EARTH'S RESOURCES & THE ENVIRONMENTS

SHAAS N HAMDAN

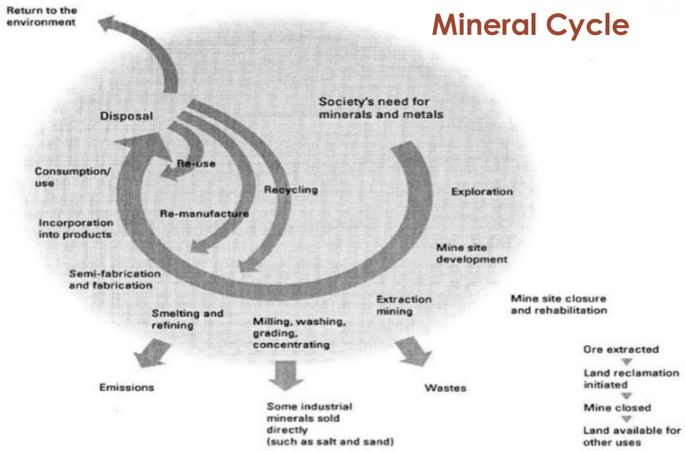
CHAPTER ONE INTRODUCTION

- **Natural resources:** are any valuable material of geologic origin that can be extracted from the earth
- **Resource**: inorganic & organic materials, extracted from crust (atmosphere, Lithosphere, hydrosphere) & whose use may impact these parts of the crust

Classification of Natural Resources	
Renewable	Materials replenished on short time (Human life) • e.g. solar energy, plant, water…
Non renewable	Fixed quantity & not replenished on short scale • e.g. oil, mineral deposits…
Resources Groups	
Energy resources	**Petroleum fuel (oil & natural gas)** is the major natural resource for human **Alternative energy** wind, tidal, solar energy **Other fuels**: coal, & uranium
Metallic resources	**Chemical elements of single or alloys:** Fe, Cu, Al, Pb, Zn, Au, Ag & valuable resources that vital for modern society
Non metallic resources	**Sandstone & Granite** used for construction **Calcite** used as main ingredient in cement **Red Clay** used to make bricks **Sand, Gravel Gypsum, Sulfur:** everyday items **Halite** is a fertilizer sources of chemicals **Soil & Water:** necessary to support all plant life

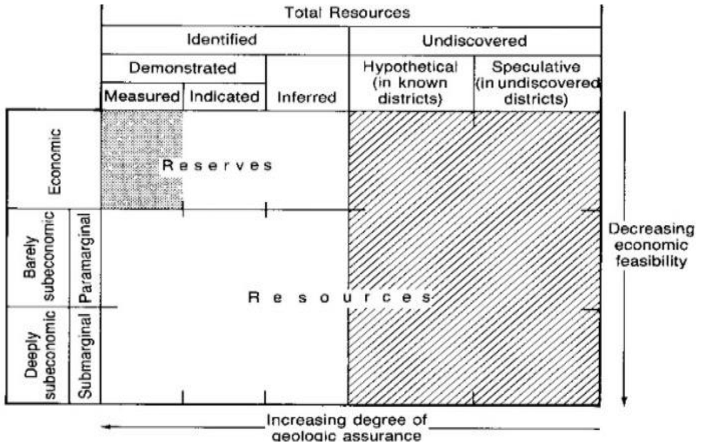
- **Petroleum:** earth material form within the Earth, burned to produce heat & electricity or made into gasoline
- **Economic Geology**: is the application of geologic principles to search & understanding of mineral deposits,
  - ➢ Another definition. is the study & analysis of valuable geologic bodies & materials (such as fuels, metals, nonmetallic minerals, & water)
- **Mineral Deposit (industrial minerals)**: naturally occurring mineral (e.g Metal ores, nonmetallic minerals) have economic value, without regard to mode of origin
- **Ore:** Natural material from which a mineral or minerals of economic value can be extracted at a reasonable profit

Types of Non-fuel Mineral Resources	
Metals	• **Metals**: class of element, opaque, fusible, malleable or ductile, characteristic by luster & good conductors of heat & electricity **1. Precious:** Au, Ag, Pl (PGMS, PGES) **2. Non-ferrous (base):** Cu, Al, Pb, Zn, Tn **3. Ferroalloys:** such as Fe, Mn, Ni, Cr, Co, V, W, & Mo **4. Fissionable metals:** uranium **5. Minor- & non-metals:** Mg, Hg, REE, Sb, Ar, Be, Bi, Cd, Se, Ta, Te, Ti, Zr
Gemstones	Valuable mineral crystals used to make jewelry such as diamonds, emeralds, rubies, garnet…
Industrial Minerals	Any rock, mineral, or natural inorganic substance of economic value, exclusive of metallic ore, mineral fuel, & gemstone, & include: **1. Minerals**: such as barite, halite, gypsum, garnet, & phosphate **2. Aggregates:** Any combination of sand, gravel, & crushed stone **3. Dimension Stone:** Rock that is cut, & can be used as a building material



- **Sustainable development (التنمية المستدامة)** development that meets needs of the present without compromising the ability of future generations to meet their own needs التنمية التي تلبي احتياجات الحاضر دون التأثير على قدرة الاجيال القادمة بتلبية احتياجاتها الخاصة
- **Goals of sustainable development:**
  1. Improve material well-being for this generation
  2. Spread the well-being more equitably
  3. Enhance the environment
  4. Strengthen the ability to manage problems
  5. Pass on stocks of "capital" to future generations
- **Challenges for the Minerals Industry (development)**
  1. Will be an engine of sustained economic growth for countries تتوقع الدولة ان تنمي هذه المشاريع اقتصادها
  2. Provide employment, & infrastructure for local communities ان تحسن هذه المشاريع حياة السكان المحليين
  3. The industry's employees expect safer & healthier working conditions, a better community life يتوقع موظفو الصناعة ظروف عمل امنة وصحية وحياة مجتمعية افضل
  4. Local citizens & human rights campaigners expect companies to respect & support basic rights يتوقع السكان والناشطون الانسانيون ان تحترم الشركات الحقوق الاساسية
  5. Environmental organizations expect a much higher standard of performance & will avoid ecologically & culturally sensitive areas تتوقع المنظمات البيئية العمل باحترافية كبيرة والابتعاد عن المناطق الحساسة بيئيا وثقافيا
  6. Investor expect higher returns المستثمر يتوقع ربح كثير
  7. Consumers expect safe products produced & manner that meets environmental & social standard يتوقع المستهلكون منتجات امنة وتلبي البيئة الاجتماعية
- For best comparison of mineral deposits, the classification scheme is based on the following
  1. **Geological characteristics**: grade, tonnage, thickness, & depth of deposits
  2. **Profit assessment** metal price, value, extraction cost
- **Mineral resources**: concentration of solid, liquid, or gas within the crust that can be extracted economically
- **Reserves**: is the amount of material in the ground that possible to mine & can be extracted at a profit, & classified based on the degree of certainty

