hot solids in a rotating kiln, is largely energy self-sufficient
  - ➢ Some of the hot processed shale is re-circulated in the retort with fresh shale to provide pyrolysis heat by direct, solid-to-solid heat transfer
  - ➢ ATP reported to increase kerogen oil & gas yields, improve thermal efficiency, reduce process water needs, & minimize residual coke on spent shale, enabling environmentally safe disposal.

Figure 1. Gas Combustion Retort



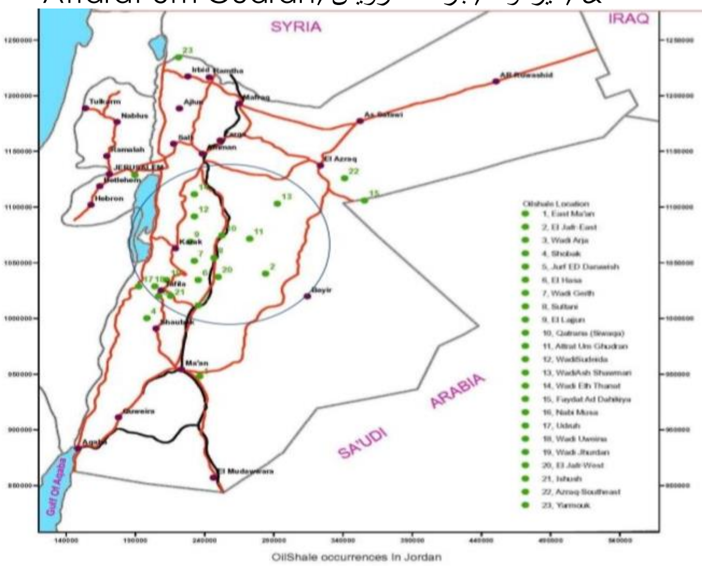


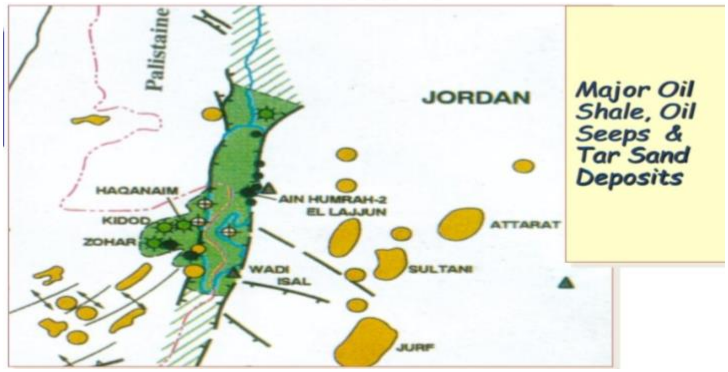


Oil Recovery (Pyrolysis)

Oil Shale in Jordan

- **Characteristics:** Avg. thickness 20m, over-burden up to 4, Proven Reserves 4×10^{10}, & Recoverable Oil 4.0×109 (4×1010 × 10 %) which equal to Jordan energy consumption for 1000yr (by using 4.0M/y)
- **Chemistry**: Recoverable oil content is <10%, Sulfur content is high (10%), with High concentration of V, Mo, Zn, Ni, Cr, Co, & U
- **Stratigraphy**:
  1. Muwaqqar Chalk Marl Formation (Maastrichtian-Palaeocene)
  2. Wadi Shallala Formation (Eocene)
- **Location**: حوض اللجون, السلطاني, Ath-Thamad, Attarat Um Gudran, جرف الدراويش, اليرموك, & شلالة





Magmatic Deposits

- **Magmatic ores**: found within intrusive rocks (UM-M) emplaced from deep, mantle sources

