ROCKY MOUNTAIN MINERAL LAW FOUNDATION
Science and Technology Series

AN INTRODUCTION TO GEOLOGY AND HARD ROCK MINING

By Dr. Willard Lacy

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A NOTE ABOUT THE AUTHOR

The Rocky Mountain Mineral Law Foundation is grateful to Dr. Willard Lacy's family for permission to publish this reformatted version of *An Introduction to Geology and Hard Rock Mining*. Dr. Lacy's work will continue to assist lawyers, landmen and others to gain an overview of this important field of work.

Dr. Lacy's family has provided a brief biography of Dr. Lacy to the Foundation. The Foundation is pleased to include it here in his honor.

Willard C. "Bill" Lacy passed away on December 7, 2013, having celebrated his 97th birthday.

Bill was born in 1916 while his parents were home on furlough from their posting as educational missionaries in China. He graduated from DePauw University and the University of Illinois and with World War II on the horizon, Bill interrupted a Harvard Ph.D program to take a job with Titanium Alloy Manufacturing Company to search for rutile, zircon and tantalum, materials that were critical to the war effort. Bill eventually enlisted in the Navy and was assigned to the Naval Aviation Supply Depot in Oakland, CA.

As the war ended, Bill went to work for the Cerro de Pasco Copper Company in Peru, where he rose to chief geologist in 1953. In 1955, Bill returned to the United States and was appointed full professor geology with tenure at the University of Arizona, where he established and served as the head of a combined Department of Mining and Geological Engineering.

In 1965, after a sabbatical leave, he was offered the position as the inaugural Professor of Geology at James Cook University in Townsville, Australia, where, with his colleague Roger Taylor, he put together a M.Sc. course that would allow working geologists to use their holiday periods, plus additional educational breaks allowed by the participating companies, to attend concentrated two-week short courses over a two-year period. This revolutionary idea was not welcomed by the Academic Board, which declared that it lacked academic excellence. It nevertheless proved to be an immediate success and hundreds of geologists have found the program to be a key to success in industry.

In 1977, Bill accumulated all the background research, selected the sites, and wrote the first rough script for what became a seven-part TV series, "Out of the Fiery Furnace," produced by Australian television. The series has been telecast world-wide and has been a major contribution to popular mining education.

After retirement in 1982, Bill returned to the United States, where Bill continued teaching short courses. He was the recipient of many professional awards and a lecture series at The University of Arizona's Lowell Institute of Mineral Resources is named in his honor.

An Introduction to Geology and Hard Rock Mining is Bill Lacy's voluntary effort to educate mining lawyers in the technology of the minerals industry.

February, 2015

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AN INTRODUCTION TO GEOLOGY AND HARD ROCK MINING
by Dr. Willard Lacy

INTRODUCTION

This paper is an introduction to selected topics in geology and hard rock mining. It is an overview and is intended to help the legal professional to learn basic information concerning these topics. References are provided to allow the lawyer or landman to delve more deeply into the subjects covered.

The broad goal of the Rocky Mountain Mineral Law Foundation is to educate professionals in natural resources law. The Foundation serves practitioners, academics, and others who work with natural resources law. The objective of the Foundation's *Science and Technology Series* is to assist lawyers, landmen, legislators, and teachers to understand the basic technology, economics and science underlying the practice of natural resources law. This paper is the first in that *Series.*

CHAPTER 1

PRINCIPAL REFERENCES FOR THE SCIENCE AND TECHNOLOGY OF GEOLOGY AND HARD ROCK MINING

The practitioner seeking additional information about the topics discussed in this paper will find many technical and scientific references available. The following principal references are listed in order of importance.

1) *SME Mining Engineering Handbook*, 1992, H.L.Hartman, ed., Society for Mining, Metallurgy and Exploration, Inc., Littleton, CO, 2260 p.

2) *Nonfuel Mineral Resources and Public Lands*, 1969, Prepared for The United States Public Land Law Review Commission by: The University of Arizona, G.F.Leaming, W.C.Lacy Investigators, 5 Volumes.

3) *Anatomy of a Mine, From Prospect to Production*, 1977, U.S.D.A. Forest Service, General Technical Report INT-35, Prepared by H.Banta, 69 p.

4) *Minerals - Foundations of Society*, Ann Dorr, 1984. League of Women Voters of Montgomery County, M.D.Inc. 56 p.

CHAPTER 2

BASIC GEOLOGY

I. FIELDS OF BASIC GEOLOGY AND DEFINITION OF MINERALS

Geology is the study of the earth, its surface configurations, and the physical and chemical processes acting upon its surface and its interior. It is the study of the earth's composition and physical and chemical processes which act upon it. Geology has developed into several areas of special interest (**Figure l**).

PHYSICAL GEOLOGY deals with the physical behavior of the earth, how it was formed, and the processes which have, or have had, effects upon it.

GEOPHYSICS is a more specialized study of the physical properties of the earth (e.g. its vibrations, density, magnetism), the basic physical forces which affect it (e.g. gravity), and the effects of these forces.

GEOCHEMISTRY is the specialized study of the composition of the earth, its components, and the chemical processes taking place at the surface (e.g. reactions of the lithosphere with the atmosphere and hydrosphere), and reactions at depth under the influence of heat, pressure and deformation forces, radioactive decay and isotopic relations.

HISTORICAL GEOLOGY deals with the history of the earth, its changing environment and the development of life forms.

GEOCHRONOLOGY involves the study of the ages of rocks, minerals, plants, fossils and events as measured by ratios of radioactive decay elements found in existing rocks, analyses of tree rings and sediment layers.

MINERALOGY AND PETROLOGY are concerned with the chemical composition, physical characteristics, nature of formation, occurrence, and atomic structure of minerals and rocks. Minerals are the component materials of all rocks and soils. Petrology involves investigation of the mineral and chemical composition of rocks, and the various chemical and physical processes which led to their formation.

A **MINERAL** is any naturally occurring element or inorganic substance having a definite (or variable within fixed limits) chemical composition and crystalline structure. Deposits of coal, petroleum and naturally occurring brines do not fit such a rigorous definition, but have in generic terms also been considered minerals, principally because they are not readily identifiable as either animal or vegetable. (This is an area of controversy.) Supplies of groundwater have been described by some to be mineral in character, because water is a naturally occurring substance found in the earth's crust that is not organic in origin. (**Figure 4**)

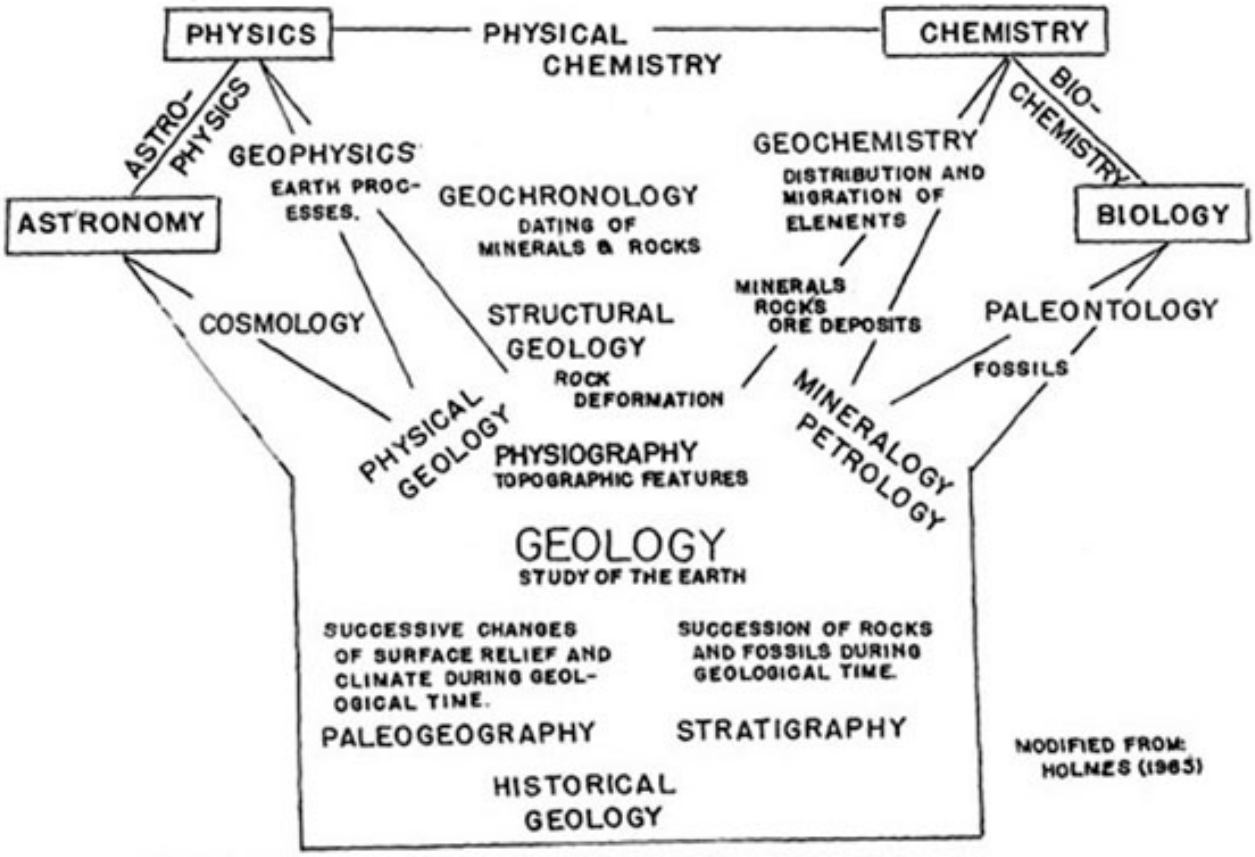


Figure 1: Fields of Basic Geology -- EXPLANATORY NOTE.

The broad field of geology, "the study of the earth," calls upon concepts and laws established in many fields of science. Figure 1 illustrates those areas of shared interests.

ROCKS are solid, cohesive aggregates of one or more types of minerals, which have formed as a result of various geological processes. Rocks are classified not only according to their mineral content, but also in accordance with their mode of formation (igneous, sedimentary, metamorphic), chemical composition, grain-size, and physical appearance.

UNCONSOLIDATED SEDIMENTS consist of loose rock fragments of all sizes which have been transported by water, air, ice, gravity and accumulated on floodplains, and in valleys, lakes and oceans.

SOILS, from a geological point of view, constitute a surficial mantle over rock in which physical and chemical processes of weathering cooperate in close association with biological and agricultural processes.

SEDIMENTOLOGY is that branch of geology concerned with the transport and deposition of sediments and sedimentary rocks.

HYDROLOGY is concerned with all aspects of the earth's hydrosphere - water in the atmosphere, surface and subsurface water, and the effects of the hydrosphere on climatic changes and the water balance.

STRUCTURAL GEOLOGY is that branch of geology concerned with the attitudes and positions of rock formations relative to each other, the sequence of events that caused these formations to arrive at their existing configurations, and the forces responsible for these events. The geological map is the principal tool of the structural geologist. It shows existing rock relationships and permits interpretation of past relations and forces.

ECONOMIC GEOLOGY involves the theories of formation, the physical and chemical characteristics, the environments favorable for formation, and different methods and techniques for discovery of potentially economic mineral deposits. It involves a familiarization with mining and metallurgical technology, and the economics of the mineral industries.

II. GEOLOGICAL PROCESSES

Figure 2 is an overview of the geological/geochemical cycle.

A. IGNEOUS PROCESSES

Pressure and temperature within the earth increase gradually with distance below the surface. At depths of several tens of miles the material which makes up the earth's crust (depending upon its composition) may become partially molten. This molten material is MAGMA, and is normally less dense than the overlying solid rock. As the magma is subjected to tectonic forces, it may be squeezed upward along weak zones in the crust. This process by which magma penetrates the crustal rock is called INTRUSION. The intrusive magma which has cooled and solidified is known as IGNEOUS ROCK (granite, granodiorite, diorite, gabbro).

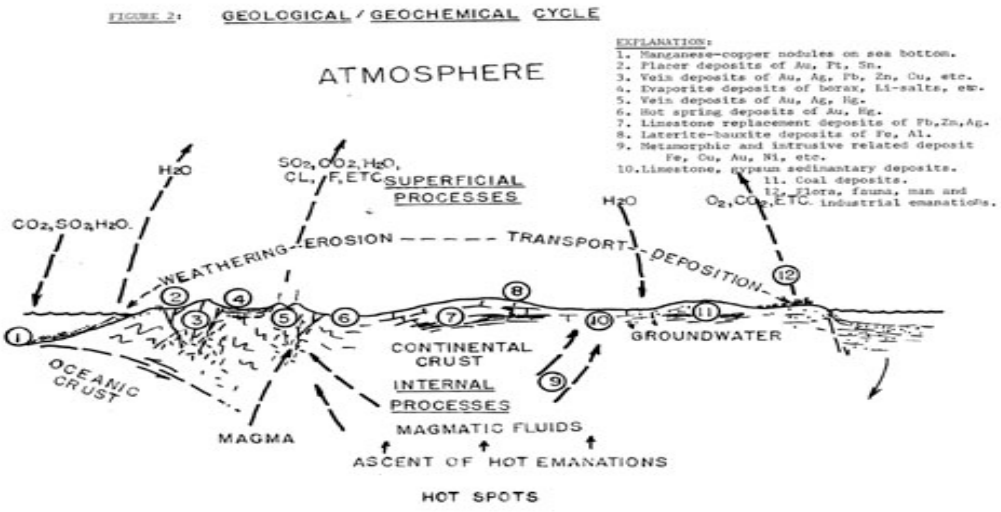


Figure 2: Geological/Geochemical Cycle -- EXPLANATORY NOTE.

Physical and chemical processes interact at the earth's surface (SUPERFICIAL PROCESSES) between the exposed rocks of the lithosphere, the atmosphere, the hydrosphere, and flora and fauna. Rocks are weathered, taking water, carbon dioxide, oxygen, and sulfur dioxide from the atmosphere. Weathered products are physically transported and sorted by stream, lake and ocean currents, or carried in solution to lakes or seas where they may be precipitated (limestone, gypsum, iron oxide, etc.) or retained as a brine (salt, magnesium sulfate, etc.).

The oceans release water to the atmosphere, and absorb carbon dioxide and sulfur dioxide from the atmosphere to form limestone and gypsum.

Tectonic frictional forces and/or concentrations of radioactive materials within the earth's crust and mantle generate heat, partially melting crustal rocks to form magma and releasing emanations into the crustal host rocks (INTERNAL PROCESSES), and on the surface as hot springs, and into the atmosphere as various gases (H20, S02, C02, Cl, F, etc.). These in turn may react with rocks of the lithosphere or are absorbed by the oceans.

These processes serve to concentrate mineral and metal components - by stream and ocean currents as placer deposits (Au, Pt, Sn. diamonds), within hot spring deposits (Au, Hg, Mn, Fe), as evaporite deposits in playa lakes (salt, borax, Li-salts, etc.), as veins and disseminations and replacements within fractured rocks (Au, Ag, Cu, Pb, Zn, etc.), and as segregations within the solidifying magma (Cu, Ni, Fe, etc.).

Flora absorb C02 from the atmosphere to form carbon products and releases oxygen to the atmosphere. Accumulations of plant material under reducing conditions results in the formation of peat and coal.