Reserves & Resources classification based on certainty degree	
Indicated (probable)	some degree of certainty, giving confidence that we are reasonably certain of its tonnage & grade
Measured (proven)	Material sampled so thoroughly that we are certain of its outline, tonnage & grade
Inferred (possible)	There is some basis for believing it exist (Assumed to extend beyond known resources)



- To form **orebody**: elements of interest must be enriched to higher level than their normal crustal abundance
- **Concentration factor**: The degree of enrichment

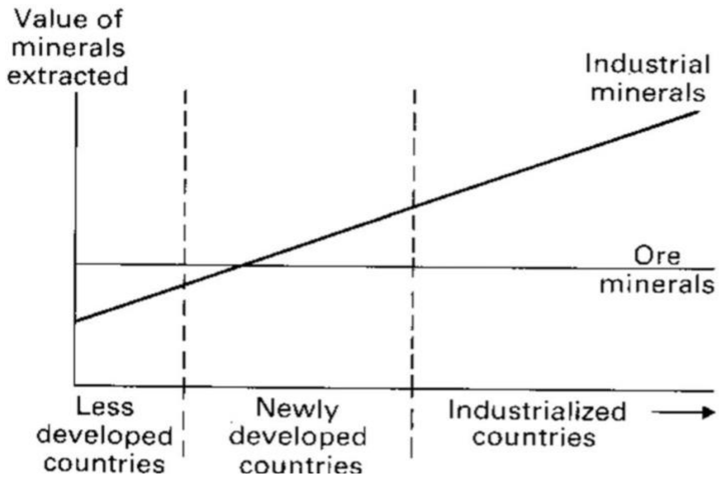
Elements	Avg crustal abundant ppm*	Avg min. exploitable grade ppm*	Concentration factor
Al	80,000	300,000 – 350,000	4
Fe	50,000	250,000 – 690,000	5 (4-14)
Ni	70	5,000	71
Cu	50	7,000	140 (80-160)
Ag	0.004	1.5	375
Mn	900	350,000	389
Zn	70	40,000	571
Tin (Sn)	2	5,000	2500
Cr	100	300,000	3000
Pb	10 - 15	40,000	2500 - 4000
U	1	10,000	10,000
Au	0.004	10	2500
Hg	0.1	1000	10,500

*to convert ppm into %, Multiply the number by ten thousand

- **Goldschmidt classification of geochemical elements:** based on compositions of 3 phases (metals, sulfides, silicates) in meteorites & smelter slags, & occurrences

Goldschmidt classification of geochemical elements	
Siderophile elements	**Occur with native iron, include:** Fe, Co, Ni, Ru, Rh, Pd, Re, Os, Ir, Pt, Au, Mo, Ge, Sn, C, P, (Pb, As, W)
Chalcophile elements	**Concentrated in sulfides, include:** Cu,Ag,Zn,Cd,Hg, Ga,In,TI,Pb,As,Sb,Bi,S, Se, Te, (Au,Ge,Sn,Fe,Mo,Re)
Lithophile elements	**Occur in or with silicates, include:** Li, Na, K, Rb, Cs, Be,Mg,Ca,Sr,Ba,B,Al,Sc,Y,REE,Si,Ti,Zr,Hf,Th,V,Nb, Ta,O,Cr,W,U,Mn,F,CI,Br,I, (C,N, P, Fe, H, Ti, Ga, Ge)
Atmophile	**Occur in atmosphere:** H,N,Inert gase,(F,C,O,CI,Br,I)

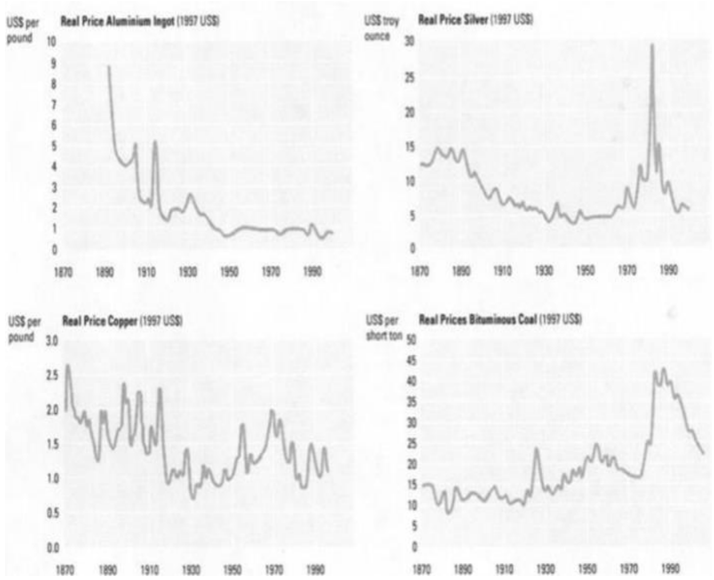
- **Grade**: quantity of metal per mass of rock, expressed in percent %, ppm, or ounce/ton (opt) for precious metals
  - ➢ 1% = 10,000 ppm (grams), I ounce = 28.349 grams
- **Ore grade**: The grade at which rock mined economically
- **Cut-off grade:** grade below which rock not sent to mill
- **Grade of rock mined is a function of**: mining methods (mining costs), metal prices, & value of by-products
- **Gangue minerals:** minerals discarded in ore processing
- Reserves are not an adequate measure of long-term availability of a metal, & change through time due to:
  1. **Additional exploration**: may change *indicated or inferred reserves*, not change measured reserves
  2. **Change in metal prices**: if prices go up *measured reserves* increase, & down may fall
  3. **Changes in mining costs**: if costs go up the *measured reserves* may fall
  4. **Mining companies** may not report all known reserves due to tax requirements
- Mineral resources are finite, non-renewable commodities, & We commonly predict long-term availability of mineral resources
- Predictions of long-term mineral availability (Resource Availability) based on reserves are not accurate because
  1. Reserves represent a minor fraction of known ore
  2. New deposits may be found
  3. Breakthroughs in extraction technologies occur
  4. Gradual technical, economic, & social adaptation alter projected demand
- **Importance of Industrial Minerals Exploitation in Evolving Economies**: Mature economies characterized by greater economic importance of industrial mineral production than metals production