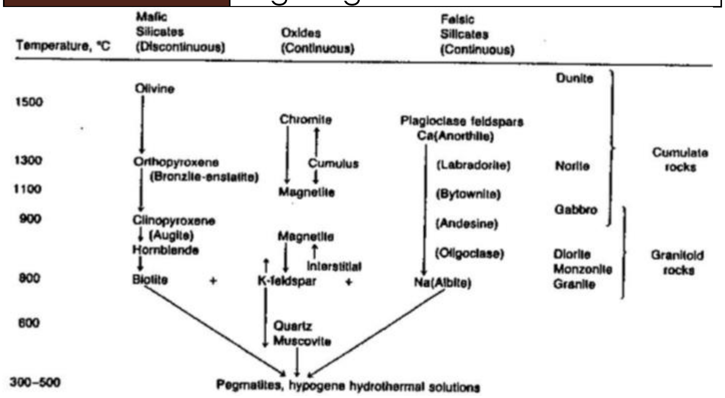
<table>
<tr><th colspan="2">Magmatic Ore Deposits</th></tr>
<tr><td>Processes of forming</td><td>1. Fractional crystallization of silicates: Cr deposits & some Fe-Ti deposits
2. Immiscible sulfide melt: Pt, PGE, Ni-Cu-PGE
3. Carbonate-melt crystallization:carbonatite
4. Inclusion of mantle minerals: diamonds</td></tr>
<tr><td>Environ-ments</td><td>1. Layered mafic intrusions: Cr, PGE, Ti, V, & Ni
2. Ultramafic & gabbroic intrusions as feeders for seafloor or flood basalts (Cr,Ni,Cu,PGE)
3. Komatiite (ultramafic extrusive): Ni,Cu,PGE
4. Carbonatite intrusions: REE, & Cu
5. Anorthositic intrusions: Ti
6. Kimberlites: diamonds</td></tr>
<tr><td>Large deposits dominate</td><td>1. Bushveld layered complex: large Cr & PGE
2. Stillwater layered complex: large PGE
3. Noril'sk intrusions: very large Ni-Cu-PGE
4. Sudbury-astrobleme layer intrusion: Ni-Cu
5. Diamonds: S-Africa field, N-Canada, Russia</td></tr>
<tr><td>Magmatic ore deposit deposits</td><td>• Only source of: Ni, Cr, Pt, Pd, & diamond
• The major of: Cu, REE, & Ti
<table>
<tr><td>Process</td><td>critical for</td></tr>
<tr><td>Magma mixing</td><td>Cr, Ni, Cu, PGE</td></tr>
<tr><td>Ore contamination</td><td>Cr, Ni, Cu, PGE</td></tr>
<tr><td>Sulfide saturation</td><td>Ni, Cu, PGE</td></tr>
</table>
• metals strongly partition into a sulfide liquid
• Source of sulfur is critical for many deposits
• Deposits form from deep crustal levels (layered intrusion) to surface (komatiites)</td></tr>
</table>

- **Mafic rocks** (45-52%SiO_2, mafic minerals <90%)
- **Ultramafic rocks**: <45% SiO_2, >90%mafic mineral

Plutonic Mafic Rocks (M)	
Anorthosite	calcic Pl, <10%mafic minerals
Gabbro	Calcic Pl (An>50), Cpx>Opx, Ol, Hbl
Norite	Calcic Pl (An>50), Cpx<Opx, Ol, Hbl
Troctolite	Calcic Pl, ol, little or no pyroxene
Volcanic Mafic Rocks (M)	
Tholeiitic B	Calcic Pl, Opc, Cpx

Plutonic Ultramafic Rocks (UM)			
Pyroxenite	Px, 30%Ol	Harzburgit	Ol, Opx
Bronzitite	Fe-Opx	lherzolit	Ol, Cpx
Peridotite	30-90Ol, Px	Dunite	90-100Ol

Volcanic Ultramafic Rocks (UM)	
Picritic basalt	Ol-rich basalt
Komatiite	High Mg basalt

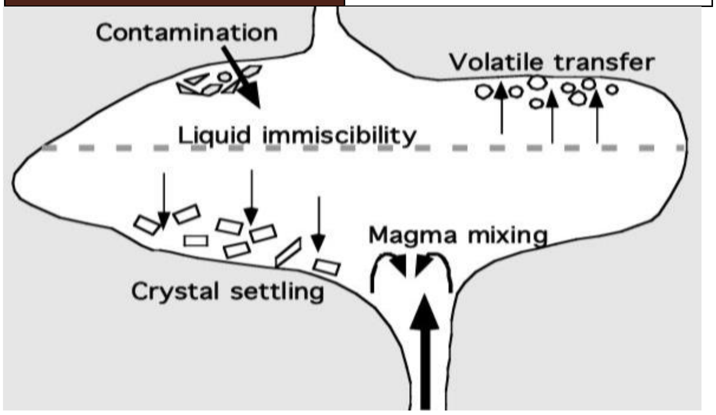


Bowen's Reaction Series

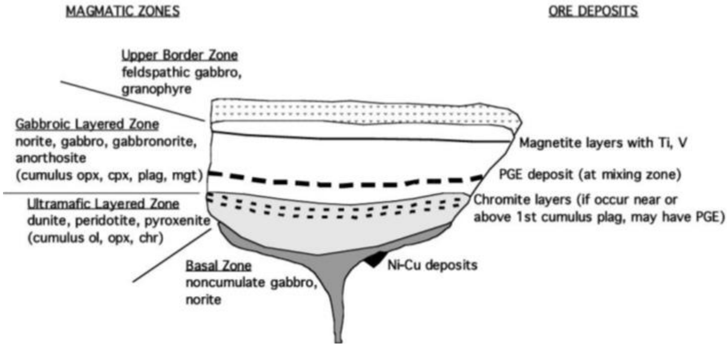
order of crystallization of mafic & felsic magmas

Magma Chamber Processes

Processes	Caused by
Magma Mixing	Mixing of magma intrusion
Immiscibility	Mixing of magma intrusion
Fractional crystallization	Cooling:volatile exsolution
Magma Settling	Cooling:volatile exsolution
Contamination	Reaction with wall rocks



Magma chambers are dynamic environments



Layered Mafic Intrusion (rang: from Km-8Km thick)