Some magma reaches the surface of the earth and pours out, explosively or slowly, from volcanoes or fissures in the earth's crust in a process known as EXTRUSION. A magma which pours out over the surface is called LAVA, as long as it is molten, and VOLCANIC ROCK when solidified. When the magma erupts rapidly and explosively into the air, it is fragmented into small particles which solidify into VOLCANIC ASH. Larger particles called CINDERS, VOLCANIC BOMBS, and angular rock fragments comprising BRECCIA and AGGLOMERATE. When the ash settles to the ground and solidifies it may in time be compacted into TUFF, or if welded by contained heat in GLOWING AVALANCHES, it is called IGNIMBRITE.

Heat source for the formation of magmas may be residual heat from the earth's formation, heat generated by tectonic movements, or 'hot spots' from local tectonic heating and/or concentrations of radioactive materials.

B. WEATHERING AND EROSION

Decomposition and disintegration of rocks at or near the surface by physical and chemical processes is called WEATHERING. The products of weathering are normally carried off by EROSION. Water percolating into the ground dissolves some minerals from the rocks and forms acidic or basic solutions which further attack the rock and break it down chemically.

The action of groundwater is selective under certain conditions, and may leave some elements or minerals in place while altering or leaching others. The weathering and subsequent erosion of aluminum or nickel bearing rocks may leave residual or secondary deposits (LATERITES) of materials rich in these metals.

Downward slope movement of soils and rock fragments impelled by gravity, MASS WASTING, is an important part of erosion. Decomposed rock materials are transported by wind (as sand and dust), by water (in streams, rivers, and ocean currents) and by ice (in glaciers).

C. SEDIMENTATION

The process of sedimentation entails the physical and/or chemical movement of the products of weathering to sites of deposition -- through chemical precipitation, evaporation or physical settling. The accumulated weight of sediments, over time, results in compaction and chemical action (DIAGENESIS) that may cement particles together so that sediments are lithified and converted into SEDIMENTARY ROCKS (shale, sandstone, limestone, etc.). Sediments are usually deposited in nearly horizontal layers. Changes in character and rates of deposition may cause development of distinct planes called BEDDING PLANES, which separate the sedimentary layers.

D. METAMORPHISM

Heat and fluids emanating from magma may alter the adjacent rock creating a halo of CONTACT METAMORPHIC ROCKS. Rocks which become deeply buried are subjected to heat and pressure, which with the aid of contained or introduced fluids, and tectonic forces are metamorphosed. Original bedding may be destroyed and a FOLIATED structure developed.

E. TECTONIC PROCESSES

The earth is a dynamic body, undergoing constant movement of both continental and oceanic crust, driven by convection currents and readjustments in the earth's mantle. Different portions of the earth have, at different times, been uplifted above or depressed beneath the seas. Other areas have crumpled rock layers into FOLDS, FAULTS, OVERTHRUSTS, while other areas have been pulled apart forming RIFTS, HORSTS AND GRABENS. The contact between drifting continental masses and spreading oceanic crust is particularly subject to deformation and intrusive/volcanic activity resulting from the SUBDUCTION of the oceanic crust under the continental crust at CONVERGENT MARGINS. Where DIVERGENT MARGINS occur, RIFTS form in the MIDOCEANIC RIDGE (**Figure 2**).

F. MINERAL DEPOSITION

Groundwater solutions (METEORIC WATER), and/or solutions emanating from a cooling magma (HYDROTHERMAL FLUIDS), and/or fluids ejected from compressing sediments (POREWATER or CONNATE WATER) penetrate along fractures and tiny pore spaces between mineral grains in the rock. Under certain conditions these solutions, which contain different compounds, may dissolve, deposit other minerals, or alter the rock-forming minerals (ROCK ALTERATION).

Leaching, or the decomposition, dissolution and removal of soluble minerals from the rocks may be caused by hydrothermal or meteoric solutions. The dissolved mineral products may be dispersed or redeposited elsewhere as the same or different minerals, leaving often greater concentrations (ENRICHED). For example, relative content of gold may be increased by the removal of originally associated minerals, leaving an enriched residual gold deposit. And, portions of a copper sulfide deposit in the weathered zone may become enriched through the leaching of the copper content from the surface rocks by downward percolating meteoric waters and redeposition at the watertable.

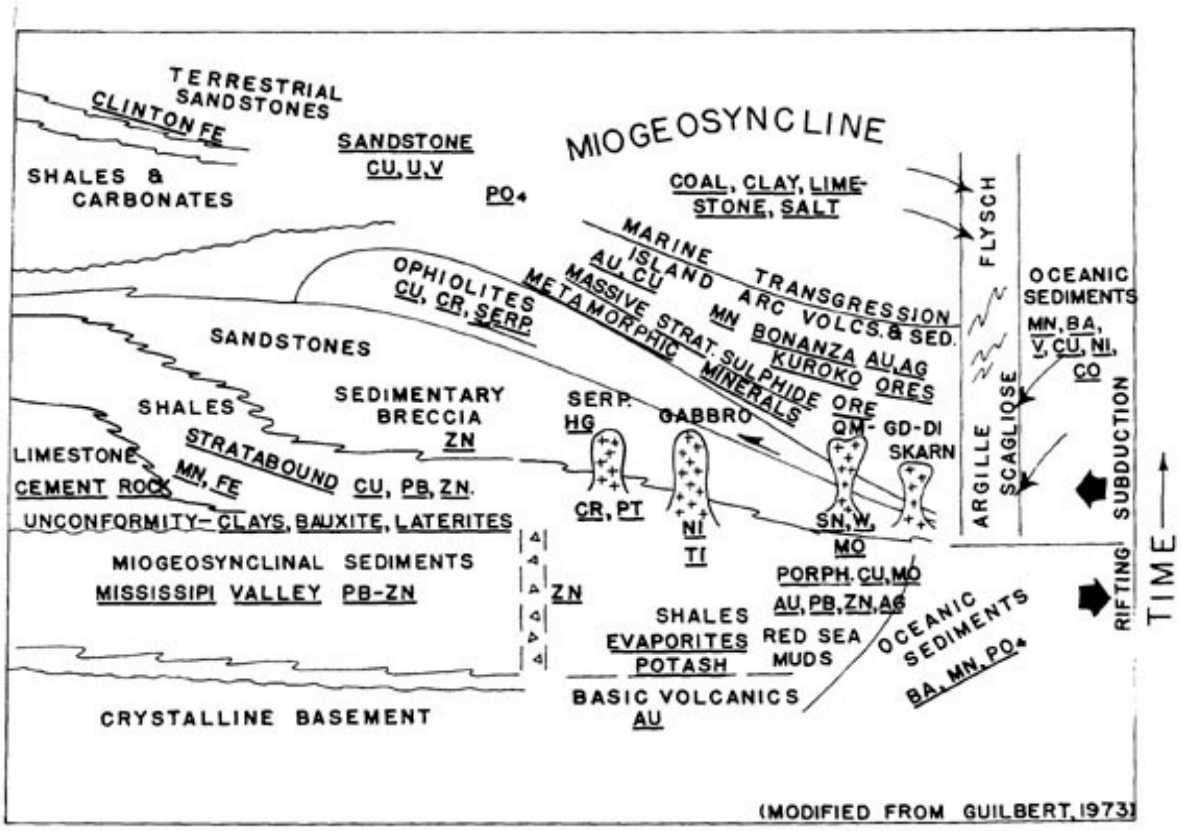


Figure 3: Time/Distance Chart -- EXPLANATORY NOTE.

The Time/Distance chart illustrates the environments of ore deposits relative to major tectonic features. The Appalachian Region of North America serves as the illustrating model with different types of ore deposits related to periods of crustal rifting, and to periods of crustal subduction. The exploration geologist with an understanding of stratigraphic and tectonic history of the rocks of an area can predict "most likely" discoveries - metal content, types of deposit, and age of host rocks.

III. GEOLOGICAL STRUCTURES

A. IGNEOUS STRUCTURES

Any intrusive igneous body is a PLUTON. Intrusives occupying a small area, having an irregular to cylindrical shape, and cutting across the intruded rock is called a STOCK. If such an intrusion occupies an extremely large area, it is referred to as a BATHOLITH. Some cross-cutting plutons gradually lose their penetrating force during the latter stages of intrusion, and merely push the overlying rocks upward rather than cutting through them, thus form DOMES or LACCOLITHS. DIKES are tabular intrusions which cut across enclosing rock, while intrusions that penetrate parallel to bedding or foliation are called SILLS. (Igneous structures are shown in Figure 3a.)

Extrusive structures result from volcanic activity. During such activity the extruded material (lava, ash or cinders) may spread outward in gently-dipping layers, or may flow from a fissure or vent. Often, however, this material accumulates adjacent to the volcanic crater in the form of a CONE. CALDERAS are enlarged craters, formed through partial collapse of underlying rock, or through explosive activity. The subterranean conduit for a volcano is called a PIPE, PLUG, or NECK.

Igneous intrusions often brecciate the rock along their margins and the path in advance of their path forming STOCKWORKS and BRECCIA PIPES, and a complex of mineralized fractures.

A VEIN is a relatively narrow tabular mineralized structure. A LODE is either a single vein or a system of related roughly parallel vein. A STOCKWORK is a mass of intersecting veins. All are related to late magmatic hydrothermal fluid deposition, or deposition from circulating ground waters.

B. SEDIMENTARY STRUCTURES

Horizontal and/or vertical movements of the earth's crust and the effects of igneous intrusions may crumple layers of sedimentary rocks into folds. Downwarped beds form SYNCLINES and upwarped beds form ANTICLINES. Long, relatively narrow, and very large warps of the earth's crust are designated as GEOANTICLINES or GEOSYNCLINES. Where the downwarping is large, significant portions of the continental crust may become flooded and become the site of widespread deposition of sedimentary rocks, often attaining great thicknesses -- the environment of great thicknesses of limestone. Smaller rounded downwarps are designated as BASINS. (Sedimentary structures are shown in Figure 3a.)

Formations of sedimentary rocks are seldom uniform in thickness. The deeper portions of sedimentary troughs or basins receive thicker sediments, and the layers of sediments thin and pinch out at the margins of depositional areas. Shifting currents in the water or air or obstructions may result in beds deposited at angles to each other (CROSS-BEDDED).

Silt, sand and gravel deposited in and on the margin of streams or rivers (FLOODPLAIN DEPOSITS) form discontinuous, serpentine-shaped deposits. Melt-waters from melting glaciers deposit a variety of OUTWASH GRAVELS, ESKERS, MORAINES, TILL, etc., that form distinctive land forms.

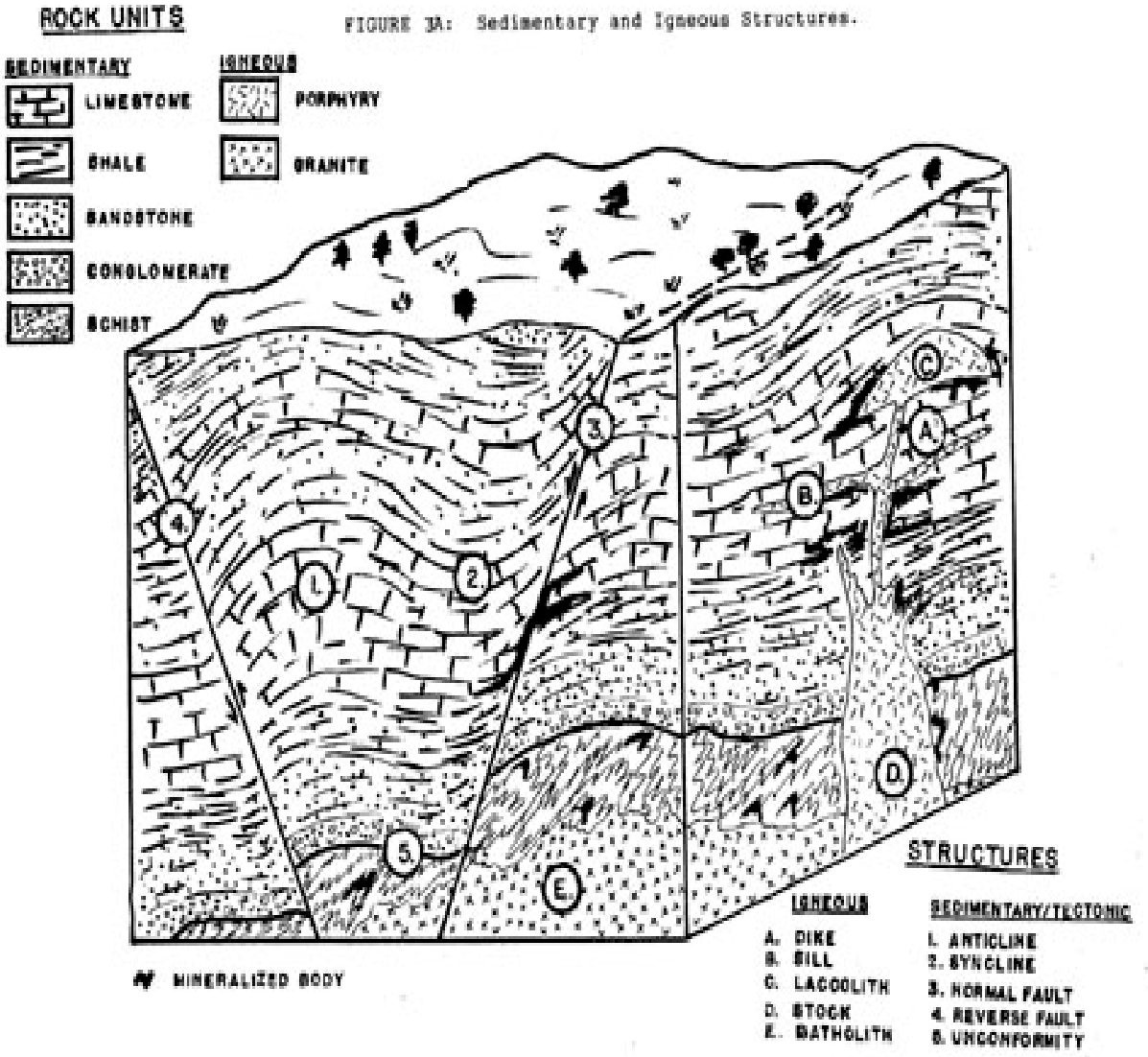


FIGURE 3A: Sedimentary and Igneous Structures.

Sedimentary beds deposited on an older erosion surface are said to unconformably overlie the older rock. The older and younger beds may be parallel (DISCONFORMITY) or the younger beds may rest on tilted older beds (ANGULAR UNCONFORMITY).

C. TECTONIC STRUCTURES

Where forces exerted by the earth movements exceed the strength of the rock or its ability to bend into folds, the rock is broken and segments on opposite sides of the break may be moved relative to each other. The rock is designated as FAULTED. Relative movement along FAULTS may be vertical, lateral or diagonal (or all three at various times) with relative displacement from less than an inch to hundreds of miles laterally, and tens of miles in depth. Different faults range in attitude from nearly horizontal to vertical.

Rock caught between opposing walls of a fault may be ground completely to rock flour (GOUGE) or crushed into angular fragments (FAULT BRECCIA).

D. LANDFORMS

Erosional processes (air, water, ice) etch the land surface revealing underlying rock structures and rock character. In addition, surface processes (fluvial, glacial, volcanic, etc.) leave deposits having characteristic forms, and mass-wasting leaves evidence of landslides, mud flows, etc. This evidence facilitates geological analysis using aerial photographs and satellite imagery.