Factors in Evaluation of a Potential Orebody	
Geological factors	• Ore grade, & by-product values • Size & shape of deposit • Deleterious elements (smelter penalties) • Mineralogical Form, Grain size & Shape • Rock quality & Water contents
Political & economic factors	• Location, Societal impact, & Political factors • Environmental considerations • Commodity Prices, Cost of capital, Taxation

Metal Prices

- **Metal prices are erratic & hard to predict:**
  1. **In the short-term prices respond to:** particular events strike, mine closures, country instability…
  2. **In long term (in decades) prices respond to**: world business activity
- Prediction of price is important for calculating reserves in a project & determining project economics



CHAPTER TWO
MINERAL EXPLORATION

- **Principal Steps in the Establishment of a Metals Mine**
  1. **Discover an orebody-mineral exploration**
  2. **Feasibility study**: deposit is potentially economic?
  3. **Mine development**: establish the infrastructure & construct the mine & mill complex
  4. **Mining**: extraction of ore from the ground
  5. **Mineral processing**: milling of the ore طحن الخام, & separation of minerals from gangue (waste material)
  6. **Smelting**: purifying the metal تنقية المعدن
  7. **Marketing**: supplying a customer with the metal
- **Geologists are generally in charge of the discovery & feasibility study stages** of this process & mining
- **Mineral Deposit Exploration:** a number of techniques are used in mineral exploration separately, sequentially, or jointly, & include:
  1. Geological Exploration Techniques
  2. Geochemical & Geophysical Techniques
  3. Imaging & Drilling Exploration Techniques
- **Prospecting & Random Exploration:**
  1. Unguided exploration
  2. Prospectors (determination & hope)
  3. Prospecting for gold, oil, & water (based on shows, sense, believes, random drilling…)

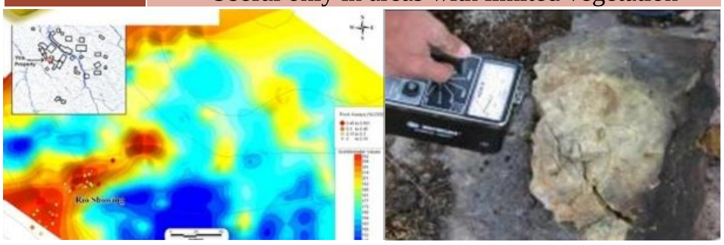
Geological Exploration Techniques

Basis of Geological Exploration	
1st stage	**Field study** • Prospecting for outcropping mineral deposit • Development for the mineral formation • Unravel structural complexity (faulting, folding) • Provides Geological information for input into geochemical & geophysical models
2nd stage	**Surveying, Mapping, & Sampling** • Detailed geological mapping, Stratigraphic correlation, & Structural & lineament maps • Selected & preliminary sampling of outcrops
3rd stage	**Office work** • Petrographic & petrological studies • Mineral Determination, & Chemical analysis • Interpretation & evaluation of collected data

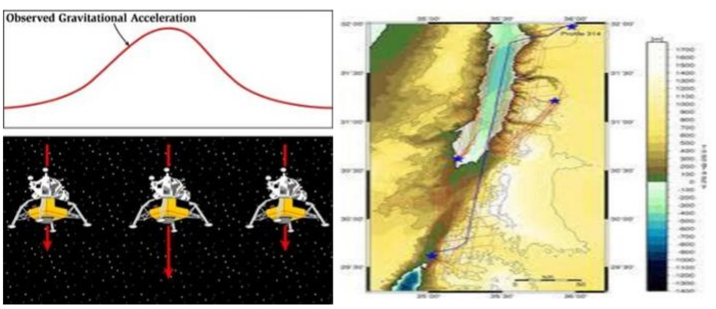
Geophysical Exploration Techniques

- **Prospecting of Geophysical Exploration Techniques is based on physical properties of mineral deposits** (Magnetic intensity, Density, Composition, Electrical conductivity, Radioactivity, & seismic waves velocities)
- **Can be detected:**
  1. Presence of elements (metals)
  2. General nature of buried rocks
  3. **Geophysical anomalies** (abnormal values)
- **Characteristics (Advantages) of this Exploration**:
  1. Depends on physical properties of rocks & minerals
  2. Can be made from the air (Airborne Survey)
  3. Can detect ore bodies in the subsurface
- **Types of Geophysical Exploration:**
  1. **Metal survey**: Magnetic, Electrical, Resistively, Electromagnetic, Radioactivity, & Gravity
  2. **Oil & gas Exploration**: Seismic, Well logging