- **Cumulate**: layered complex rock, consisting of gravitationally settled grains (cumulus crystals) cemented by trapped or interstitial magma (intercumulus & postcumulus liquids)
- **Cumulus crystal**: grow in equilibrium with main magma body & then gravitationally settled
- **Intercumulus liquid**: portion of the silicate melt trapped between cumulus minerals
- **Postcumulate minerals**: forms by crystallization of intercumulus, overgrowths or secondary enlargement of cumulus minerals, & partial replacement of cumulus minerals
- **cumulate classification**: done by cumulate mineral rather than by their total mode
- **Mode:** the actual mineral composition of rock
- **Poikilitic texture**: large, anhedral intercumulus crystals (oikocrysts) that enclose cumulus grains
- **Rhythmic layering:** have scales between mm-100'sm; individual layer are commonly graded
- **Cryptic layering**: layering based on mineral composition trend & trace element distribution
- **Crystallization sequence layering**: defined by changes in cumulus mineral assemblage. the most important type to study layered intrusions
- **band or seam layers:** caused by abrupt mineral changes & not part of rhythmic layering. Describe of African occurrences (Cr-seam) & analogouser at the Stillwater

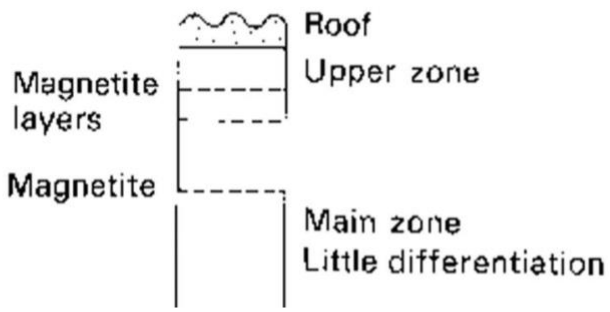
Textural Criteria for Cumulus & Postcumulus Minerals		
Criteria	Cumulus	Postcumulus
Habit	Columnar, Equant, Tabular, Rounded, Embayed	Olikocrystals, Space Filling, Replacement of cumulus crystals
Shape	Subhedral,Euhedral	Anhedral
Size	0.1mm – 1mm	<0.5mm – 30cm
Orientation	Multiple orientation in single thin-section	<3 orientations in a single thin-section

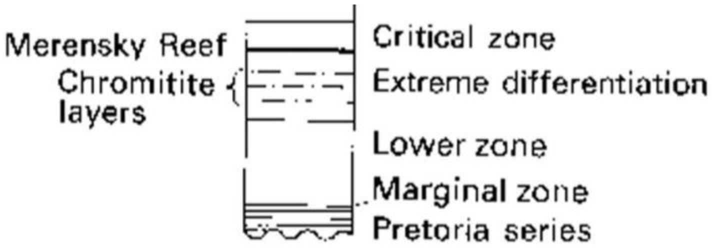
Naming Cumulus Rocks Ol:Olivine, Pl:Plagioclase, Opx:Bronzite, Cpx:Augite		
Rocks	Cumulus	Abbreviation
Dunite	Ol	oC
Bronzite	Opx	bC
Harzburgite	Ol + Opx	obC
Anorthosite	Pl	pC
Norite	Pl + Opx	pbC
Gabbro	Pl + Cpx	paC
Gabbronorite	Pl + Opx + Cpx	pbaC
Troctolite	Pl + Ol	poC
Ol-Gabbro	Pl + Opx + Ol	paoC

Bushveld Complex, RSA

- **Three major lithological units:**
  1. **Rooiberg felsites:** And. to Rhyo. lava flows
  2. **Rustenburg Layered Series:** layered UM to M intrusive rocks (with Cr, PGE,V)
  3. **Bushveld granite**: closing stage
- Complex emplaced into Transvall Sequence, 11km thick succession of calcareous & pelitic sediments with volcanic horizons
- **Mafic rocks are intruded in four bodies**:
  1. Potgietersrus Compartment Complex
  2. Far western Bushveld Complex
  3. Complex–western Bushveld Complex
  4. Complex–eastern Bushveld Complex

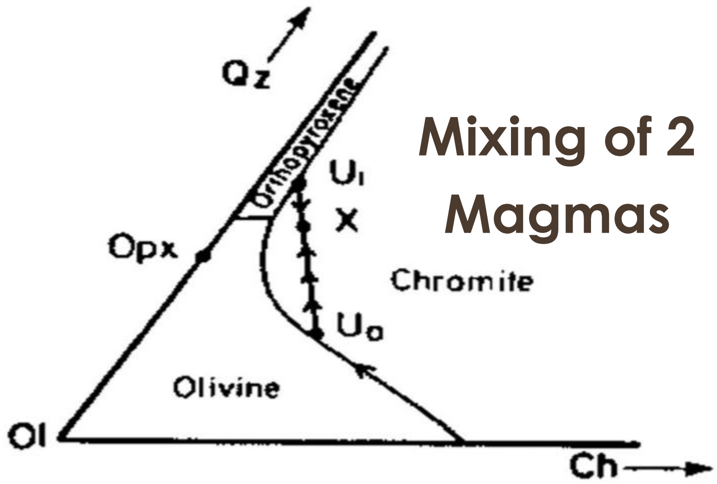
Zone	Subzone
Upper	**D:** Appearance of cumulate apatite **C:** Reappearance of cumulus Ol (Fe) **B:** Ol-rocks above magnetite layer **A:** Appearance magnetite cumulus
Main	**C:** pyroxenite, anorthosite, & gabbro **B:** sequence of massive gabbronorite **A**mottled anorthosite,norite,gabbronorite
Critical	**Upper critical zone (anorthosite subzone):** abundant Pl (upper chromitite) **Lower critical zone (pyroxenite subzone)** lower chromitite
Lower	**Pyroxenite, harzburgite, dunite, & norite**
Marginal	**Called Marginal zone or Basal zone** Fine-grained gabbros, norites, pyroxenites, & peridotites