IV. GEOLOGICAL TIME SCALE

The history of the earth falls into distinct ERAS (**Figure 7**). The oldest era, the PRECAMBRIAN (ARCHEOZOIC and PROTEROZOIC), was by far the longest and is the period about which we know the least. Rocks formed during the Archeozoic resulted from extensive intrusive and extrusive igneous activity and have been affected by profound metamorphism. They comprise the BASEMENT COMPLEX on which younger sedimentary rocks rest. The younger Precambrian (Proterozoic) sediments can hardly be distinguished in places from the overlying PALEOZOIC SEDIMENTS.

The more recent eras of geologic time (PALEOZOIC, MESOZOIC, CENOZOIC eras) have many subdivisions and are partly defined by mountain-building OROGENIES or REVOLUTIONS, and partly by changes in the types of plant and animal life evidenced by fossil remains.

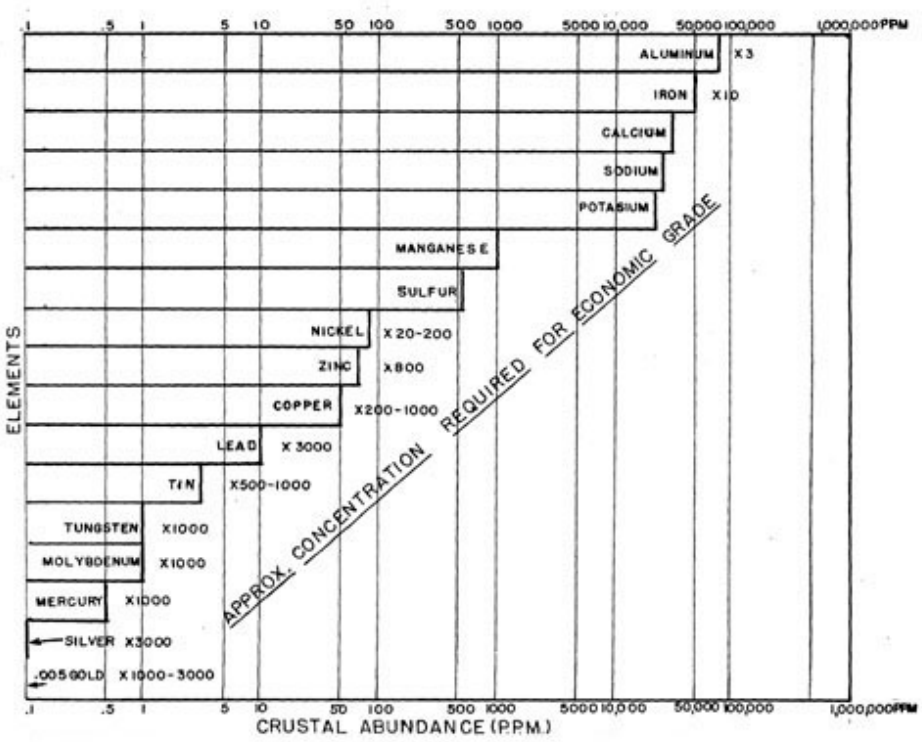


Figure 4: Crustal Abundance of Metals in the Earth's Crust -- EXPLANATORY NOTE.

The earth's crust contains all of the natural elements, but, normally in concentrations well below economic grade. In order to increase the concentration to a level that can be economically mined, concentrated and marketed, geological processes (chemical and/or physical) must enrich the element by solution and selective precipitation, by removal of unwanted material, or by selective physical transport and deposition.

For example, aluminum, which comprises approximately 8% of the earth's crust, requires about three times concentration to achieve an economic grade. This is usually accomplished by leaching of silica from rocks under tropical weathering conditions. Gold, on the other hand, is contained as five part per billion average in the earth's crust. In order to attain an economic level of concentration, it requires enrichment 1000 to 3000 times. This may be accomplished chemically through selective precipitation from solution, or physically as a consequence of its high specific gravity.

V. ECONOMIC GEOLOGY

The earth's crust is not a homogeneous rock mass, and, although every element may have an average crustal concentration, in very few specific areas does any element exist in exactly that average concentration. Geologic processes, past and present, may result in concentration or depletion of certain elements. Some crustal regions show concentrations of certain elements and are identified as METALLOGENIC PROVINCES. Also, certain periods in the earth's evolution favored the concentration of certain metal components. These periods are identified as METALLOGENIC EPOCHS. For example, most banded iron formations were formed between 3500Ma and 1800Ma, and porphyry copper-moly-tin deposits were formed between 130Ma to the present. Identification of metallogenic provinces and epochs are important in broad guidance of mineral exploration programs (**Figure 6**).

The useful elements in the earth's crust do not normally occur in sufficient concentrations and in the proper chemical combinations to allow for them to be commercially extracted from the earth for man's use at the present time. They must be found in a relatively concentrated state and in a specific chemical form in order to be utilized. Such concentrations of the proper chemical compounds, enriched within the GEOCHEMICAL CYCLE in the earth's crust we refer to as VALUABLE MINERAL DEPOSITS. Concentration is brought about through various geological processes.

Chemical elements, including the ore metals, are unevenly dispersed through the lithosphere and are continuously being cycled and redistributed under the influence of the earth's dynamic geological processes. The geochemical cycle represents the complex physiochemical changes and varieties of processes that earth materials and their contained elements follow in response to those processes. It entails both deep-seated and surficial geological environments (**Figure 2**).

VI. DEFINITIONS

A. ORE

ORE is a concentration of minerals that can be mined processed and marketed at a PROFIT. It is economically defined.

(A distinction must be made between ORE and ORE MINERALS. A deposit of ore minerals in geological terms is not always an ore deposit.) While an ore mineral (**Table 1**) is a mineral from which a metal can feasibly be extracted, an ore deposit (or an orebody) is a mass of rock from which a metal or mineral can be profitably produced. What is, or is not, becomes dependent upon economic, technological, and political factors as well as geological criteria.

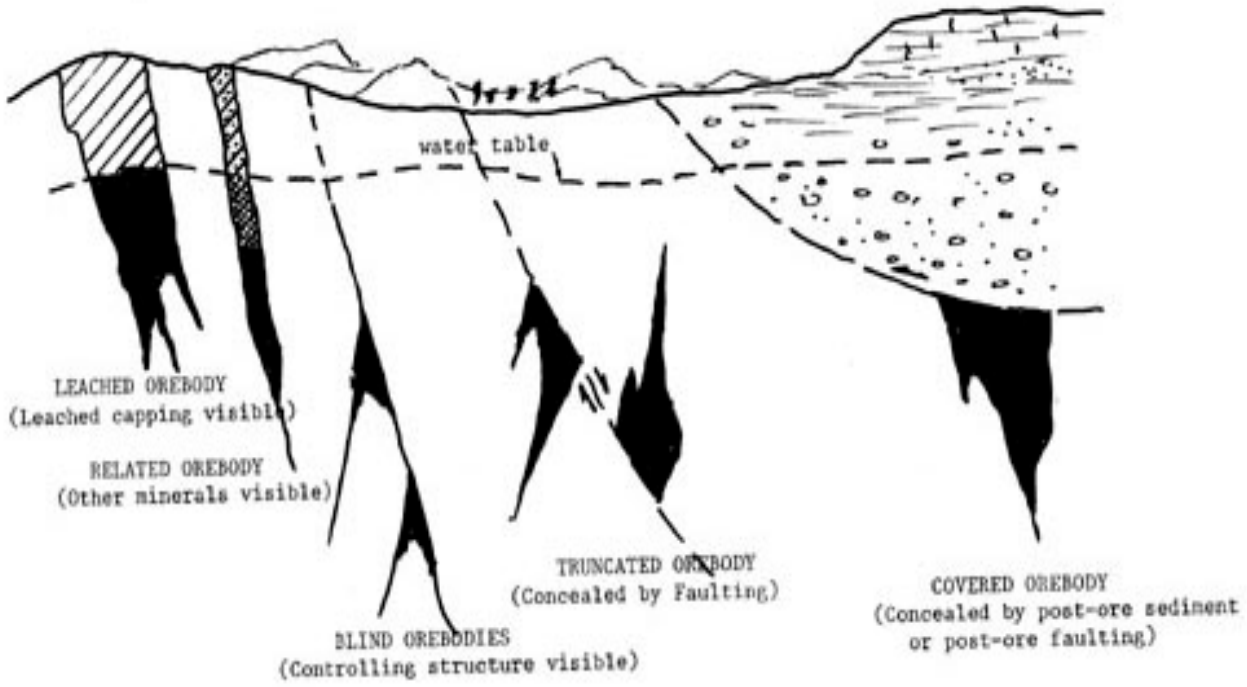


Figure 5: Concealed Orebodies -- EXPLANATORY NOTE.

The search for mineralized bodies with economic concentrations requires interpretation of what can be seen at the surface, and what may exist in depth. Figure 5 illustrates some of the situations the exploration geologist may confront, from leached and weathered outcrops of deposits, mineral concentrations that are localized by structures at depth, to deposits concealed by post-mineralization cover.

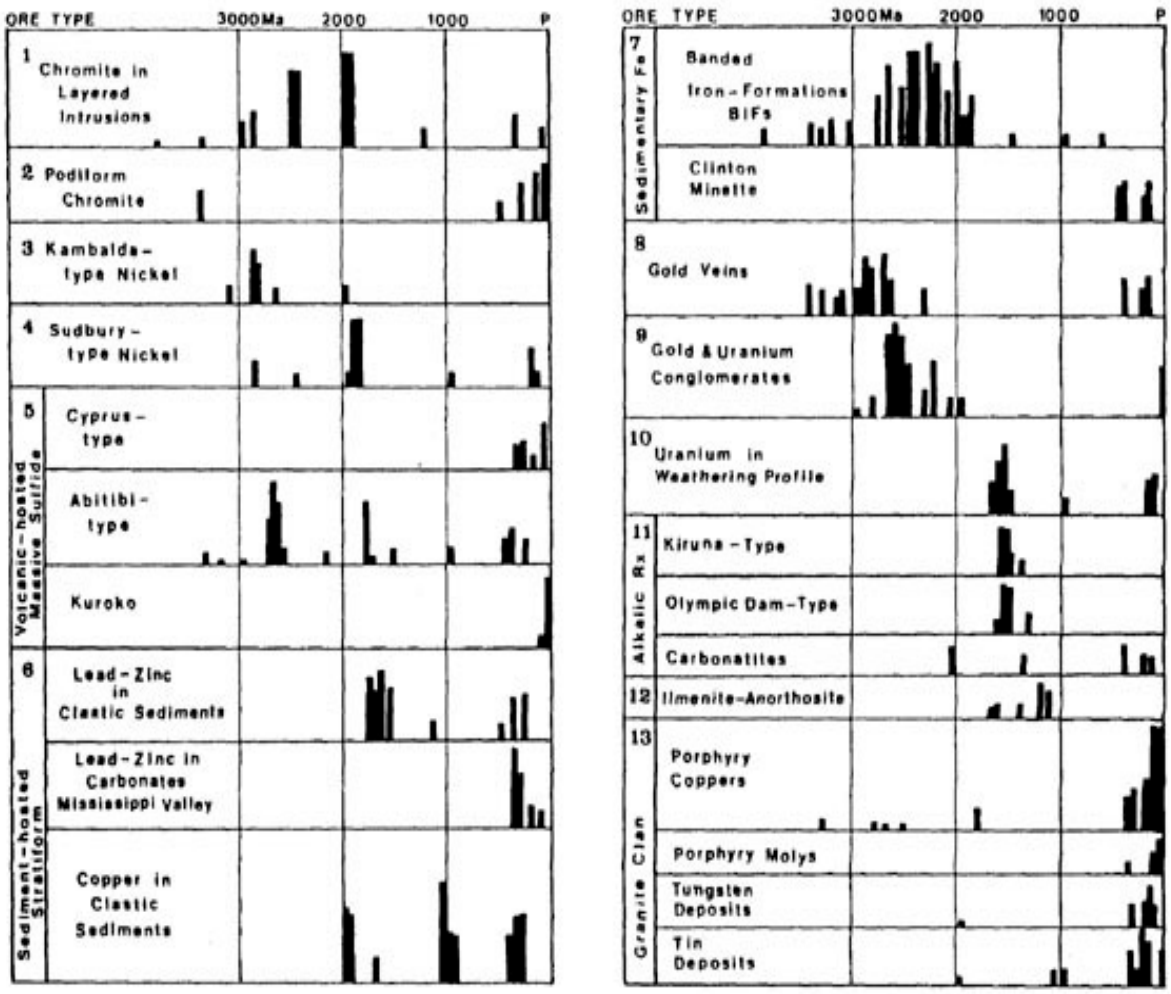


Figure 6: Time Distribution of Metal Deposits -- EXPLANATORY NOTE.

The earth, its interior, hydrosphere and atmosphere are undergoing evolutionary changes with time. These changes are reflected in the nature and timing of metal concentration processes. The result is development of METALLOGENIC EPOCHS. The exploration geologist is thus able to predict 'most likely discoveries' of metal and type of deposit in rocks of known age.

B. WASTE

Within a given mineral deposit ore minerals are normally associated with other minerals which are less valuable or lack value. These are termed GANGUE MINERALS (**Table 2**). The rock which does not contain an adequate percentage of ore minerals to be economically valuable as a source of these minerals is called WASTE.

Waste, like ore, is an economic rather than a geologic term, and changing technology, economic, or political conditions may change waste to ore, or back again, many times. For example, the Mount Morgan gold/copper mine in Australia underwent four life cycles. The first was when gold was easily extracted by gravity separation. The second was when flotation processes were introduced and copper sulfide could be recovered. The third was when mining shifted from selective underground mining to open pit bulk mining. The fourth was hydrometallurgical processing of "waste" materials.

C. CUT-OFF

Many factors: cost of mining and metallurgical treatment, percentage of recovery of metal values during treatment, deleterious elements present, cost of transport and marketing, metal or mineral pricing, taxes and royalties, etc. all influence the ore/waste transition. The transition from ore to waste is known as the CUT-OFF.

VII. ORE-FORMING PROCESSES

See Figure 2.

A. Weathering and erosion

Weathering and erosion results in the breakdown of rock minerals. Elements may be concentrated as resistant elements left behind, or in the mobile elements removed and transported in solution, or carried and concentrated during the erosional processes.

B. Igneous/volcanic processes

Igneous and volcanic processes may result in concentrations through crystallization and differential gravity settling, concentration in end phases of crystallization, evolved fluids, or as a consequence of heat energy introduced by the intrusives.

C. Sedimentation/diagenesis.

Gravity separation and concentration may occur within clastic sediments in streams, lakes, and by ocean shore currents. As pore-waters are expelled from compacting sediments they may selectively leach, carry and deposit specific elements.

Figure 7:

Geological Time Scale.