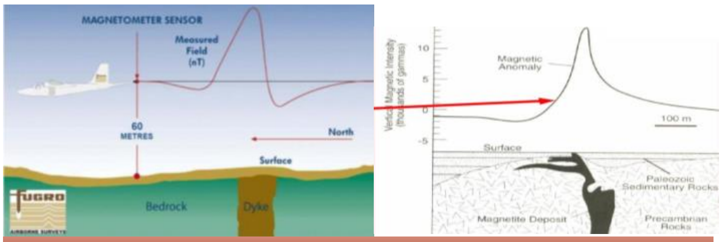
Geophysical Exploration Techniques for Mineral Deposits	
Electrical method	**Induced polarization (IP):** Application of electric field into the earth which causes parts of the electronic conductor's rocks to become polarized (Current flow ceases the polarization cells, & discharge causing a brief flow in the opposite direction which can be measured) • This technique works best with disseminated sulfides, porphyry Cu-deposits, & graphite
Electro-magnetics (EM) Method	Measurement of alternating magnetic fields associated with currents in the subsurface • respond only to large changes in resistivity & are thus utilized primarily for massive sulfides
Magnetic Method	Measurement component of geomagnetic field (Rocks produce different magnetic signatures based on amount of magnetic minerals in rock • Fe-ore deposits (magnetite) display significant magnetic properties & form distinct anomalies
Gravity Method	Measures earth's gravity (gravitational field), based on the difference between the observed value of gravity at any point & theoretically calculated value • based on topography & rock type (density) • can indicate a dense mass (metallic deposit)
Seismic Method	Energy release (via explosion or vibration) & recording of reflection waves from rock layers (The different density of rocks with orientations reflect energy back to surface at different times) • **Seismic Survey**: Determine arrival time of refracted & reflected wave from bedding plane, Gives 3D cross-sections of subsurface geology • Rarely used in mineral exploration (high cost), & Used to locate position & dimension of traps
Radio-activity	Geiger Counter (α-radiation), Scientillometer (γ-radiation), Y-ray spectrometer (γ-radiation)
Aero-magnetics	Airborne, measures different magnetic responses of different rock types & helps to determine geology
Well-Logging	Gives information about physical properties of the penetrated beds during drilling in drill hole
Space-borne Spectral Imaging	Satellite imaging systems used to determine the spectral response of individual minerals (clay, Fe-ore) associated with metallic deposits • **Limitations** to date resolution of imagers (pixel sizes 10's m) & ability to discriminate spectra of individual minerals • Useful only in areas with limited vegetation



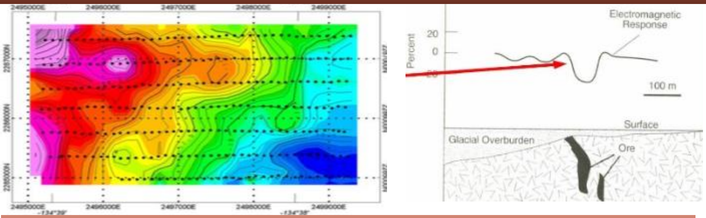
Methods of Radioactivity Survey



Gravity Survey



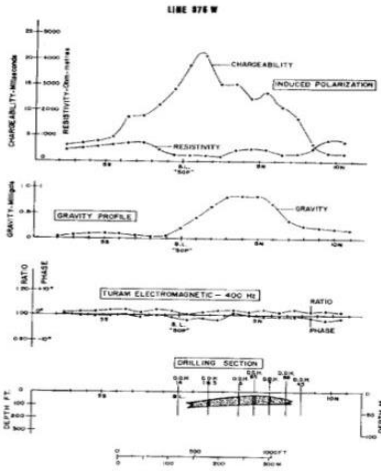
Magnetic Method (magnetic anomaly)

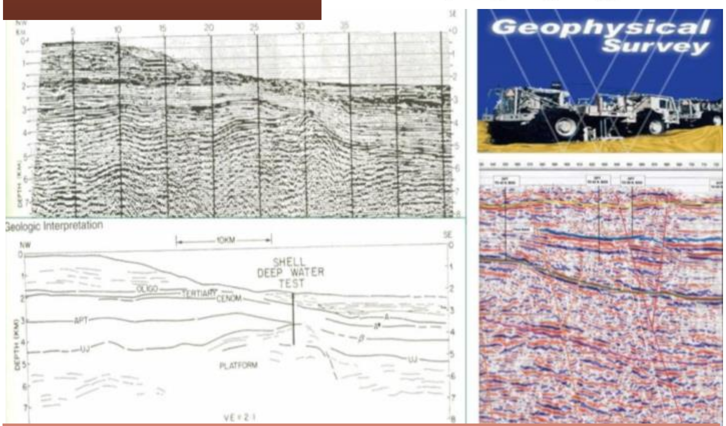


Electromagnetic Method

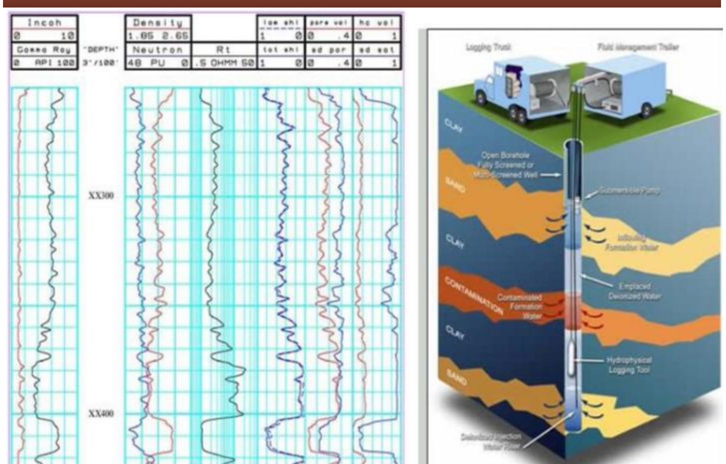
Combined Method

Results of induced polarization (top), gravity, & EM surveys The body displays a distinct chargibility anomaly (pyrite), low resistivity (dolomite), anomaly gravity (dense sulfides compared to less dense carbonate), & virtually no EM response (luck of pyritic or magnetite-rich massive sulfides)





Seismic Survey



Well-Logging Survey

Drilling Exploration Techniques

Drilling	
Percussion drilling (RAB)	Hammer drilling driven by compressed air & rock chips forced to surface by compressed air • Roughly related to hole depth, but contamination from hole sides & differential upward movement of chips depend on size & density
Reverse circulation (RC)	Double walled string of drill rods with percussion hammer or rotating coring bit to cut rock • Drilling fluid is supplied to the cutting surface between the rods & rock chips are returned to surface through the center of the rods & thence to a cyclone where they are captured • Method precludes much contamination from hole walls; still has chip density problems but not as severe, chips give little geological information (Drilling is cheap & relatively fast)
Diamond core drilling	A diamond armored Current wire-line technology allows the core barrel to be pulled to surface without pulling the entire string of drill rods • Gives the best sample but is most expensive