Chromite in the Bushveld Complex	
Host	**Chromitite seams** occur in Lower & Upper Critical Zones in gabboric composition (Opx+Pl
Form	**Chromite bodies:** occur in parallel layers, in a recognizable position (<1m thick), Bushveld Steelport main seam continuous for 55km **Inclusions in seams** are abundant & consist of other rock from surrounding zones (Critical Zone), display compaction structure near them
Ore texture	**Euhedral to subhedral** aggregates with variable amounts of intercumulus & postcumulus silicate **Range from** massive polygonal to net(poikilitic) where cumulus silicates become predominant
Chemical variations	Seams have a consistent & large change in mineralogy towards lower Cr/Fe & Mg/Fe ratios **Only miniscule chemical variations laterally:** imply post-cumulus & subsolidus equilibration limited to thin subsystem across whose vertical boundaries equilibration never took place
Origin	**Formed by** fractional crystallization **Problem:** Chromite crystallizing with silicates not have density difference to concen-trate by gravitation alone, but Mixing of magmas can cause the resulting mixed magma to move into the chromite field & only crystallize

Mixing of 2 Magmas



Bushveld Geochemistry

Upper Critical Zone	• **5-6 cyclic units:** UG1, UG2, UG3, Pseudoreef (some area), Merensky & Bastard Reef, & the lower portion of all unit have PGE • **The cyclic units are defined by**: from top 1. **Chromitite-Norite-Anorthosite** sequence 2. **MgO decrease** due to **less bronzite up-section** in each cycle 3. **Bronzite shows Fe-enrichment trend up section** through all the cycles 4. **Plagioclase:** very poorly defined, **Anorthite (An)** increase up section in each cycle 5. **Sr increase upwards** in each cycle due to an **increase of plagioclase** 6. **There is distinct decrease in 87Sr/86Sr** ratio **upward** through Upper Critical Zone 7. The break is abrupt & coincides with the **Merensky Reef horizon**

UG-2 Chromitite

Located within bronzite cumulates (base of UG2)
Main chromitite character: 75-250cm, 60-9%Cr, 5-15%Pl, 5-25%bronzite, with accessory Cpx, Bio, sulfides, PGE, ilmenite, magnetite, & rutile
There is a close correlation between Ni, Cu,& PGE
Maxima of PGE concentration: one at the base & one at the top of the chromitite Cryticl zone
Avg grade of UG2 = 5-10 times Merensky Reef

Merensky Reef

Ore zone: at the base or higher of Merensky unit
PGE concentrated with sulfide,vicinity of Cr-layers
Contain: graphite, apatite, & hydrous phases compared to rest of the intrusion
Characterized by pegmatoid zones (have developed because of aqueous or hydrothermal fluids
Merensky Base: marked by dimpling & scalloping of underlying norite or anorthosite (range from dimples/m^2 with 5-10cm relief, to major unconformities or potholes up to 1km with & 10m relief)
The Merensky unit bronzitite fills potholes Ideas to the formation of potholes include:

1. scouring by magmatic currents
2. melting of the underlying layer as a result of increased volatiles introduced
3. disruption of cumulate pile by streaming upwards of intercumulus liquid

PGE tenor is high: 20ppm in Merensky unit sulfides (Pt content in 100% sulfides), & 250-600ppm in Merensky Reef sulfides
Magma Mixing Model of Merensky unit (PGE): new magma rises via a series of density stratified layers crystallizing Pl & bronzite, entrains some of magma & ponds beneath Pl-rich liquid higher in chamber, then convects turbulently, scavenging PGE to sulfide melt before cooling, becoming less dense & sinking through crystallizing Pl & bronzite

Fe-Ti Oxides

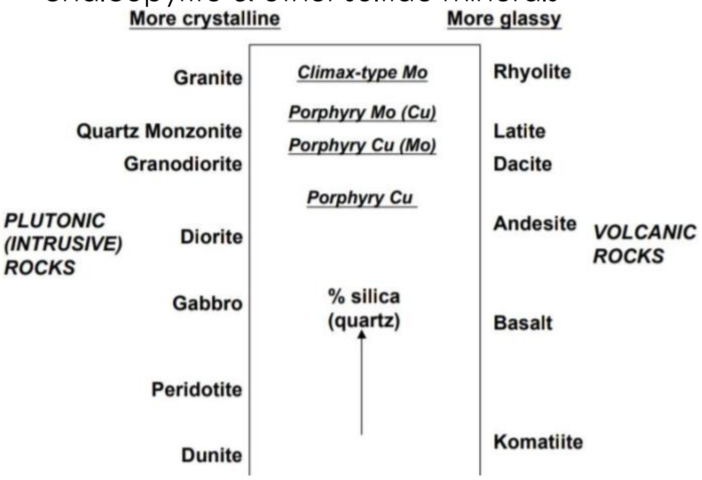
restricted to the Upper Zone of the complex
From base:

1. **Primary Magnetite:** 0.1-10m thick concordant with the igneous layering
2. **8% disseminated magnetite**
3. **>20 discrete magnetite layer enclosed by anorthosite or troctolite or gabbro**: Main Magnetite Layer (most economic important) with 1-2.5m thick, exhibits 200km strike length in W-Bushveld, 120km in E-Bushveld,100km in Potgietersus lobe

- **The lower contacts** between individual layers & footwall are sharp, but often dimpled
- **Upper contacts** gradational with gradual decrease in magnetite (magnetite layer 13 in E-Bushveld displays reverse contact relationships with a sharp top & diffuse base)
- The magnetite layers consist of Fe-Ti oxides together with silicate minerals, primarily Pl
- The oxides are dominantly magnetite with <6% ilmenite، Magnetite crystals commonly exceed 10mm (3times larger than the average grain size of disseminated magnetite in silicate-rich portions of intrusion
- In magnetite layers, magnetite forms massive aggregates in which crystals acumulate texture & show "annealed" 120° contacts
- **There is a regular variation in composition of magnetite with stratigraphic height**: at the base high V_2O_5 (2%) & low TiO_2 (10%), Near the top low vanadium (½%) & high TiO_2 (20%)
- **Genesis of Fe-Ti Oxides:** period of fractional crystallization of basalts results in concentration of substantial amount of Fe-Ti-V in the late-stage residual magma, Magnetite is able to precipitate once the T decreased to intersect magnetite-spinel stability field
- Crystallization of Pl lead to increase total Fe-content & the density of the residual liquid which accumulate as a stagnate layer on floor of magma chamber, When this liquid achieves proper Fe_2O_3/FeO ratio (function of oxygen fugacity, T, & water content) it will precipitate magnetite (magnetite-layers)
- With magnetite crystallization density of the residual liquid decrease until it is the same as the overlying liquid. At this point the liquid will mix with the overlying magma and magnetite precipitation will cease
- Repeated cycles of residual liquid formation & magnetite precipitation account for the different magnetite layers. The change in V_2O_5 & TiO_2 values reflect the early depletion of the melt in vanadium due to its preferred partitioning into magnetite, & concentration of titanium in residual melt

Copper Deposits

- **Porphyry**: igneous rock of any composition that contains conspicuous phenocrysts (crystals) in a fine-grained groundmass
- **Porphyry copper deposit**: A large body of rock (felsic-intermediate porphyritic stock) that contains disseminated & veinlet-controlled chalcopyrite & other sulfide minerals

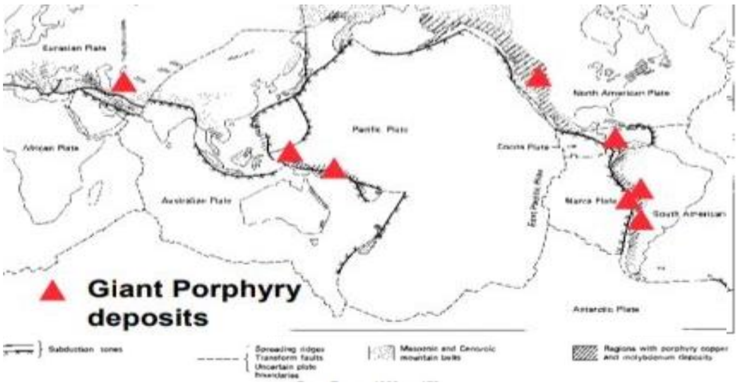


IGNEOUS ROCKS CLASSIFICATION

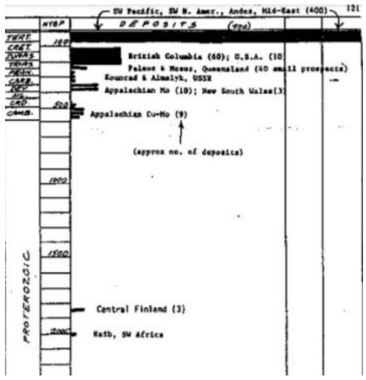
- **The porphyry deposit** centered on intrusive porphyritic stock (intrusion)
- **Porphyry-style mineralization** may be in the mineralizing stock & in the surrounding rocks, & consists of veins & veinlets of silicate + sulfide minerals with some disseminated sulfide
- A very large volume of rock is affected by these systems (up to 1000 km³), only a small portion of this volume usually makes ore
- **Porphyry systems** contain broad scale (km's) vertical & horizontal wallrock alteration zones which are predictable (mineral assemblages are controlled by wallrock composition)
- Porphyry systems contain evidence of mineralizing events & changes in sulfide-silicate assemblages through time based on fluid composition & temperature
- **Porphyry Cu-deposits** represent 50% of world Cu-production, & characterized by very large tonnage & low grade, & are important source of by-product of Au, Mo, Ag
- e.g. N-American porphyry deposit, Chilean porphyry deposit, SW-Pacific porphyry deposit