EON	ERA	PERIOD		EPOCH	AGE (m.y. ago)
Phanerozoic	Cenozoic	Quaternary		Holocene	0.01
				Pleistocene	1.6
		Tertiary	Neogene	Pliocene	5.3
				Miocene	23.7
			Paleogene	Oligocene	36.6
				Eocene	57.8
				Paleocene	66.4
	Mesozoic	Cretaceous		Late	
				Early	144
		Jurassic		Late	
				Middle	
				Early	208
		Triassic		Late	
				Middle	
				Early	245
	Paleozoic	Permian		Late	
				Early	286
		Carboniferous	Pennsylvanian	Late	320
			Mississippian	Early	360
		Devonian		Late	
				Middle	
				Early	408
		Silurian		Late	
				Early	438
		Ordovician		Late	
				Middle	
				Early	505
		Cambrian		Late	
				Middle	
				Early	570
Precambrian	Proterozoic	Late			900
		Middle			1600
		Early			2500
	Archean	Late			3000
		Middle			3400
		Early			3800?
	pre-Archean				4550

Geologic time scale. Age estimates of time boundaries are in millions of years (m.y.). Ages (subdivisions of epochs) are not shown. Sizes of time "slots" do not reflect proportionate lengths of time intervals. Rocks older than 570 m.y. are called Precambrian, a time term without specific rank. Geologic time prior to 3,800 m.y. ago is called pre-Archean, a term also without specific rank. The Mississippian and Pennsylvanian Periods, recognized in the United States, are collectively referred to as the Carboniferous Period, a term commonly used by geologists in other parts of the world. The Neogene and Paleogene are subperiods of the Tertiary Period. Modified from Palmer, 1983, p. 504.

Figure 7: Geologic Time Scale -- EXPLANATORY NOTE.

Dating of rocks has become an accurate science based upon relative positions, isotope ratios of intrusives and carbon content, fossil content, etc. Although terminology of rock units varies throughout the world, there is good correlation of the major time units.

TABLE 1:
COMMON ORE MINERALS

Metal	Ore Mineral	Composition	Percent Metal
Gold	Native gold	Au	100
	Calaverite	$AuTe_2$	39
	Sylvanite	$(Au,Ag)Te_2$	
Silver	Native Silver	Ag	100
	Argentite	Ag_2S	87
	Cerargyrite	AgC_l	75
Iron	Magnetite	$FeO{\cdot}Fe_2O_3$	72
	Hematite	Fe_2O_3	70
	Limonite	$Fe_2O_3{\cdot}H_2O$	60
	Siderite	$FeCO_3$	48
Copper	Native copper	Cu	100
	Bornite	Cu_5FeS_4	63
	Brochantite	$CuSO_4{\cdot}3Cu(OH)_2$	62
	Chalcocite	Cu_2S	80
	Cholcopyrite	$CuFeS_2$	34
	Covellite	CuS	66
	Cuprite	Cu_2O	89
	Enargite	$3Cu_2S{\cdot}As_2S_5$	48
	Malachite	$CuCO_3{\cdot}Cu(OH)_2$	57
	Azurite	$2CuCO_3{\cdot}2H_2O$	55
	Chrysocolla	$CuSiO_3{\cdot}2H_2O$	36
Lead	Galena	Pbs	86
	Cerussite	$PbCO_3$	77
	Anglesite	$PbSO_4$	68
Zinc	Sphalerite	ZnS	67
	Smithsonite	$ZnCO_3$	52
	Calamine	$H_2Zn_2SiO_5$	54
	Zincite	ZnO	80
Tin	Cassiterite	SnO_2	78
	Stannite	$Cu_2S{\cdot}FeS{\cdot}SnS_2$	27
Nickel	Pentlandite	$(Fe,Ni)S$	22
	Garnierite	$H_2(Ni,Mg)SiO_3{\cdot}H_2O$	
Chromium	Chromite	$FeO{\cdot}Cr_2O_3$	68
Manganese	Pyrolusite	MnO_2	63
	Psilomelane	$Mn_2O_3{\cdot}xH_2O$	45
	Braunite	$3Mn_2O_3{\cdot}MnSiO_3$	69
	Manganite	$Mn_2O_3{\cdot}H_2O$	62
Aluminum	Bauxite	$Al_2O_3{\cdot}2H_2O$	39
Antimony	Stibnite	Sb_2S_3	71
Bismuth	Bismuthinite	Bi_2S_3	81
Cobalt	Smaltite	$CoAs_2$	28
	Cobaltite	$CoAsS$	35
Mercury	Cinnabar	HgS	86
Molybdenum	Molybdenite	MoS_2	60
	Wulfenite	$PbMoO_4$	39
Tungsten	Wolframite	$(Fe,Mn)WO_4$	76

TABLE 2:
COMMON GANGUE MATERIALS

Class	Name	Composition
Oxides	Quartz	SiO_2
	Other silica	SiO_2
	Bauxite, etc	$Al_2O_3 \cdot 2H_2O$
	Limonite	$Fe_2O_3 \cdot H_2O$
Carbonates	Calcite	$CaCO_3$
	Dolomite	$(Ca,Mg)CO_3$
	Siderite	$FeCO_3$
	Rhodochrosite	$MnCO_3$
Sulfates	Barite	$BaSO_4$
	Gypsum	$CaSO_4 + 2H_2O$
Silicates	Feldspar	
	Garnet	
	Rhodonite	$MnSiO_3$
	Chlorite	
	Clay minerals	
Miscellaneous	Rock matter (sic)	
	Fluorite	CaF_2
	Apatite	$(CaF)Ca_4(PO_4)_3$
	Pyrite	FeS_2
	Marcasite	FeS_2
	Pyrrhotite	Fe_7S_8
	Arsenopyrite	FeAsS

Source of Data: January 1961, *Field Manual for Mineral Engineers,* U.S. Dept. of the Interior, Bureau of Land Management

D. Tectonic/metamorphic processes

Tectonic and metamorphic processes may result in the breakdown and transformation of rock minerals and concentration of certain elements by expelled fluids or diffusion.

Whether or not a deposit containing a valuable element or mineral is likely to become a VALUABLE MINERAL DEPOSIT depends upon engineering, economic and political factors as well as geological conditions and concentrations. In general terms - a valuable (or potentially valuable) mineral deposit contains some commodity (rock or mineral) which can be, or has the potential of being removed from the earth and marketed either before or after some form of processing.

VIII. CLASSIFICATION OF MINERAL DEPOSITS

Under existing technological conditions, certain minerals are more valuable than others because a particular element (usually a metal or chemical material) can be readily prepared from them or because they have useful physical properties. It has been customary to classify useful mineral deposits according to whether they were chiefly valuable as a source of metal (METALLIC DEPOSITS), as a source of chemical, building materials, etc. as NONMETALLIC DEPOSITS or INDUSTRIAL MINERALS AND ROCKS (**Tables 3**,**4**), or as a source of energy materials (FUELS). This subdivision has become inadequate and confusing. For example: uranium may fall into two categories, as a metallic deposit or as a fuel. Salt (NaCl) may be utilized as the chemical, rock salt, or as a source of sodium metal. Even the mineral bauxite is used as the principal ore from which aluminum is derived, or as an industrial mineral used in refractories and abrasives.

Table 3: . Twofold Subdivision of Nonmetallics

Aspect	Group 1	Group 2
Bulk	Large	Small
Unit value	*Low*	*High*
Place value	High	Low
Imports and exports	Few	Many
Distribution	Widespread	Restricted
Geology	Simple	Complex
Processing	Simple	Complex

Source: Adapted from Bates, 1960, p. 17.

Table 4: Examples of Industrial Rocks and Minerals

	Commodity	Unit Value	Place Value
GROUP 1	Granite	Low	High
	Slate	Low-Intermediate	Intermediate-High
	Aggregate	Low	High
	Sandstone	Low-Intermediate	Intermediate-High
	Clay	Low	High
	Limestone	Low	High
GROUP 2	Mica	High	Low
	Beryl	High	Low
	Fluorspar	High	Low
	Graphite	High	Low
	Quartz Crystals	High	Low
	Diamonds	High	Low

Source: Bates, 1960.

The simple three-way classification of metallic, industrial minerals and rocks (non-metallic), and fuels is no longer adequate. (**Table 5** provides a list of commodities classified according to the traditional system.) Some of the problems with such a classification may be readily apparent in the overlapping of classes and the extreme heterogeniety within the non-metallic/industrial minerals and rocks category.

In many respects, classifications such as those shown in **Table 5** are irrelevant and should not be used as a basis for legislation. **Table 6** and its continuation, **Table 6a**, classify the most significant economic minerals according to the environments in which they commonly occur. Under this method of classification the overlapping is apparent. In sum, any system of classifying mineral deposits which proposes mutually exclusive categories is contrary to geologic reality.

The recoverable value within an ore deposit and the cost of extraction and sale determine the profit margin. Deposits with a high profit margin, generally small with a high gold-silver content and selectively mined, are commonly referred to as BONANZA DEPOSITS. Those deposits with large tonnage and low profit margin, mined in bulk are referred to as BULK LOW-GRADE DEPOSITS and include such deposits as the porphyry copper/gold deposits.

TABLE 5:

GROUPING OF MINERALS ACCORDING TO ESTABLISHED CLASSIFICATION SYSTEMS

A. Industrial Classification of Metals

1. Ferrous Metals

Iron

2. Ferro-alloy Metals
(sometimes included in the ferrous classification)

Manganese
Chromium
Nickel
Molybdenum
Cobalt
Tungsten
Vanadium
Columbium

3. Light Metals

Aluminum
Magnesium
Titanium
Zirconium

4. Non-Ferrous Base Metals

Copper
Lead
Zinc
Tin
Antimony
Cadium
Bismuth

5. Nuclear Elements

Uranium
Thorium
*Beryllium

6. Precious Metals

Gold
Silver
Platinum

B. Non-Metallic Minerals (also termed industrial minerals and rocks)

Potash
Sodium Carbonate (Trona)
Sodium Sulfate
Salt
Borax and Borates
Gypsum
Lithium minerals
Strontium minerals
Barite
Phosphate
Flourite
Limestone
Dolomite
Magnesite
Chalk
Diatomite
Clay
Sandstone, Quartzite
Shale
Bentonite
Perlite
Graphite
Mica
Asbestos
Talc and Soapstone
Vermiculite
Pyrophyllite
Slate
Sillimanite Group (topaz, kyanite, andalusite, sillimanite, dumortierite)
Garnet
Crushed Stone
Sand and Gravel
Dimension Stone
Sulfur
Diamonds
Bauxite

*Beryllium is also a common ferrous and non-ferrous alloying metal.

TABLE 6:

CLASSIFICATION ACCORDING TO COMMON ENVIRONMENT OF OCCURRENCE

1. **Association with igneous intrusions**

   Iron
   Ferro-alloy metals
   Non-ferrous base metals (copper, lead, zinc, tin)
   Precious metals (gold, silver)
   Nuclear elements
   Titanium
   Magnesite
   Barite

2. **Association with sedimentary rocks–concentration by weathering and/or precipitation as sedimentary deposits**

   Iron (in oxides)
   Manganese (manganese oxides)
   Aluminum (bauxite)
   Uranium
   Vanadium
   Copper
   Nickel

3. **Extraction from sea water**

   Magnesium
   Salt

4. **Beach and stream placer deposits–beaches, streams, rivers**

   Monazite (rare earths, thorium)
   Titanium minerals (rutile, ilmenite)
   Tin (cassiterite)
   Gold
   Mercury
   Zirconium (Zircon)
   Silica sand (high-purity quartz sand deposits)

5. **Pegmatite deposits**

   Feldspar
   Quartz
   Rare-earth minerals (Columbium, tantalum, hafnium)
   Lithium minerals
   Beryllium

(TABLE 6 cont.)

6. **Evaporite deposits**

   Potash
   Sodium Carbonate
   Sodium Sulfate
   Salt
   Borax and Borates
   Gypsum
   Lithium minerals

7. **Chemically precipitated sedimentary rocks**

   Sulfur
   Phosphate
   Strontium minerals
   Barite
   Limestone
   Dolomite
   Magnesite
   Chalk

8. **Other sedimentary rocks**

   Diatomite
   Clay
   Shale
   Sandstone, Quartzite
   (silica sand)

9. **Volcanic rocks**

   Bentonite
   Perlite

10. **Metamorphic rocks**

    Graphite
    Mica
    Asbestos
    Talc, Soapstone
    Vermiculite
    Pyrophyllite
    Slate
    Sillimanite group (Topaz, Kranite, Andalusite, Sillimanite, Damarticrite)
    Garnet (abrasive)
    Magnesite
    Diamond

11. **From sedimentary, igneous, and metamorphic rocks**

    Crushed Stone
    Dimension Stone
    Sand and Gravel

A. Titley's classification

Titley (1992) proposed a geological classification of mineral deposits based upon genetic considerations as to environment of formation (**Tables 7, 8**).

- Ores formed at or near a contemporary surface:
    - Laterites, placer deposits, chemical precipitates, shale-hosted base and precious metal deposits, stratiform copper deposits, sea-floor nodules, ocean ridge spring deposits, and volcanogenic massive sulfide deposits.
- Ores formed in bodies of rock:
    - Ores formed by weathering, ores formed by cool solutions of uncertain provenance, ores formed in the epicrustal volcanic environment, ores formed in the deep volcanic environment, ores formed in pluton-centered environments.
- Ores formed by magmatic segregation.
- Ores formed by metamorphic processes.
- Ores composed of common rock varieties.

B. Additional classifications

A further classification currently in use is a dual breakdown as: PRIMARY DEPOSITS or SYNGENETIC DEPOSITS; and SECONDARY DEPOSITS or EPIGENETIC DEPOSITS. This classification overlaps the classification proposed by Titley and supplements it.

Primary mineral deposits may be created as a result of rock-forming processes, such as intrusion, extrusion, and sedimentation, that result in the concentration of specific elements or minerals. Or, they may be created by the introduction into existing rocks by fluids (hot or cold) containing elements and compounds which crystallize upon cooling or reaction with the rock. During the crystallization and cooling of some igneous rocks specific minerals may be trapped as widely disseminated grains, or they may be more or less segregated and concentrated within the rocks as zones or bands (copper, nickel, platinum, chromium, iron).

Table 7: Environments and Ore-forming Processes at or Near Contemporary Surfaces

Processes / Environments	Chemical Weathering (Leaching)	Subaerial Chemical Precipitation	Erosion, Transportation, Deposition	Subaerial/ Submarine Precipitation	Submarine Precipitation	Volcanic Processes	Hydrothermal Processes
Subaerial Surfaces	Bauxite, Clay, Mn, Fe Laterites	Ni Laterites, U Calcretes				Sulfur, magnetite, hematite in volcanic flows	Hot Springs, Hg, As, Sb, Ag, Au
Alluvial, Fluvial Environments			Placer deposits, Precious metals, U, Gems, Resistates	Reduction in algal mats, Base metals, Au, Ag, U			
Lacustrine Environment, Playas				Brines, Borax, U			Hot springs, B, Sb, Hg(?), U(?)
Platform, Low-High Tide Sabkha Environ				Base metals, Au/Cu ores (Zambia?)	Cu ores, Pb/Zn ores (Kupferschiefer?)		
Shelf Environment					Carbonate facies Banded Iron Fm, Shale-hosted Pb/Zn	Algoman Banded Iron Formation	
Euxenic Environment of Basins, Rifts					Pyritic black shale Birmingham Iron, Shale-hosted Pb/Zn	Algoman Banded Iron Formation	Hot springs, Au Fe, Ni, Ag, Cu, W, Sn
Cratonic Basins					Superior-type Banded Iron Formation		
Abyssal Plains > 4.5 km (2.7 mi) Depth					Deep-sea nodules Mn Fe, Ni, Cu, Co		
Marginal Basins Extensional Environment					Volcanogenic Massive Sulphides	Volcanogenic Massive Sulphides Greenstones, Kuroko	Sea-floor hot springs
Ocean Ridge, Spreading Center							Cyprus-like deposits, Cu

Primary mineral deposits often result from sedimentation, diagenesis, and metamorphism. Beds and lenses of limestone, potash, diatomite, phosphate, gypsum and sodium carbonate (TRONA) are the result of sedimentary rock forming processes. High pressure and temperature may convert shale to slate and garnet, organic matter to graphite, limestone to marble. The evicted fluids may carry and concentrate gold values.