Drill Sizes	Hole [mm]	Core [mm]
AQ	48	27
BQ	60	36.5
NQ	75.8	47.6
HQ	96.1	63.5

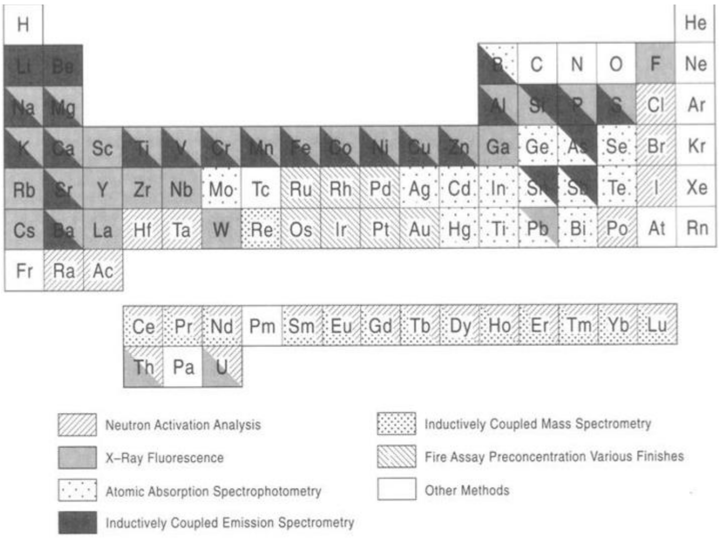
Geochemical Exploration Techniques

- Geochemistry prospecting from alluvial(placer) deposits

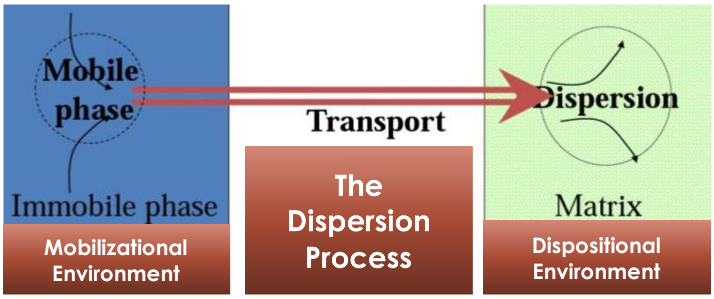
Techniques	Detect
Stream sediment	Trace metals derived from upstream deposit
Shallow soil geochemistry	Concentrations of minor residual or transported metals in soils
Laterite	Metals in or below highly weathered soils
Water geochemistry	Minor concentrations of metals in water flowing over or through a mineral deposit
Soil gas geochemistry	Hydrogen sulfide or other gases given off by oxidation of buried mineral deposits
Vegetative geochemistry	Abnormal concentration of metals in plants above or lateral to mineral deposit or recognize plants require high metals in soil
Bacteriological geochemistry	Detect metal-loving microorganisms living in soil above or lateral to mineral deposits

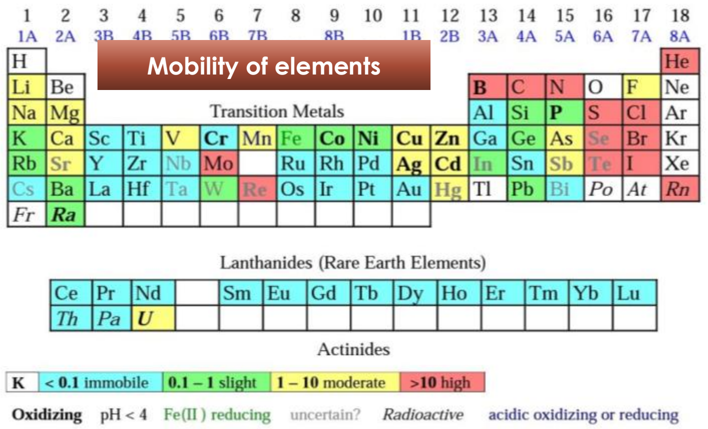
- **Geochemical Analytical Methods:** Analysis determine the elemental concentrations of metals in a sample. It is impossible to analyze all elements simultaneously at the required levels so different techniques are used

Geochemical Analytical Methods (differ in cost, detection limits, speed, and the need to take material into solution)	
ICP-ES	**Inductively Coupled Plasma Emission Spectrometry** $3/analysis (High cost, sophisticated lab, for trace metal)
ICP-MS	**Inductively Coupled Plasma Sourced Mass** $5/analysis (Very high cost, very sophisticated lab) • Very good precision for a wide range of metals • Used for water analyses, not mineral exploration
AA	**Atomic Absorption Spectrophotometry**: $1-4/analysis • Moderate capital costs, less sophisticated • Single element analysis & Good precision
XRF	**X-ray Fluorescence**: $17/lanalysis, multi-element • High capital cost, sophisticated laboratory • Utilize solids (not into solution), Good precision
Fire assay	Precious metals extracted by melting & result "button" is extracted from slag & analyzed by AA, & ICP-ES-MS • High cost, sophisticated lab depending on finishing method. Requires large sample, $10 – 50/analysis

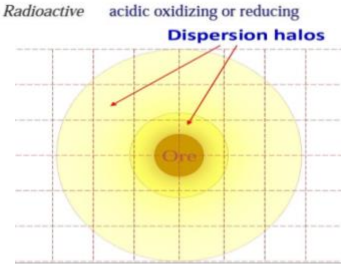


- **Geochemical Exploration** Surface geological processes disperse the components of the mineral deposits into the surrounding water, regolith, soil, vegetation & air