Types of Porphyry Copper Deposits	
Types	**Associated with**
Cordilleran calc-alkaline	Granodiorite, Qz-monzonite 55-70%Si Such as Andes (US)
Cordilleran (alkaline)	Monzonite-Syenodiorite (47-55%Si) Such as British Columbia
Island Arc (Gold) type	Qz-diorite-granodiorite (55-65%Si) Such as: SW Pacific, Central America

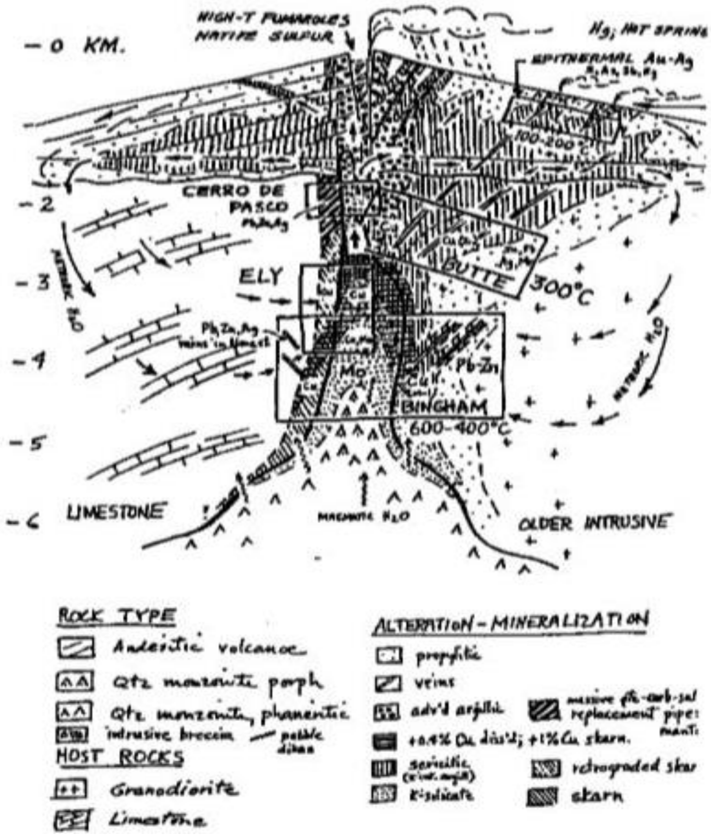
- **Location of Porphyry Cu-Deposits:** linear belts of andesitic volcanism related to subduction of oceanic crust along continental margins & Island arcs, form beneath subaerial volcanoes



- **Age of Porphyry Systems**: Most porphyry Cu-deposits are late Mesozoic-Cenozoic (<200Ma) but there are several significant older porphyry deposits (e.g. Almalyk/Uzbekistan)



- **Most of porphyry Cu-deposits are young, Why?** Porphyry copper deposits form in subvolcanic environments (1.5-4 km above subduction zones) & These areas are uplifted with erosion of volcanic edifices & deeper to regional magma chambers (batholiths). many deposits are eroded relatively soon after formation.



- **Age of any Porphyry Systems:** varies by region & reflecting periods of igneous activity
- **Porphyry Belts:** linear belts of porphyry deposit, represent positions of igneous activity in different subduction configurations, & the quality of the deposits may vary by belt

Cu-DEPOSITS FORMATION

- Porphyries are related to intrusions & consist of veins indicating brittle deformation of the rocks
- **Veins** contains silicate & sulfide minerals which precipitated from an aqueous fluid

Aqueous Fluid Sources in Porphyry Systems

Magmatic

- **Most silicate magmas require** 2-4% H_2O to stabilize hornblende & biotite (both common in diorites to granites)
- **F-IN intrusive magmas:** 1-2%H_2O
- **(2-4%)-(2-1%)=0-3%** available for ultimate ejection from the melt, & This water contains high F, Cl, S, metals (incompatible elements in minerals crystallized from the melt)

Meteoric

- Emplacement of large body of hot magma will set up convection cells of groundwater (derived from meteoric water) if present
- depending on Cl, S contents of these waters, they can also dissolve and transport metals

Magma Crystallization & Expulsion of H_2O for Porphyry Pluton

Stage 1

Pluton crystallizing & reached saturation (water comes out of the melt), Due to its low density, this water migrates to the top of the chamber & trapped by previously-crystallized intrusive rock

- Water expands as released from the melt. & volume increase causes increase in internal pressure within the magma chamber
- Increased internal P in the magma chamber causes increased water solubility (water tries to go back into the melt), but this also lowers the crystallization temperature of the melt
- With increased crystallization, more water is released to melt with consequent increase in internal P (mechanism as pluton is cooling)

Stage 2

If the internal P in the magma chamber exceeds the confining strength of wallrocks, the chamber catastrophically fails & the accumulated water is suddenly released

- The drop in internal P causes much of the water dissolved in the melt to be suddenly released as well (increasing the pressure)
- Failure leads to overall P decrease that causes effective melting T of magma to rise
- The loss of heat from the rapidly escaping water causes the T of the melt to fall
- This combination causes the melt to quickly quench, releasing still more water & resulting in fine-grained groundmass & a porphyritic texture if large crystals are present in melt