Primary mineral deposits formed through the introduction of hydrothermal fluids may occur as fillings in previously open spaces in rocks as replacement of the rock's original minerals, or in the adjacent fractures, breccias and faults. Many deposits of base and precious metals and uranium were formed in this manner.

Secondary mineral deposits are formed at the contemporary surface by the action of geologic processes on primary mineral deposits. Weathering and erosion, for example, cause the formation of bauxite (aluminum ore) deposits by residual concentration after weathering has broken down aluminum-bearing minerals, and subsequent erosion has removed the non-aluminum-bearing minerals. Iron and nickel may be similarly enriched in laterite ores.

Placer gold, platinum, tin, and diamonds are also secondary in nature. Ore mineral-bearing rock fragments are broken down as they move down slope and transported in streams and rivers. Resistant and heavier minerals become separated from the gangue minerals, and, because they are heavier, sink to the bottom of the stream. Placer deposits are usually formed where currents decrease in velocity, permitting the heavier minerals to come to rest.

Other secondary mineral deposits form at or near the surface by chemical leaching of primary mineralization by groundwater. This action results in lateral and downward transportation of copper, silver, zinc, lead, gold and uranium compounds in solution. Redeposition from solution below the water table or in localities of organic material form secondary deposits of these elements.

Table 8 :Subsurface Crustal Environments and Ore-forming Processes

Environments	Processes	Supergene Processes; Reaction and Precipitation	Hydrothermal Processes Meteoric H_2O → Increasingly Primitive → Juvenile H_2O (?) Temp. Cool (100°) ---- to ---- Hot (500°(?))			Magmatic Segregation
	Near surface environment	Secondary Supergene Enrichment; Cu,Pb, Zn, Ag, Au				
0.5	Shallow Crustal Environment (Telethermal*)	Sandstone U,Cu,Mo	Sandstone Uranium, Red Bed Copper, Miss. Valley Pb/Zn/F deposits			
1	Shallow Volcanic and Hot Spring Environment (Epithermal*)		Precious metals, Complex metal assemblage Veins and breccia filling textures			
2-5	Intermediate to Shallow Environment (Mesothermal*)			Base and precious metal *ores* in stockworks, veins and replacement bodes—mostly intrusion centered		
10-15	Deep to Intermediate Environment (Hypothermal*)				Au, Sn, Cu, W veins and replacement ores Batholithic and deep greenstone and crustal environment; metamorphic terrances?	
??						In granitic rocks, pegmatites (U,Nb,Ta,F,Sn, REE, Li,Be); in mafic rocks.

IX. STRUCTURES OF MINERAL DEPOSITS

SEDIMENTARY DEPOSITS. Mineral deposits formed as a consequence of sedimentary processes occur generally as lenses or beds which parallel enclosing sedimentary rocks, and may extend for thousands of feet or tens of miles, but are rarely more than a hundred feet thick. These deposits occur in sedimentary basins, along ancient slopes and stream channels, and in ancient lagoons. However, similar deposits may occur as a consequence of replacement of reactive beds of limestone or dolomite - usually at the base, or as impregnation of a permeable strata unit, giving the impression of initial deposition.

STRUCTURAL DEFORMATION. Structural deformation may alter the form and attitude of some of these deposits. For example, salt domes along the coast of the Gulf of Mexico result from the squeezing of the salt from flat-lying beds, intruding upward along zones of weakness. Many limestone beds have been severely tilted and even overturned.

METAMORPHIC PROCESSES. Lenticular masses, veins, lodes and zones of disseminated mineralization result from metamorphic processes. These deposits may conform to the attitudes of the enclosing rocks or they may be cross-cutting (pegmatite veins).

VEINS/LODES. Veins and lodes consist of aggregates of minerals containing base and/or precious metals, uranium, etc. which have been deposited in fractures in the enclosing rock mass, or have replaced the rock immediately adjacent to the fracture. The veins are roughly tabular, but usually thicken and thin at irregular intervals. Quartz, calcite and pyrite constitute the common gangue minerals in most metallic vein deposits. Lengths and widths of veins are usually in the order of hundreds to thousands of feet in length, less than a foot to a hundred feet in width, up to several thousand feet in depth. Veins formed in the deep volcanic environment generally have good depth continuity of values, while those formed in the epicrustal volcanic environment generally give out, or become uneconomic, at depths of 1000 to 1500 feet.

REPLACEMENT DEPOSITS may be disseminated or massive. BEDDED REPLACEMENTS, lead, zinc, silver, copper deposits in limestone, generally occur in more or less flat-lying (MANTOS) clusters having lateral dimensions of a hundred to several thousand feet, but are usually less than a hundred feet thick. The basal limestone bed in a sequence tends to be the favored horizon, particularly where it is adjacent to an intrusive, forming a CONTACT METAMORPHIC or PYROMETASOMATIC assemblage. These mineralized bodies are generally irregular in shape and variable in size, but may border porphyry-type deposits and may be mined as a part of the adjacent deposit.

Other host-rocks containing carbonate as primary or alteration minerals, or organic material are favorable hosts for replacement by ore minerals as disseminations. Sizes and shapes are dependent upon the favored host.

PORPHYRY-RELATED deposits are formed in the epicrustal volcanic environment and constitute a principal source of copper-gold-molybdenum. Shallow porphyry intrusives,

stockworks and breccia systems form large tonnage (up to several billion tons) low-grade deposits amenable to low-cost bulk mining and treatment. They are generally one to ten miles in diameter and may extend to a mile in depth. Commonly thy are capped by a barren leached capping which is underlain by a zone of SECONDARY ENRICHMENT of values.

Deposits formed at the surface by WEATHERING CONCENTRATION (bauxite, iron and nickel laterites) have more or less tabular forms with large lateral dimensions (several thousand feet to several miles, and thicknesses to a few hundred feet.

STREAM PLACER deposits are usually not more than a few tens of feet thick, with valuable minerals (gold, platinum, tin, diamonds) occurring in relatively narrow and relatively long horizontal patterns. BEACH PLACERS tend to be roughly rectangular in outline and may have adjacent, related dune concentrations.

The structures of common mineral deposits are shown in the accompanying illustrations. **Figure 8** depicts structural controls affecting the localization of ore shoots. **Figures 9**, **10**, **11**, and **12** illustrate the environments of saline deposits, phosphate deposits, calcium carbonate deposits, and iron mineral deposits, respectively. **Figure 13** shows the beneficiation process for iron ores, and **Figure 14** illustrates advanced processing of iron ores. **Figure 15** shows the environments for copper ores, and **Figure 16** depicts the beneficiation of copper ores. Finally, **Figure 17** shows the environments of gold, tin and tungsten mineral deposits, and **Figure 18** illustrates the environments of lead, zinc, and silver mineral deposits.

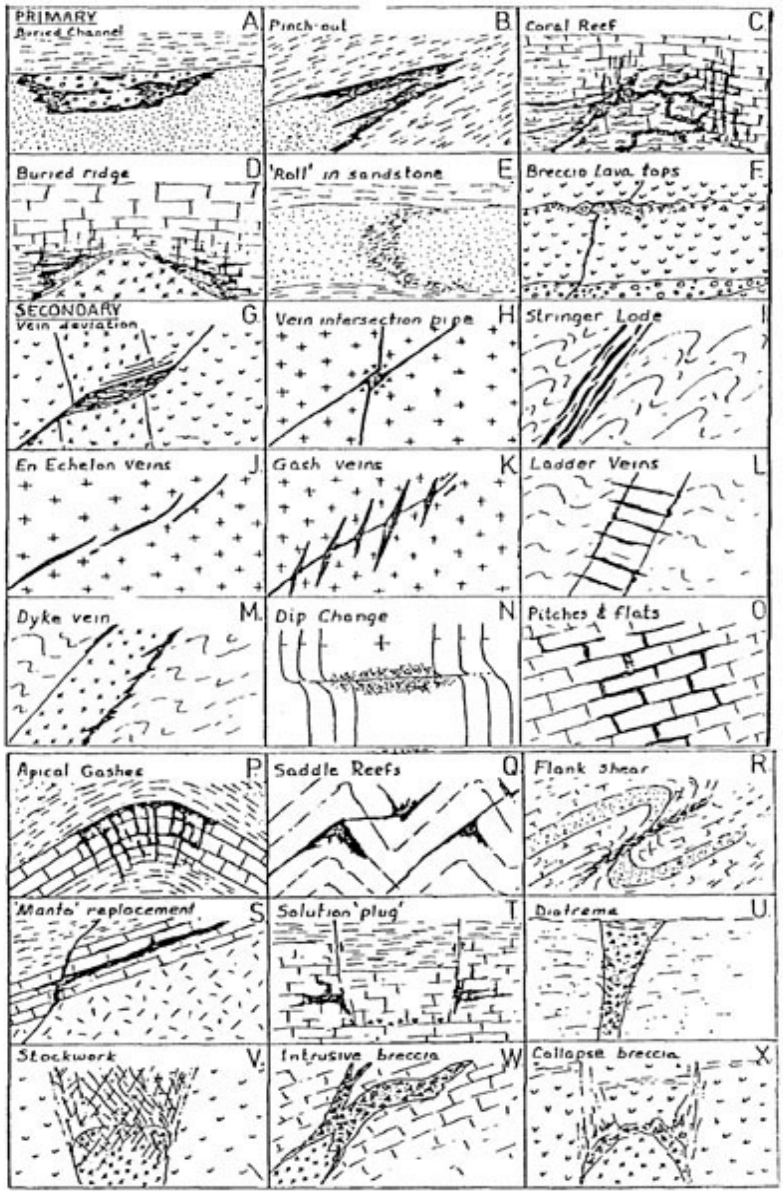


Figure 8: Local Structural Control -- EXPLANATORY NOTE.

Mineral concentrations in rocks are generally controlled by three major factors: 1) Areas of greater permeability permitting access of mineral-bearing fluids, and/or 2) a chemical environment favoring precipitation of the metal/mineral component, and/or 3) a rapid decline of rock pressure or temperature. A variety of rock structural environments favoring concentration of values is shown in Figure 8.

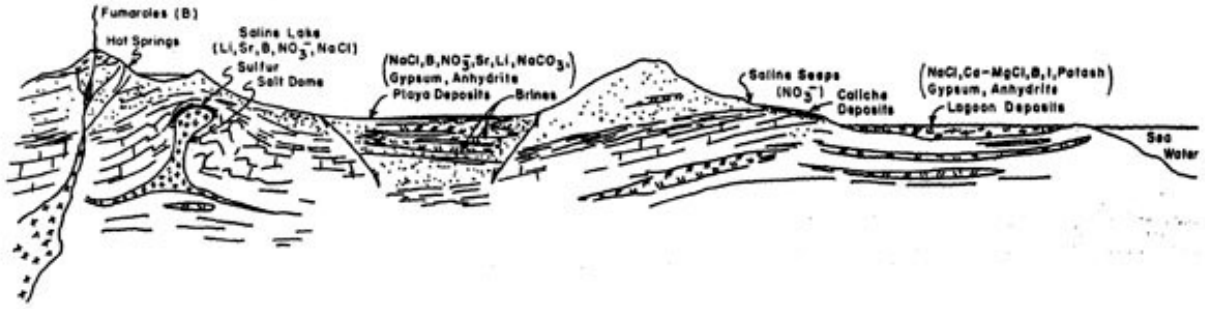


Figure 9: Environments of Saline Deposits -- EXPLANATORY NOTE.

Elements comprising deposits of salt (NaCl), borax, lithium and strontium salts, sodium carbonate, etc., have been derived from volcanic emanations and weathering and chemical breakdown of rocks. These soluble products are carried by streams and accumulate in playa lakes, lagoons, etc. where evaporation serves to concentrate the brine and precipitate the salts in sedimentary layers. Historically man has always obtained salt from the evaporation of seawater.

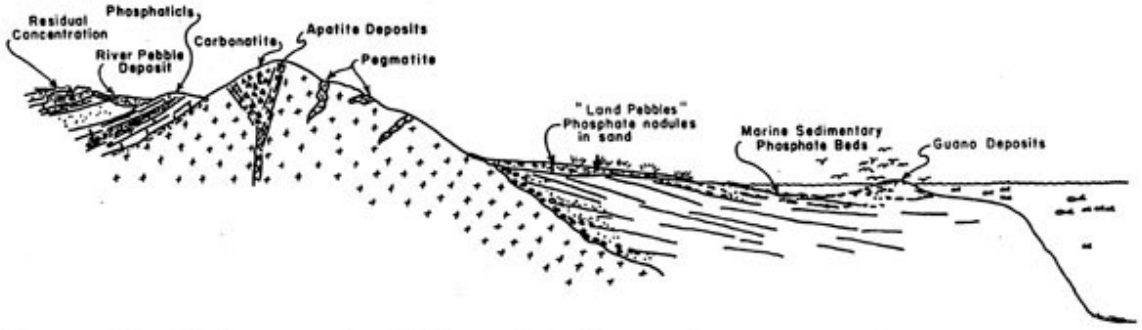


Figure 10: Environments of Phosphate Deposits -- EXPLANATORY NOTE.

Phosphorus is an important content of bone development in all animal life. It originates primarily from weathering and chemical breakdown of granite and its differentiation products. It serves as an important component in plant growth and is thereby contributed to faunal diet. Marine fauna concentrate phosphate in their bone structure, and the droppings from birds feeding on the fish accumulate as guano deposits on coastal islands.

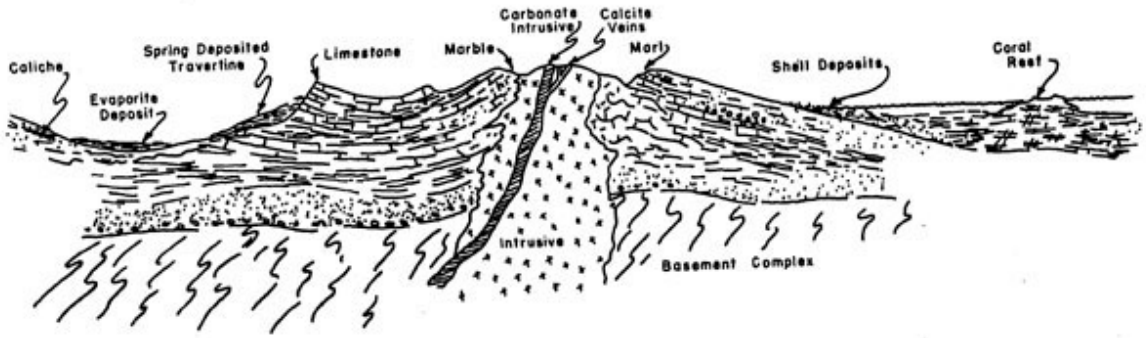


Figure 11: Environments of Calcium Carbonate Deposits -- EXPLANATORY NOTE.

Calcium carbonate originates primarily from weathering and chemical breakdown of rocks of the lithosphere, combining with (50%) carbon dioxide from the atmosphere. It is an essential component of marine fauna -- shells and coral reefs where it forms great thicknesses of limestone. Other deposits may form as a consequence of chemical precipitation resulting from evaporation of brines in confined basins or of spring emanations.