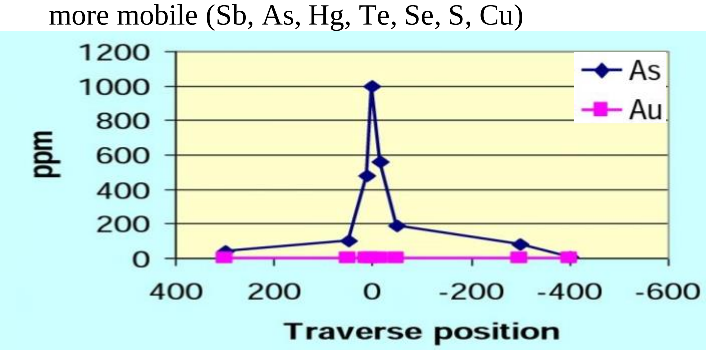




- **Geochemical Anomaly:** are chemically enriched zones (finger print occur in form of circular halos)
- **Indicator Elements (IE)**: Elements that associated with mineral deposits

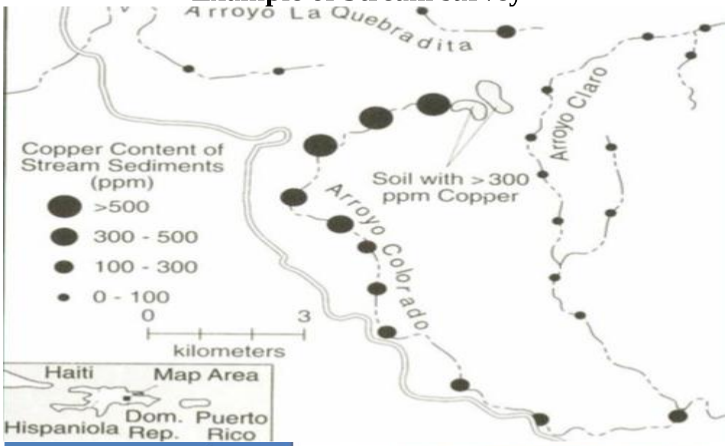


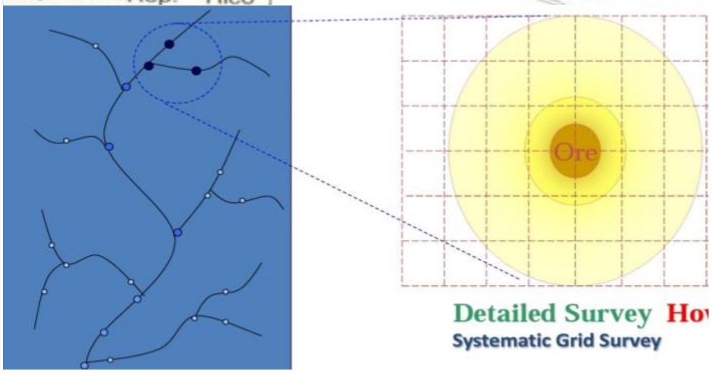
- **Pathfinders**: IE that are easier to analyze, to interpret & more mobile (Sb, As, Hg, Te, Se, S, Cu)



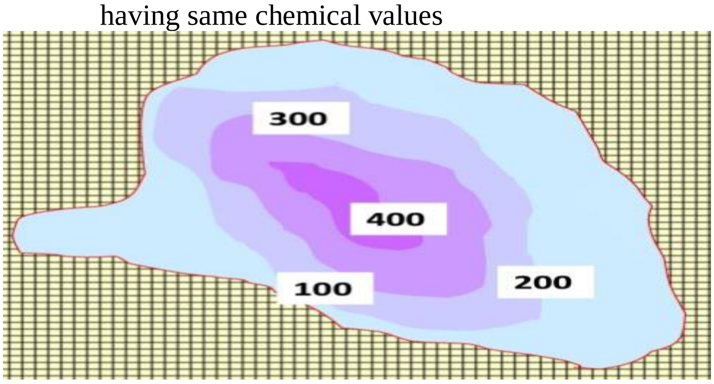
- **Methods of geochemical explorations:**
  1. Direct observations
  2. Analysis of samples (rock, water, soil or plant roots)
  3. Detection of gas leaks (radon, CH_4, He, Hg, sulfur)
- **Types of Geochemical Exploration:**
  1. Stream Survey
  2. Heavy Mineral Concentrates (panning) Survey
  3. Systematic Grid Survey
  4. Litho-Geochemical Survey

Example of Stream survey

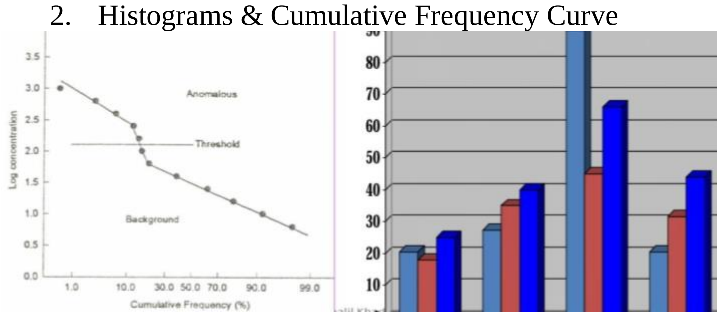




- **Interpretation of Data is to locate:** Background, Threshold, & Anomaly
- **Interpretation of Data is to locate include:**
  1. **Geochemical Contour Maps:** lines between point having same chemical values



  2. Histograms & Cumulative Frequency Curve



  3. Calculated threshold

$$\textit{Threshold} = \textit{Mean} + 2X\ \textit{Standard Deviation}$$

CHAPTER THREE

FORMATION OF ORE-DEPOSIT

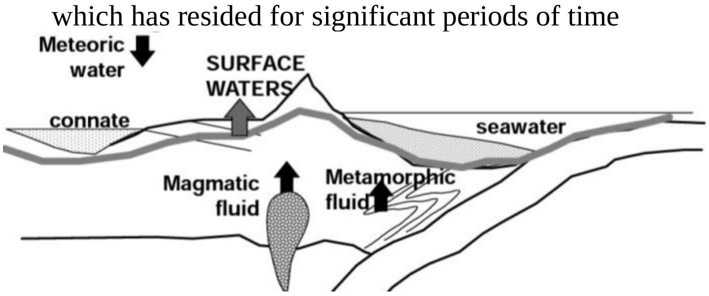
- **Requirements for formation of Ore Deposit:**
  1. Element of interest (source) & Energy
  2. Means of transport & Means to concentrate (trap)
- **All requirements are chemical processes**: Chemistry gives the parameters of possible, The great usefulness of chemistry in the study of ore deposits is less in attacking the deeper questions than in limiting the possibilities
- **Sources of Metals:**
  1. **Magmas**: juvenile rocks from lower crust & mantle
  2. **Crustal rocks & Seawater**