Stage 3

- If catastrophic failure causes fluids (aqueous fluid+melt) to rise to earth surface, volcanic eruption occurs, the volatiles (H2O, CO2, SO4) & much of the metals are lost to the atmosphere as volcanic gas and ash
- To form a porphyry Cu-deposit, the volatiles & metals must be trapped in fractures (veins) in uppermost portion of the rapidly chilling porphyry stock & in the surrounding wallrock

Magmatic Fracture Associated with P Release - Hydrothermal Alteration & Mineralization

Potassic Alteration

- The aqueous fluid near the top of the magma chamber contains alkalis (K-rich), silica, volatiles (CO_2, SO_4, Cl), & metals
- This fluid may cause pervasive alteration of semi-crystallized magma (biotization)
- With P release & catastrophic failure, veins form in the quickly cooling magma
- Veins are filled with orthoclase (Ksp), biotite, quartz, and/or anhydrite, & chalcopyrite.
- These early veins & alteration zones are characterized by K-bearing minerals - the alteration is termed "**potassic**"
- There are multiple, cross-cutting sets of potassic veins. Early veins tend to be:
  1. Biotite
  2. Quartz- biotite-orthoclase-magnetite
  3. Quartz-orthoclase-biotite
  4. Quartz-orthoclase
  5. Quartz - orthoclase – chalcopyrite
- multiple vein sets indicate repeated failure of single chamber or failure of multiple magma chambers (small stocks, dikes, etc.)
- Much of Cu (& Mo & Au) emplaced during these potassic alteration & veining events

Propylitic Alteration

Moving out- & upward from the zone of potassic alteration & veining, wallrocks around intrusions display a pervasive to vein controlled style of alteration where mafic minerals are converted to chlorite & calcic plagioclase is partially converted to epidote & calcite

- chlorite & epidote are green colored giving this rock green to dark green color
- This type of alteration is termed "propylitic." & form around zones of potassic alteration, & can be formed around any intrusive body which has given off aqueous fluids

Fluid Evolution in data from Fluid Inclusions

- Fluid inclusion studies at porphyry deposits indicate paragenetically veins (K-alteration) have high homogenization T (magmatic in vein) & high salinities (aqueous fluid contained alkalis, volatiles, & metals)
- Paragenetically later veins display progressively lower homogenization T & are commonly less saline
- Fluid inclusions in late Qz-sericite(illite-mus)-pyrite veins in 250-200°, show low salinities
- HF derived from the magma or pulled into the system by convection (meteoric water). Stable isotopic studies indicate that both type of fluids are involved in these late veins

QSP (Phyllic Vein)

QSP = late Phyllic stage of Quartz-Sericite-Pyrite

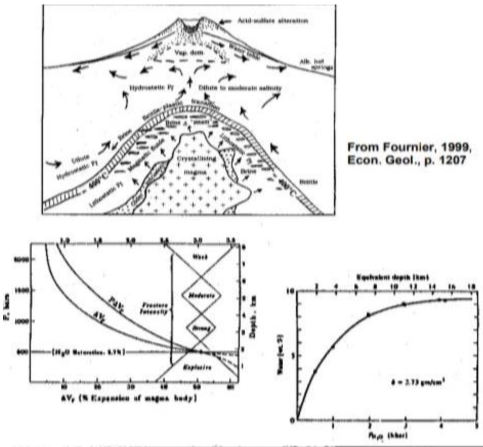
The early potassic veins (& may be propylitic veins) are cut by Qz veins with sericite (illite to muscovite)selvages

Qz-veins contain pyrite & may contain chalcopyrite & formed at lower T than the potassic veins

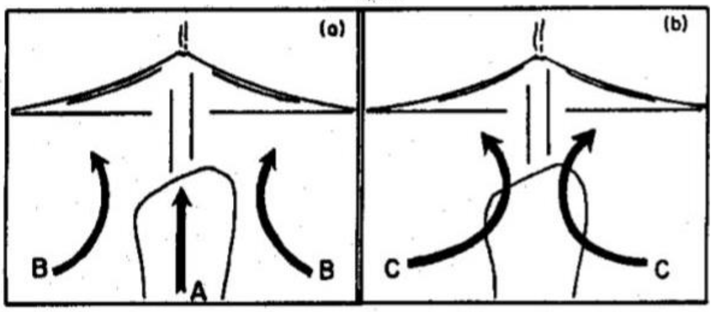
Qz-veins are most common near the top of the zone of potassic veins ore above the potassic zone

Meteoric Water " Collapse"

- Emplacement of a body of hot magma will set up convection cells of groundwater (derived from meteoric water)
- The convective fluid circulation patterns are controlled by pluton & wallrock permeabilities, depth of intrusion, pluton geometry, & the presence or absence of impermeable boundary within rock column
- Convective flow minimize thermal gradients in & above the pluton, while increasing them at depth & in the inflow zone along the sides of the pluton
- Convection will lower T in the crystallized & fractured upper portions of he pluton to below magmatic T (to 300 - 350°C).
- Depending on the Cl, S, etc. content of the convective waters, they may also be able to dissolve & transport metals.