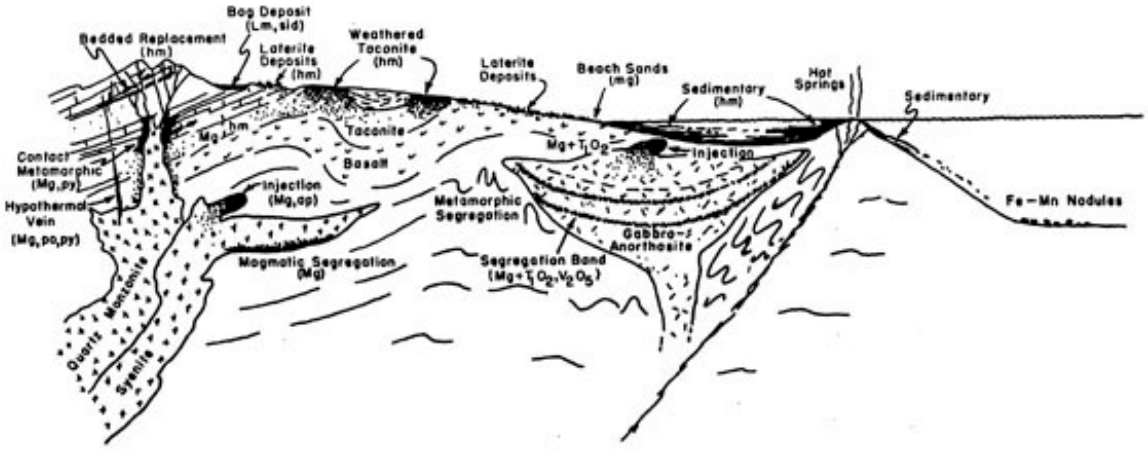


Figure 12: Environments of Iron Mineral Deposits -- EXPLANATORY NOTE.

Iron is an abundant element in the earth's crust (5%) and is concentrated in many ways: magnetite may crystallize early in a solidifying magma and may settle into layered concentrations, some may remain in the magma to be injected into host rocks or occur in veins or replacements of carbonate rocks. Iron oxide minerals are resistant to weathering and collect in outcrops, and in stream and ocean placers. However, most economic deposits were formed in ancient seas at a time when volcanic/intrusive magmas emitted fluids rich in iron.

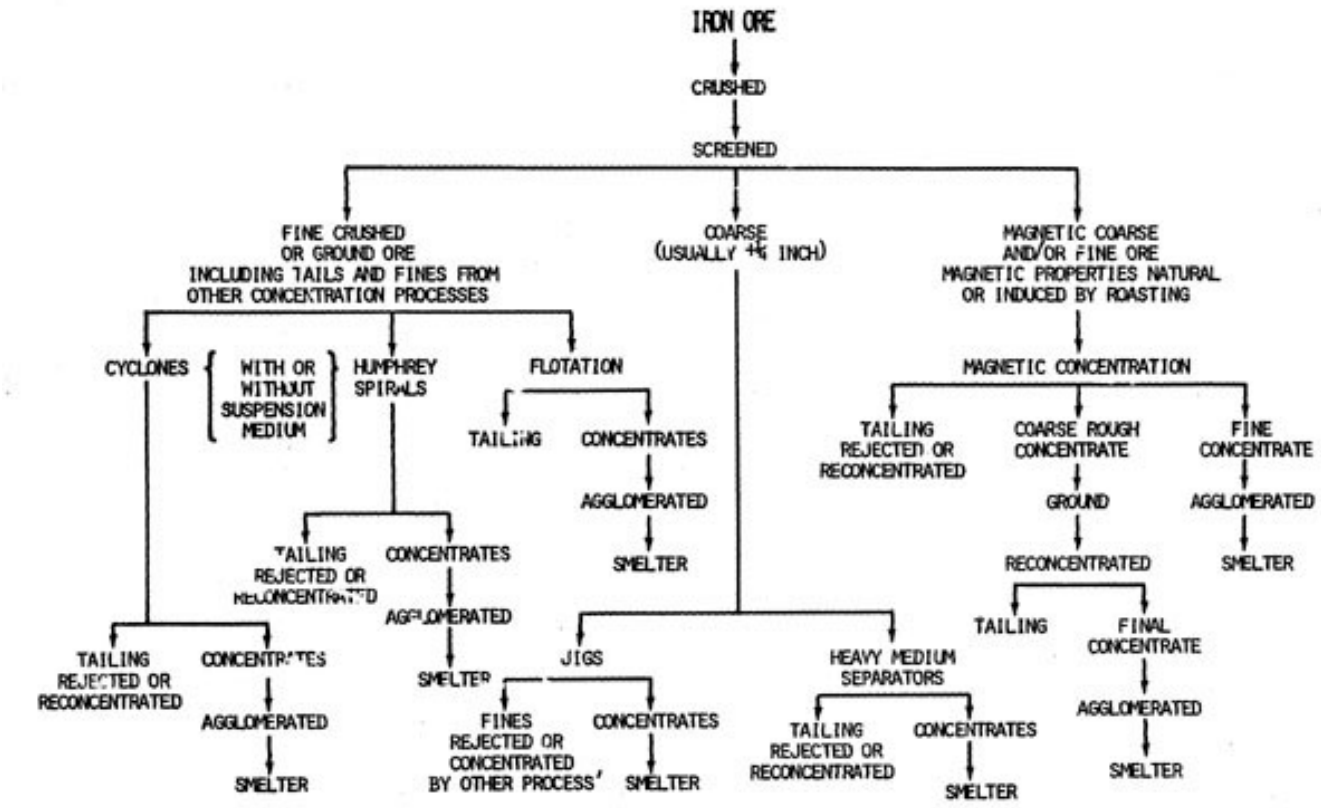


Figure 13: Beneficiation of Iron Ores -- EXPLANATORY NOTE.

Beneficiation of iron ores into steel is a complex process entailing crushing of the ore, separation of the iron minerals by gravity, magnetic properties, or froth flotation to form a 50% iron concentrate which is shipped to the smelter. At the smelter the concentrate is melted with fluxing materials to remove silica and other impurities to produce 'pig iron.' The pig iron is in turn refined in furnaces to produce commercial steel.

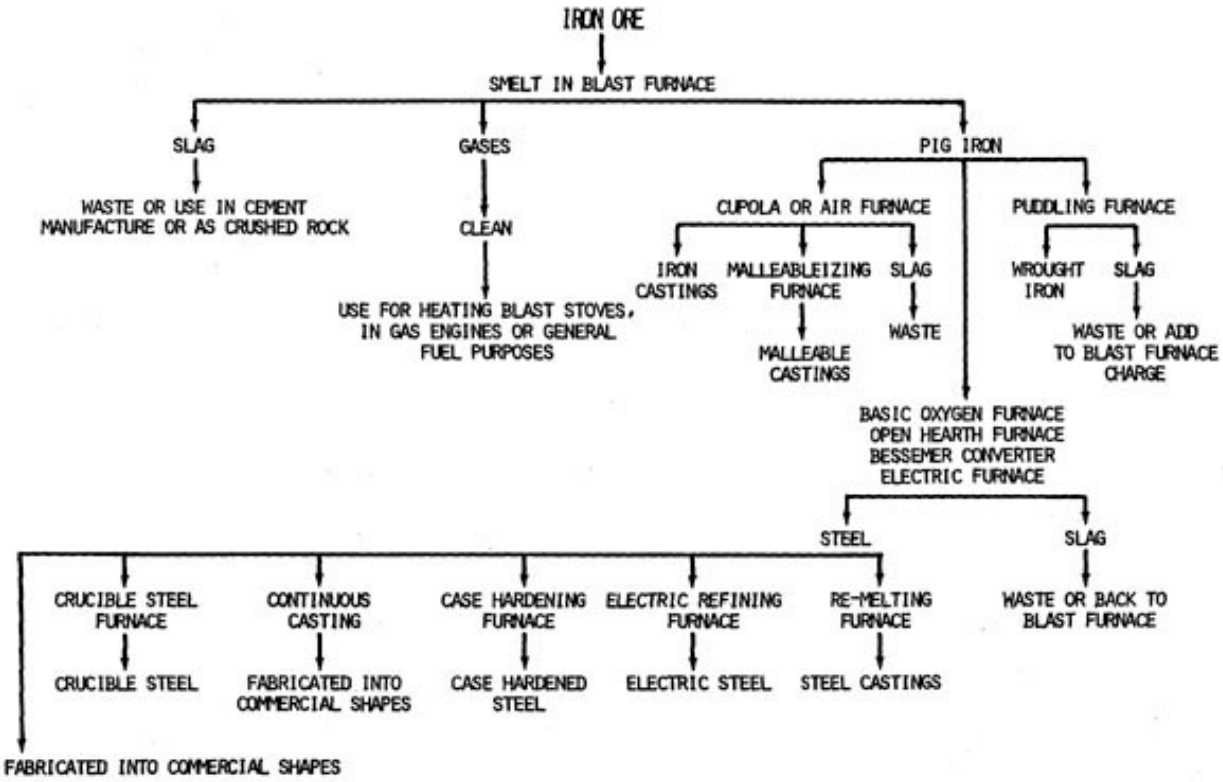


Figure 14: Advanced Processing of Iron Ores -- EXPLANATORY NOTE.

Beneficiation of iron ores into steel is a complex process entailing crushing of the ore, separation of the iron minerals by gravity, magnetic properties, or froth flotation to form a 50% iron concentrate which is shipped to the smelter. At the smelter the concentrate is melted with fluxing materials to remove silica and other impurities to produce 'pig iron.' The pig iron is in turn refined in furnaces to produce commercial steel.

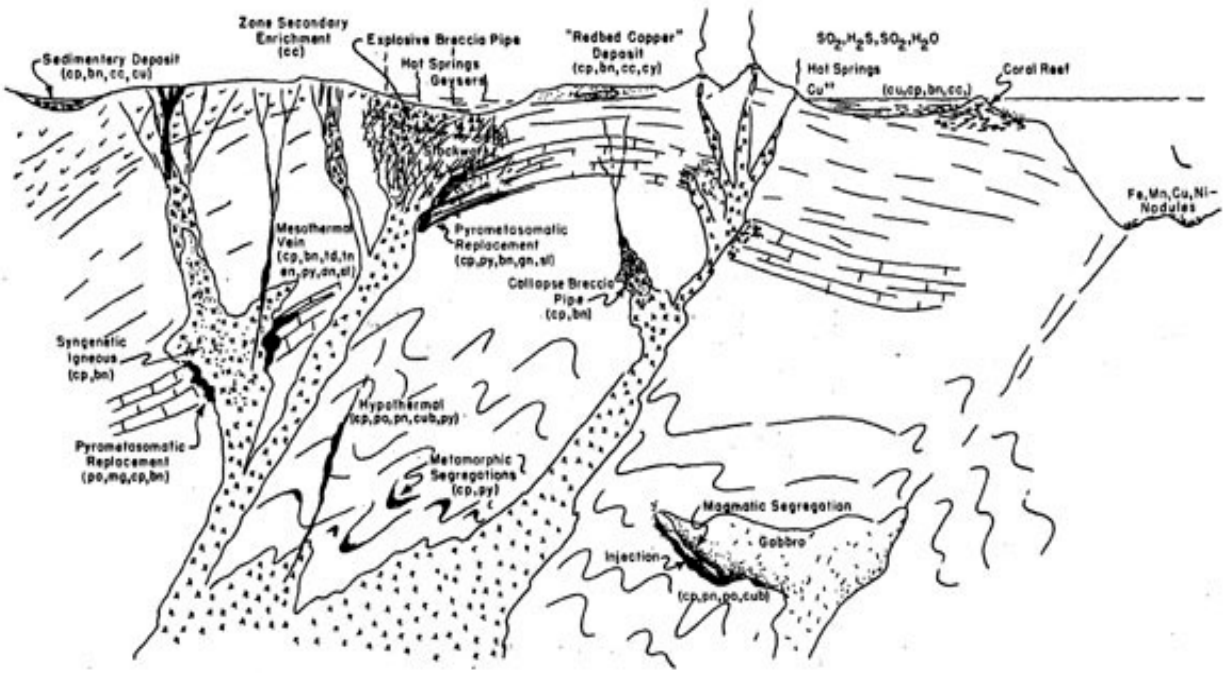


Figure 15: Environments of Copper Mineral Deposits -- EXPLANATORY NOTE.

Copper is present in the earth's crust with an average concentration of 50 parts per million, and it must be enriched through geological processes 200 to 1000 times to achieve economic value. The concentration required is a function of deposit geometry (size and depth) and distribution of values. Most of the concentrating processes takes place during crystallization of the magma of a near surface intrusive. It may result by early gravity separation of copper sulfide, as a component of late magmatic fluids forming veins and stockworks, or as replacements in carbonate rock. Some deposits result from spring deposition into playa or lagoonal environments where reducing conditions may precipitate the copper minerals, or within deep ocean environments where combined with manganese, nodules accumulate.

Under weathering conditions copper sulfide minerals may go into solution and the copper carried down where it is precipitated by sulfides, thus forming a zone of secondary enrichment.

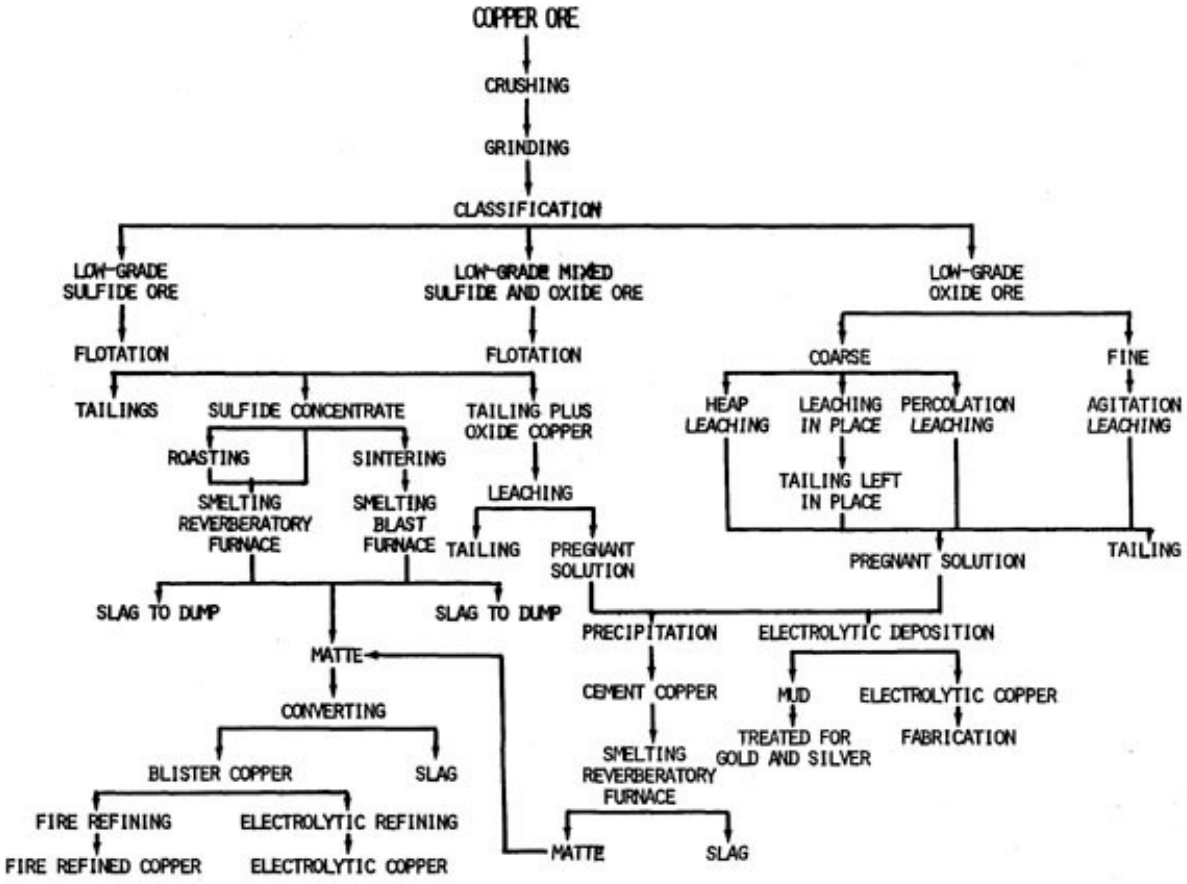


Figure 16: Beneficiation and Advanced Processing of Copper Ores -- EXPLANATORY NOTE.