Question: Must a magma or rock mass be abnormally enriched in a metal before it can serve as a metal source?	
Yes	For **elements with crustal abundances < 1 ppm** (TI, Sb, Bi, Ag, Hg, Au): a concentration prior to reaction with fluids is commonly necessary (a metal-rich magma, prior concentration by earlier fluids, etc.)
No	• **For elements with crustal abundances of > 1ppm** (Fe, Mn, Ba, Cr, Ni, Zn, Cu, Co, Pb, U, etc.) • The important factor is whether the silicate are present or react with a fluid to release trace elements ➢ **K-feldspar-rich arkose or rhyolite** yield Pb-rich solution if broken down to release their Pb ➢ **pyroxene & olivine basalt** yield Cu-rich solution if mafic minerals are broken down to release Cu

- **Metals are Transported by Fluids such as**
  1. **Magma**: transport liquid silicate melts
  2. **Aqueous fluids**: water dominant (most important)
  3. **Non-aqueous fluids**: CO-rich & Hydrocarbon fluids

AQUEOUS FLUIDS

- **Sources of Aqueous Fluids**:
  1. **Surface waters**: seawater, atmospheric, & connate
  2. **Magma-water:** exsolved from crystallizing magma
  3. **Metamorphic-water**: derived from dehydration reactions during metamorphism (e.g. Conversion of clay to mica; of mica to other non-hydrous silicates)
- **Atmospheric water (meteoric):** water from atmosphere that then enters the lithosphere as groundwater
- **Connate water:** trapped in the pore space of sediments which has resided for significant periods of time



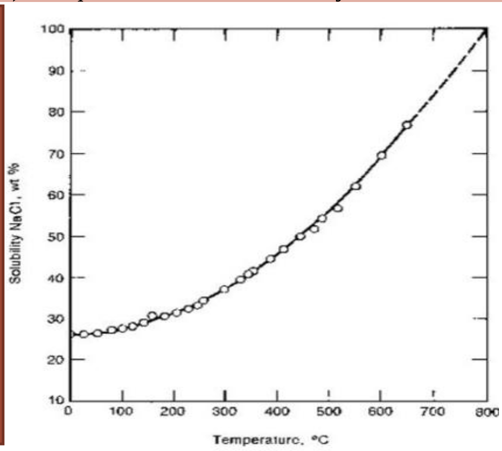
- Geologic occurrence indicates that many of ore deposits form by ***Hydrothermal solution*** (hot water), but metal sulfides are extremely insoluble
  - ➢ For Sphalerite (ZnS) at 25-200°C, 5-9pH, the solubility = $2x10^{-5}$-$1x10^{-8} g_{Zn}/1L_{H_2O}$. as Avg solution carries 107g/L so deposit 1ton require V = $10^{10}m^3$

Source of heat for hydrothermal fluids		
Magmatic Heat	**Directly**	**Water from magma**
	Indirectly	**Convection of surface waters around buried magma source**
Burial	**Shallow**	**Geothermal gradient: 15-40°C/km**
	Meta.	**Burial with tectonism**

- **What do actual hydrothermal fluids contain**: Analysis of modern hydrothermal solutions (geothermal fields) & ancient one (fluid inclusions) indicate that are highly saline brines with significant Na, K, Ca, & CI. Ore metals are rarely present but seem to be present in levels up to a few 10's or 100's ppm (> calculated pure water)
- Examining existing of hydrothermal fluid & experiment work to determine metal solubility in solutions indicate that **complex ion in solution increase metal solubility**

Types of complex ions in hydrothermal solutions	
Reduced sulfur species	Concentration of reduced S must exceed metal species,Most hydrothermal solutions don't contain large amounts of reduced S relative to metal • If a solution is sulfur-rich, the species such as $Zn(HS)^{3-}$ can form & carry metal in a solution
Chloride complexes (most important)	In Cl-rich solution, Aqueous species($ZnCl_2$,$CuCl_3$) will form under proper conditions (T-P) & carry significant amounts of metal if solution has a low concentration of dissolve S-species (metal>sulfur) • This fits with analysis fluids, precipitation of metal as sulfide (most common metals in ores) can continue until sulfide ions are consumed, unless more sulfur is added most of dissolved metals will not drop out of solution
Complex ions (volatiles, & alkalis) sources	
Magmas	**Give off large amounts of these elements** Vol%: H_2O > CO_2 > SO (7) > HCI (½-5) > CO
Seawater	**Avg. ppm:** S=905, Cl=18,800, & Na=10,770
Sediments	**Sulfates:** have abundant S (diagenetic Fe-sulfide) **Evaporites:** Contain abundant chlorine
The metals get into the solution by 2 ways	
Magma	In magma sulfur & chlorine metals are in solution • **Sulfide minerals (metal+S)** form in certain mafic magmas & settle (magmatic deposits) • **Volatile (H_2O,CI):** don't go to crystallizing minerals & concentrated in residual liquids • **The abundance of SO_2 in magmatic gases** indicates sulfur partitions into residual liquids • These fluids can be a late stage of magmas: If the metal has not partitioned into minerals (e.g. Pb to feldspar, Cu to mafic minerals), it can be concentrated in late stage of magma
Surface waters	Volatiles in a hydrothermal solution make solution weakly to strongly acid & able to breakdown minerals into metals in the solution (alteration), & At high T fluids carry large amount of alkalis (e.g. NaCl) so aqueous solutions are carry more metal