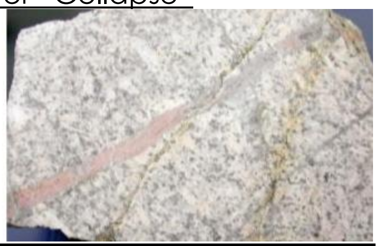
Magma Crystallization & Expulsion of Magmatic Water for a "Typical" Porphyry Pluton



Meteoric circulation with pluton still releasing magmatic fluids (A).

Meteoric circulation now entering pluton.

Hydrothermal Alteration and Mineralization- Meteoric Water "Collapse"

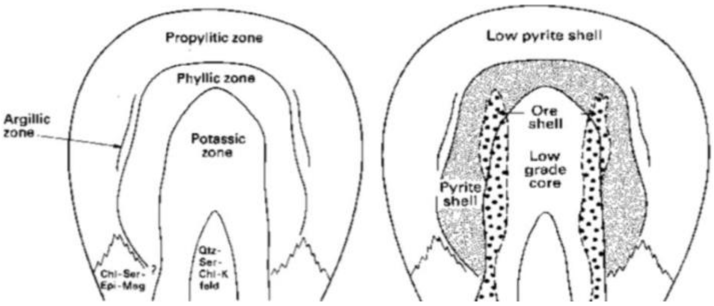



Dark biotite veins (L). Pink Ksp veins (R)


Qz vein with Ksp selvage (L), Sierrita & Qz vein with Chalcopyrite & weak Ksp selvage (R)

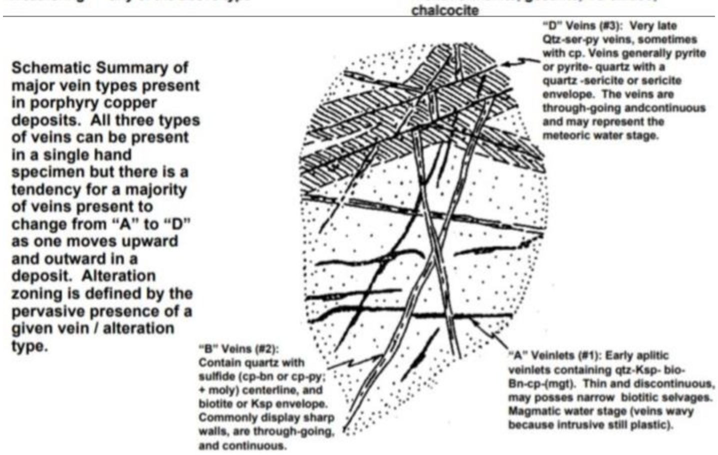
Alteration Model for Cu-Deposits

- **Lowell & Guilbert model:** standard for alteration & mineralization zonation for porphyry Cu-deposits, emphasizes different alteration types without timing relationships between different alteration & mineralization events

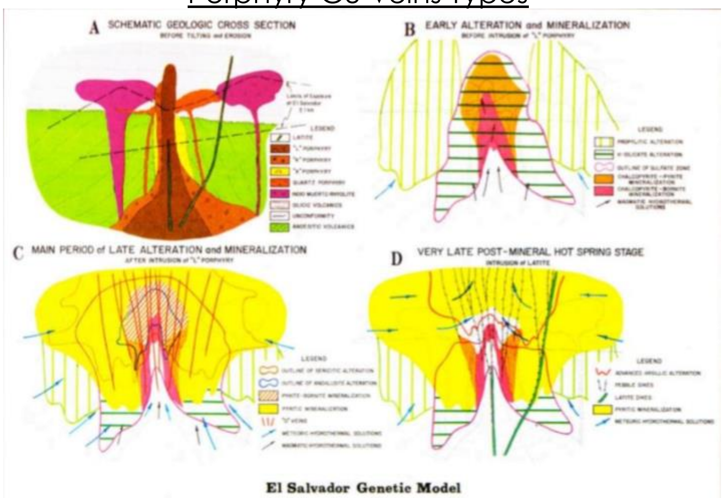


- Lowell & Guilbert recognized the different age relationships, but they not focus on temporal evolution of El Salvador, Chile systems
- Gustafson & Hunt emphasized timing relations of alteration & mineralization based on mapping individual vein types & noting cross cutting relationships at El Salvador deposit (the best published account of porphyry copper)

Alteration Type	Vein Type	Morphology	Mineralogy
Potassic	"A" Veinlet	thin, discontinuous mm's to cm's long	qtz - secondary biotite - (Ksp) < 5% sulfides: bn - mgt - cp >> py
	"B" vein	mm's to cm's wide, cm's to m's long	qtz - Ksp - (alb) - (chl) - (anhydrite) - (fluorite) <10 % sulfides; cp - py - moly
Sericitic	"D" Vein	cm's to m's wide m's to km long	sericite - qtz - py >50 % sulfides typical; Py > cp
Propylitic	veins are rare		
Argillic	like D-type		kaolinite - py - cp
Weathering	any of the above type		montmorillonite, goethite, Cu oxides, chalcocite



Porphyry Cu-veins Types



El Salvador Model for Porphyry Cu-Development