Copper ores as mined vary in copper content from high-grade ores with +2% copper to low-grade ores as low as 0.3% copper. The sulfide ores must be upgraded to 20%-40% copper through crushing and grinding to achieve liberation of the copper minerals, concentration of these minerals through froth flotation. Low-grade oxide ores may be treated by leaching, precipitation and refining.

The sulfide concentrate is smelted with flux materials to remove silica, alumina, lime, and drive off sulfur. This produces anode copper which is electrolytically refined to high-grade cathode copper (wire grade).

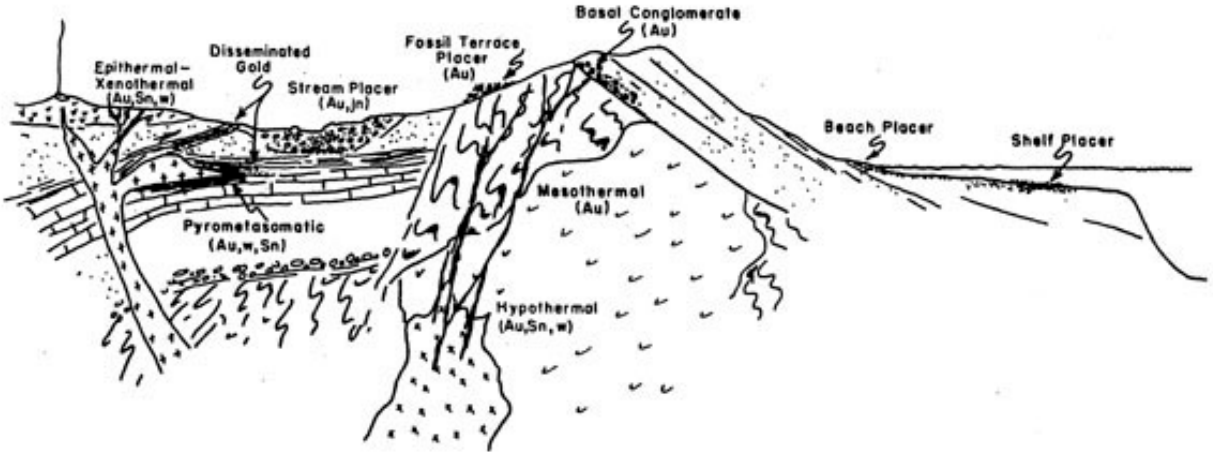


Figure 17: Environments of Gold, Tin and Tungsten Mineral Deposits -- EXPLANATORY NOTE.

Gold is present in average quantities of 5 parts per billion in the earth's crust and must be concentrated by geological processes over 1000 times to achieve economic mining values. It is often quoted that "Gold is where you find it," suggesting a wide variety of environments.

Gold, tin and tungsten minerals are concentrated by late magmatic hydrothermal processes in both deep and shallow crustal environments.

Because of their chemical stability and high specific gravity, gold and tin oxide accumulate in placer deposits after they are released from mineralized rocks by weathering processes.

Low-grade gold values are amenable to extraction by cyanide leach, whereas tin and tungsten minerals generally undergo froth flotation or gravity methods of concentration.

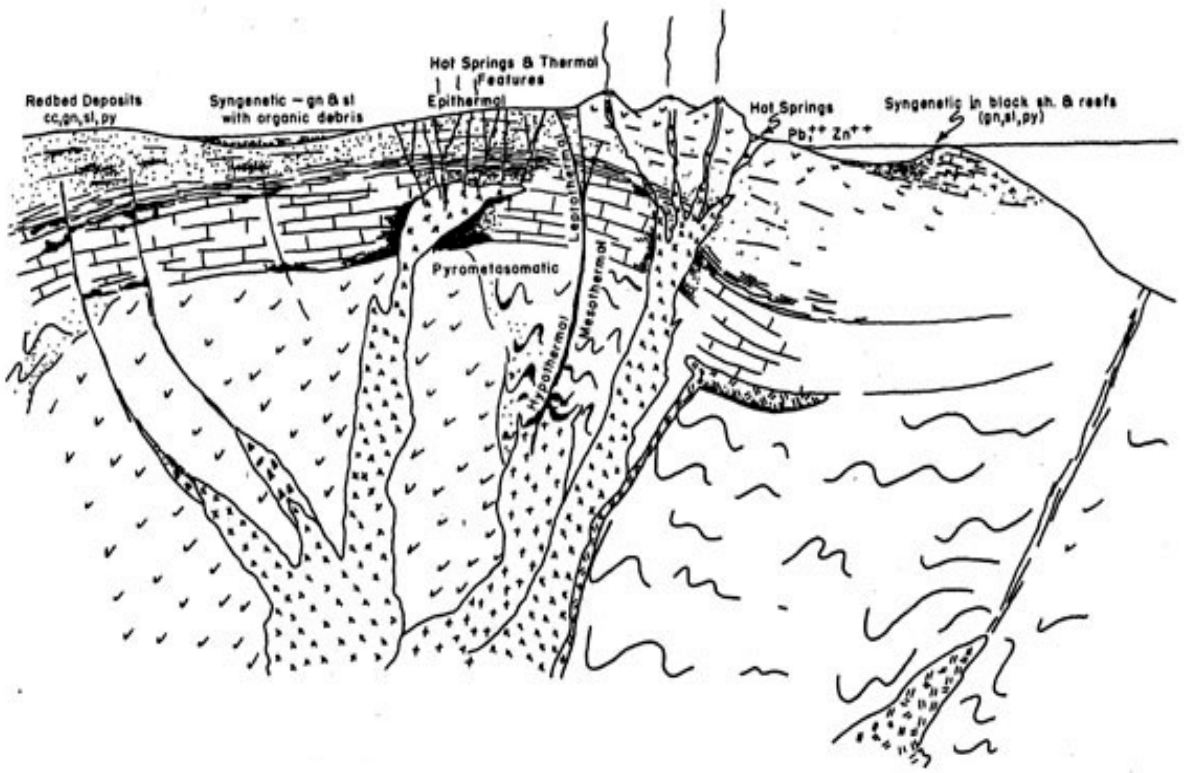


Figure 18: Environments of Lead, Zinc and Silver Mineral Deposits -- EXPLANATORY NOTE.

Lead, zinc and silver deposits have an affinity for carbonate hosts, and are generally found as veins or replacements in limestone. Metal-bearing fluids are generated by shallow intrusives and/or squeezed from thick black shale sequences during digenesis. Lead-zinc-silver, often with copper minerals, occur in veins, limestone replacements, with organic material in redbed sandstones, and in organic shales.

Concentration of the ore minerals is by selective froth flotation that separates lead, zinc and copper minerals. Lead is readily smelted with silver recovered from the lead dross. Zinc must undergo complex smelting and refining processes.

X. RECOGNITION

Recognition of the environment and existence of potentially economic mineral deposits may be based upon a variety of geological criteria:

a. Association with specific types of igneous rocks -- e.g., copper with quartz-monzonite porphyry, diamonds with kimberlite pipes, tin with granites, etc.

b. Host rock association -- e.g. lead and zinc with carbonate rocks.

c. Wallrock alteration -- e.g. a concentric pattern of feldspathization, sericitization and propylitization around porphyry copper deposits, and dolomitization around lead-zinc replacement deposits.

d. Age of mineralization -- e.g. banded iron formation deposits are characteristic of Precambrian age rocks.

e. Gangue mineral association -- e.g. gold associated with quartz-ankerite veins.

f. Trace metal association -- e.g. gold associated with arsenic and mercury in trace amounts.

g. Structural controls -- e.g. laterite deposits associated with unconformities, replacement deposits associated with crests of anticlines.

h. Physiographic associations -- e.g. silicified breccias often stand up as isolated hills; oxidized pyritic bodies in limestone generally form low covered areas.

i. Weathering effects -- e.g. oxidation of pyrite leaves a residue of iron oxide gossan marking possible underlying deposits.

j. Ore and gangue mineral in fresh or oxidized states in outcrop of derived sediments may give surface evidence of underlying or adjacent deposits.

CHAPTER 3

PROSPECTING AND EXPLORATION

I. MINERAL EXPLORATION

A mining operation begins with prospecting and exploration -- stages with long periods of investment and high risk of failure. However, prospecting and exploration are necessary forms of investment and insurance for the future of any mining company. Success in mineral exploration or the acquisition of high-potential mineral properties by negotiation determines the survival of mining companies and industrial nations.

Prospecting and exploration may discover evidence of a mineral occurrence and outline its size and character, but ore deposits that support a mining operation are "made" through the collective efforts of project geologists, geophysicists, geochemists, metallurgists, engineers, chemists, lawyers, and even politicians. Some deposits may go through multiple stages of rejection and recommendation, discovery and development, decline and abandonment, rediscovery and development, etc., as economic, technological or political conditions change or geological understanding is improved. The gold/copper deposit at Mt. Morgan in Australia illustrates this: stage l - gravity separation of high-grade oxidized gold ores in near surface workings; stage 2 - discovery of the froth flotation technique enabling recovery of sulfide copper minerals with contained gold from underground workings; stage 3 - transition to bulk mining open pit operation; stage 4 - retreatment of dumps and tailings by hydrometallurgical leaching methods.

Ore deposits occupy a small space (in the U.S. 0.3% of the land area), yet produce 4.25% of the U.S. G.N.P. and 1.34% of wages. They are generally concealed, offer complex metallurgy, and produce large quantities of waste material so are highly visible. They are capital intensive, and are faced with environmental problems. Discovery of new deposits in the U.S. is becoming more difficult in spite of improved technology, particularly since more and more of areas sparsely explored in the U.S. are being withdrawn from mineral location, and permitting procedures delay operations to the point that they are uneconomic. Exploration efforts are moving to countries with fewer restraints.

An orebody, strictly speaking, is that part of a mineral deposit which can be mined and marketed at a profit under contemporary technological, economic and legal conditions. Economic conditions and technology are constantly changing, as are the laws, taxation and restrictive policies of governments. All of these factors dictate whether a deposit of a specific mineral is or is not an orebody. Hence, mineral exploration is the search for, and evaluation of mineral deposits which have the POTENTIAL of becoming orebodies under expected conditions at some favorable date in the future.

A. OBJECTIVES

The principal objective of mineral exploration is to find economic mineral deposits that will appreciably increase the value of a mining company's stock to the shareholders on a continuing basis, or to yield a profit to the explorer. For an established mining company this may entail discovery or acquisition of new ore reserves and mineral resources to prolong or increase production or life of the company, to create new assets and profit centers by product and/or geographic diversification. Or, in the case of individuals or exploration companies, an objective may be to seek a deposit for sale to, or joint venture with, a major operating company, or to serve as a basis for stock issue and formation of a new company. On occasion manufacturing companies will seek sources of critical metals to insure a supply.

Each organization involved in exploration must define its own objectives in terms of mineral commodities, geographic locations, acceptable size, life, profitability, and acceptable risk. The exploration geologist must be aware of these limits.

B. STRATEGIES

Prospecting and exploration strategies vary widely dependent upon the mineral commodity sought, the geologic and climatic environment, political and social restrictions, and the explorer's experience and available resources.

Bailly (1972) outlines possible strategies for the acquisition of mineral deposits: (1) acquire a producing mine, (2) acquire developed reserves, (3) develop a known deposit, (4) explore known deposits, and (5) explore for new deposits - (a) near known deposits, (b) in a mining district, (c) in a mineral belt, or (d) in a favorable virgin area.

Acquisition of land or ownership position may be by: staking claims , lease/option, joint venture, royalty or purchase, and will be determined by land ownership, local customs, and the level of confidence in economic feasibility.

C. TACTICS

Most exploration programs focus progressively on areas of decreasing size, using methods increasing in cost per unit area, with declining risk of failure. **Table 9** illustrates the mineral exploration process in detail, and **Table 10** shows techniques for detecting non-ferrous metallic mineral deposits. **Table 11** summarizes geophysical exploration methods. **Figure 19** outlines the exploration, development and operation of a copper deposit. Mineral exploration tactics are described in this section.

TABLE 9:
THE MINERAL EXPLORATION PROCESS

I. *Preliminary Preparation*

A. Selection of program criteria

1. Selection of commodity or commodities to be sought
2. Selection of general guidelines for deposit location and characteristics

B. Familiarization

1. Review of available literature
2. Review of known areas of mineral occurrence
3. Review of property submittals and reports
4. Analysis of the geology and projection of trends of structure and rock formations, with the aid of maps and aerial photographs
5. Selection of regions for reconnaissance

II. *Regional Reconnaissance*

A. Geologic reconnaissance

1. Airborne reconnaissance: search for color or topographic anomalies
2. Ground reconnaissance: search for color, petrological or mineralogical anomalies
3. Examination of project submittals and prospects
4. Reconnaissance geologic mapping

B. Geophysical reconnaissance

1. Airborne
2. Ground

C. Geochemical reconnaissance

1. Of streams draining large areas
2. Of color and geophysical anomalies and/or significant areas detected by geological reconnaissance

D. Determination of land status

E. Selection of target areas

III. *Land Acquisition*

A. By staking

B. By lease with option, from private owner

C. By prospector's permit, state or federal

D. By state or federal lease

Table 9 (cont.)

IV. *Examination of the Target Area*

A. Detailed geologic mapping

B. Detailed geochemical surveys on the ground

C. Detailed geophysical surveys

D. Mineral and rock analysis by microscopic and X-ray techniques

E. Evaluation of data

F. Selection of specific deposit for evaluation

G. Fund allocation, road construction, and drill site preparation

V. *Physical Testing of the Target Deposit*

A. Initial drilling (one to five holes)

1. Log core and/or cuttings
2. Split samples and have them assayed
3. Record and plot data
4. Draw projections of data
5. Analyze data and evaluate
6. Decide to continue or abandon project

B. Follow-up drilling

1. Log core and/or cuttings
2. Split samples and have them assayed
3. Record and plot data
4. Draw projections of data
5. Analyze data and evaluate
6. Track ore mineralization and/or ore mineral indications
7. Decide to continue, abandon, or postpone project
8. Adjust area controlled

C. Drilling to define the mineral deposit

1. Log core and/or cuttings
2. Split samples and have them assayed
3. Record and plot data
4. Draw projections of data
5. Analyze data and evaluate
6. Track ore mineralization and/or ore mineral indications
7. Correct outline of mineral deposit from new drill data
8. Estimate tonnage and grade of deposit

VI. *Evaluation of the Results*

A. Make bulk analyses, metallurgical, economic, and engineering feasibility studies

B. Decide to mine, hold in reserve for more favorable conditions, or drop the property

Table 10: Detection techniques for non-ferrous metallic mineral deposits.