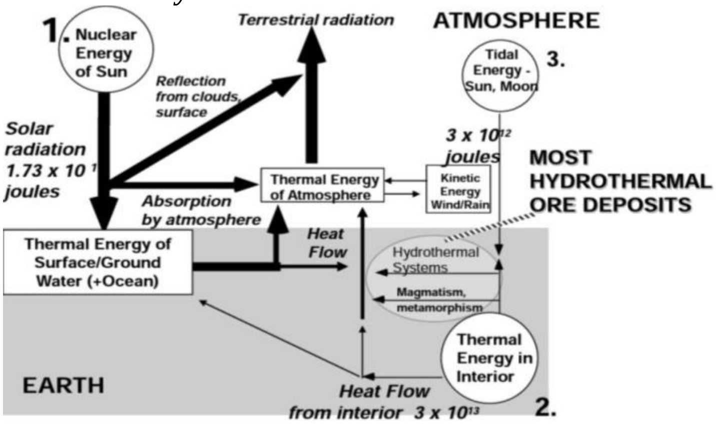
NaCl Solubility in water along the boiling curve (boundary between vapor & liquid) Extremely high [NaCl] in the fluid can occur



- **Hydrothermal Alteration:** is a type of metamorphism involving the recrystallization of a parent rock to new minerals more stable under the changed conditions

Movement of Hydrothermal Fluids

- Ore fluids travel variable distances before forming of ore deposit, In magmatic-systems the fluids may travel short (skarns) or long distance (Mississippi deposit, 100s Km)
- **In modern hydrothermal systems flow occurs by:**
  1. ***Dissolved fluids***: from cooling magmas
  2. ***Density differences***: induced by heat sources (e.g. intrusive rock), cause low-density (hot) fluids to rise
  3. ***Lithostatic pressure (compacting rock):*** reduces porosity & extrudes contained fluids upward
  4. ***Different hydrostatic head:*** between source & outlet
  5. ***Saline fluid:*** sink & displace less dense fluid upward
  6. ***Osmotic pressure***: derived from salinity differences
- **Energy needed to transported hydrothermal fluids:**
  1. ***Heat energy***: from magma or burial metamorphism
  2. ***Tidal Energy:*** derived from movement of seawater
  3. ***Tectonics***: pressure or lithostatic pressure
  4. ***Gravity***: fluids flow downhill

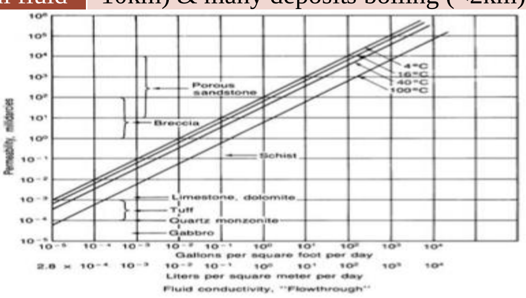


Most ore-deposits are formed by thermal energy from earth's interior. Solar & Atmosphere energy help to derive ground-water & seawater & effect hydrothermal system flow patterns

- A hydrothermal fluid must be able to flow through rock
- **Porosity:** is the ratio of pore volume to total volume (Vp/Vt), whether the pores are connected or not. (a porous rock may or may not be very permeable)
- **Permeability**: is the capacity of a rock to transmit a fluid across a pressure gradient, measured in darcies
  - ➢ **Darcy**: the passage of 1cm³ of 1 centipose viscosity in 1 second under 1atm pressure through a porous medium with 1cm² cross section area & 1cm length
- **Fluid movement depends on:**
  1. **Pressure** (**depth**): high pressures decrease porosity
  2. **Rock Type:** the permeability of rock are quantified, the movement of hydrothermal solution via a rock depend on viscosity (related to composition, ρ, & T)

Pressure	
Ore deposits	Form near surface (<3km) because these rocks transmit fluids copiously
Mineral assemblages in hydrothermal fluid	Indicate P <1000 bars (max depth 10km) & many deposits boiling (<2km)

Permeability are directly proportional to the conductivity & fluid temperatureBut inversely proportional to the density & salinity



- To form ore-deposit:
  - ➢ hydrothermal fluids must transport & then deposit their metals, but far-traveling must be in chemical & thermal equilibrium with surrounding rocks
  - ➢ hydrothermal fluid must drop (precipitate, or trap) its load of metals (weakly concentrated metals)
- **Metasomatic effects** from the passage of hydrothermal fluid are subordinate (include breakdown of specific minerals & collection of metals). So we would expect that most hydrothermal solutions would be neutral pH with respect to the wall rocks along their flow path

Means of precipitation (Trapping, or dropping) metals	
Changes in temperature	Drop in T cause reduction in the metals solubility & led to metal precipitation if the solution reache saturation (correct components are present) • T drop ≥ 20°C is needed to remove material from solution. To form ore deposit this drop must occur in a localized area which not expected with heat loss to wall rock • 2 main means of rapid T change probably: 1. **rapid adiabatic decompression (release P)** For instance when P change from lithostatic to hydrostatic over a short distance on approaching the surface or faulting which rapidly creates porosity & permeability 2. **mixing hot hydrothermal fluid with cold** near-surface water(seawater, groundwater..)
Changes in pressure	Cause solubility changes, but effect is minor unless there is separation of a vapor phase, The most important example is boiling (P drop across the vapor curve at isothermal T) • **Boiling has 2 important effects:** 1. Directly increases solution concentration 2. Volatile (such as S, & CI) are removed from solution leaving residue more alkaline & less capable of metal transport
Chemical reactions with wall rock	Observations indicate that certain ores are preferentially associated with specific wall rocks • **Kinds of reactions appear to be important** 1. **H-ions exchange with wall rock:** decrease pH (metasomatism), reduce Cl stability, & led to sulfide precipitation (e.g. dissolution of carbonates, feldspar & mafic mineral alteration or hydrolysis to form mica & clay) 2. **The addition component from wall rock:** such as addition of a reduced S-species from pyrite in a black shale, to the hydrothermal solution which causes the precipitation of a sulfides (sulfide precipitation in Cl-solution is limited by the amount of reduced sulfur) 3. **Cchange of oxidation state of a solution:** by change valence of metals (Cu, U, V) or stability of complex ions (S-species). Such as effect of carbonaceous compounds (e.g. hydrocarbons) that influence the state of metals & cause reduction of SO_4^{2-} to H_2S

Chemical changes due to solution mixing

Density of water (dashed lines) as a function of P-T
The solid line is the boiling curve, with Vapor (steam) below & water above, terminating at the Critical point where liquid water co-exists with vapor