METHODS AND TECHNIQUES	Useable at Stages				Detection* Capability for Non-Ferrous Metallic Deposits			
	#1	#2	#3	#4	Direct Detection		Indirect Detection	
	Regional Appraisal	Detailed Recomn.	Detailed Surface Study	Detailed 3-D Study	Good	Questionable	High** Discrimination Capability	Low Discrimination Capability
GEOLOGIC								
Office compilation	X							
Photogeologic Study	X	X						
Aerial examination	X	X						
Outcrop examination	X	X	X					
Geologic mapping & investigations	X	X	X	X				
Geologic logging				X				
Boulder tracking		X	X					
GEOCHEMICAL								
Stream sediment sampling	X	X						
Water sampling	X	X						
Rock sampling	X	X	X					
Specialized sampling	X	X	X					
Assaying	X	X	X	X				
GEOPHYSICS-AIRBORNE								
Aeromagnetic surveys	X	X						
Electromagnetic	X	X						
Radiometric surveys	X							
Remote sensing surveys	X							
GEOPHYSICS-GROUND								
Gravity	X	X	X					
Magnetic	X	X	X					
Radiometric		X	X					
Seismic		X	X					
Resistivity		X	X					
Self-Potential		X	X					
Induced Polarization		X	X					
Down-hole electrical				X				
THREE-DIMENSIONAL SAMPLING & EVALUATION								
Trenching			X	X				
Rotary drilling				X				
Core drilling				X				
Tunnel/Shaft work				X				
Mineral dressing tests				X	Not a detection method			
Economic evaluation				X	Not a detection method			

* Detection refers to the ability to detect a deposit if it is there. Indirect detection refers to a geological, chemical or physical response showing a deposit may be the cause of the response; this is in opposition to direct evidence of the presence of a deposit.

** Discrimination with regard to indirect methods refers to the ability to determine if a certain response (anomaly) is due to a deposit or to another cause.

Table

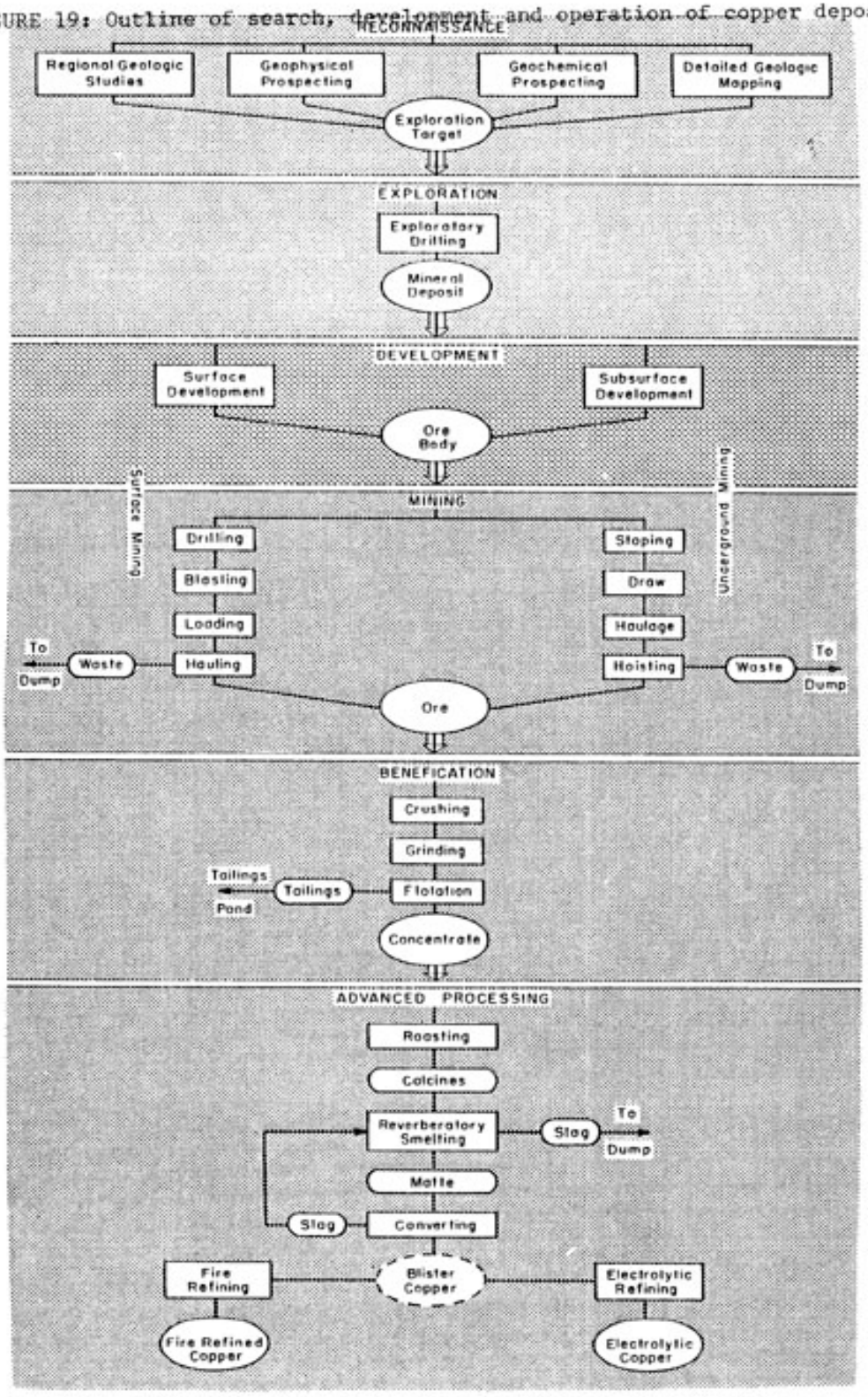
TABLE 11:
SYNOPSIS OF GEOPHYSICAL EXPLORATION METHODS

	Method	Unit	Parameter	Physical Properties	Causes of Anomalies	Major Application
	Magnetic [a,b]	Gamma= 10^{-5} Gauss	Earth Magnetic Field	Magnetic Susceptibility	Basement Rock Irregularities Magnetic Mineral Bodies Mafic Intrusives and Volcanics	Petroleum and mining-general tectonics and local structural patterns Magnetite and pyrrhotite bodies Mafic intrusives with: chromite, nickel, diamonds, hematite Magnetite sand with placer gold
	Gravity	Milligal	Acceleration of Gravity	Density	Dense Orebodies Basement Rock Irregularities Salt Domes	Petroleum and Mining-general tectonics basins, uplifts, and salt domes Chromite, sulfide, and salt bodies
ELECTRICAL	Spontaneous Polarization [a] (self potential)	Millivolt	Natural Potential Field	Conductivity	Conductive Orebodies Graphite Moving groundwater	Petroleum-"electrofiltration" of moving fluids next to drill holes Mining-sulfide bodies and fluids in fault zones
	Resistivity [b]	Ohm/ Meter	Apparent resistivity with applied current	Resistivity or Conductivity	Conductive Orebodies Conductive and resistive strata Fault zones with conductive fluid Salt domes	Petroleum-conductive fluids next to drill holes Petroleum and mining-geologic and tecton tectonics mapping using key beds Conductive orebodies Resistive bodies of: salt, potash limestone limestone, and coal
	Induced Polarization [b]	Millivolt/ Volt	Potential after momentary flow of current	Capacity Effect	Disseminated met-metallic minerals Graphite Serpentine Some clays and micas	Disseminated orebodies, including "porphyry" copper deposits

[a]Includes Airborne Application
[b]Includes Drill Hole Application

Source: W.C. Peters

FIGURE 19: Outline of search, development and operation of copper deposits.



1. RECONNAISSANCE

"Conventional Prospecting," consisting of field search for directly observable geological structures and minerals commonly associated with ore mineralization, as well as evidence of former prospecting activity.

Aerial geophysical coverage for selected minerals with diagnostic geophysical signatures (radioactivity, magnetic).

Literature and geologic research involving both satellite imagery and aerial photo analysis with the selection of geological favorable areas.

Historical notations of former production and/or observations of evidences of mineralization.

Selection of target areas with the potential of meeting company objectives.

TARGET INVESTIGATION

Investigation of a selected target area entails:

a) Determination of land status, staking of ground, obtaining lease/option, or prospecting permit, and obtaining required licenses for access and testing procedures.

b) Multistage coverage of selected target areas involving detailed geological mapping, geochemical and/or geophysical coverage, and/or use of special techniques (fluid inclusions, isotope ratios, etc.)

GEOLOGICAL MAPPING

a) Geological indications of a possible mineral body include: presence of gossans or leached capping, rock alteration.

b) Structural intersections, breccias, fold axes (**Figure 5**).

c) Favorable rock types.

d) Topographic features suggesting anomalous rock conditions.

GEOCHEMICAL SAMPLING

Exploration geochemistry, or geochemical prospecting, includes any method of mineral exploration based on a systematic measurement of one or more chemical, or chemically influenced, properties of naturally occurring material. The property measured is most

commonly the trace concentration of some chemical element or group of elements. It may also include molecular and isotopic compositions and bacterial counts. The naturally occurring material may be rock, soil, stream sediment, glacial sediment, surface water, ground water, vegetation, micro-organisms, animal tissue, particulates, or gases including air. (Coope, 1992).

GEOPHYSICAL PROSPECTING

Exploration geophysics or geophysical prospecting includes not only geophysical surveying for the purposes of mineral discovery, but also the subsurface mapping of geological units. Direct mineral deposit detection is not readily achievable, except in detection of magnetic minerals, electrical conductors, or those giving response to specific electrical charges. However, geophysical methods can provide critical information about the mineral deposit environment, even without direct detection capabilities. **Table 11** summarizes geophysical exploration methods.

Planning of the geophysical survey is one of the most important aspects. First, one must determine the most probable geologic model of the target zone in terms of depth, body geometry, and physical property contrasts of minerals and rocks. Other factors such as terrain, survey costs, land ownership, condition of the environment, and equipment availability may be important. It may turn out that blind drilling is more cost effective than geophysical prospecting (Sumner, 1992).

Analysis of satellite imagery and computer modeling are not currently direct ore-finding tools, but they may be integrated with geologic, geophysical and geochemical data to improve the efficiency of the exploration program. They can lead to a better understanding of the relationships and controls of mineralization and increase the probability of making a discovery.

2. SURFACE AND UNDERGROUND TESTING

A trenching, drilling and sampling program, and/or underground sampling by shafts, drifts and crosscuts, is essential.

It is essential in the evaluation of a mineral deposit to have, as accurately as possible, a model of the mineralized zone geometry -- shape, size, quality, variability, and limits. Physical, chemical and geological characteristics may vary greatly within a single deposit and from deposit to deposit. Critical data can be collected in a variety of ways, including drilling, surface and/or underground mapping, geophysical or geochemical surveys, or studies of rock mechanics properties, mineralogical types and relations.

Underground geological data are costly to obtain but critical for proper evaluation and mining.

DRILLING. Sampling the subsurface may involve one or more types of drilling, determined by the nature of the material to be sampled, rock conditions, and the objective of the sampling. Present exploration and development programs utilize DIAMOND CORE DRILLING or ROTARY PERCUSSION drilling with reversed circulation (RC).

ROTARY PERCUSSION is fast and the least expensive method. A hammer transmitting its force through drill rods to a rotating drill bit which does the penetration. Air or water is circulated through the drill rods to cool the bit and carry out the rock cuttings to the collar of the hole, where they are collected and prepared for study and assay. The method works well where the wallrock is competent, dry and impermeable. It has a practical depth limit of 200 to 300 feet.Metal values may be lost by seepage into the wallrock, or added or diluted by caving or seepage into the drill hole. Reverse circulation of the drill water down the hole and up the drill rods greatly improves the accuracy of the sample.

Unfortunately, the rock fragments from the rotary-percussion drilling provide little information as to the rock-mineral relations, and are best used after this type of information has been obtained by diamond core drilling.

DIAMOND CORE DRILLING is slower and more expensive than rotary percussion(RC) drilling, but provides more useful and accurate samples of a mineral deposit as to the rock-mineral types and relations, and rock structures and characteristics. WIRELINE techniques enable removal of core up through the hollow rods without pulling rods from the hole. This greatly speeds the drilling process and improves core recovery. However, it yields a smaller diameter core.

Earlier drilling techniques often produced poor core recovery, but with improved core barrels, bit design and wireline retrieval of the core, total core recovery is now the general rule except in very poor ground where recovery of sludge samples is advisable.

Disadvantages of diamond core drilling are its high cost, small size of sample and slow penetration rate.

Bulk sampling for metallurgical testing or placer deposit testing are generally obtained by the drilling of large diameter holes (plus 6-inches in diameter), or by sinking winzes.

TRENCHING. Trenching, generally using a backhoe or bulldozer, enables shallow testing and sampling (bulk sampling or cut-channel samples) on a continuous basis across the mineralized zone. Most areas now require back-filling of the trenches, once the sample is taken.

LOGGING. Before the core, rock-chip, or cut samples are reduced for assay, they must be carefully logged. Careful logging of diamond drill core enables basic three dimensional understanding of the mineral body. Proper logging takes practice under informed supervision to recognize and record critical factors that relate to ore genesis, deposit structure, metallurgical and rock-mechanics aspects, etc. Any logging must include:

location and hole attitude data, lithologic data, structural data, rock alteration and mineralization data -- shown in graphic as well as descriptive form.

Cuttings from rotary-percussion holes are more difficult to interpret. Microscopic examination of the rock fragments is necessary, with sludge boards constructed to record rock changes with depth of drilling and corresponding concentrations of heavy mineral content.

Unfortunately, logging is tedious and often relegated to the youngest least experienced member of the geological team. Important clues are overlooked and lost as the samples are prepared for assay.

Diamond cores are generally split, with one half saved for reference while the other half is prepared for assay. This splitting can be a serious source of error. Another approach is to retain a representative core sample from each unit in a core library.

SAMPLING. Samples to be analyzed may consist of rock chips, sludge and/or core from drill holes, cut channel samples or bulk samples from trenches, or underground workings. For assay, these samples must be reduced in volume and size of particles without dilution or enrichment of metal values. Errors may be introduced in many ways by careless handling and lack of cleanliness.

The desired end is preparation of homogeneous rock powder suitable for chemical analysis. The assay procedure entails the following stages:

DRYER (at oven temperatures of 220-285 degrees F, except in the case of mercury (212 degrees F).

CRUSHER (reduction to -8 mesh by JAW CRUSHER, CONE CRUSHER, ROLL CRUSHER, HAMMER MILL).

SPLITTER (to 1/4 - 1 pound by RIFFLE SPLITTER or ROTATING SECTORAL SPLITTER).

PULVERIZER (to 100-150 mesh by PLATE or VIBRATORY RING MILL.

Where samples may contain nuggety gold it is necessary to retain larger samples and to conduct multiple analyses, since the presence or absence of a gold particle will greatly affect the assay.

ASSAYING. Two basic assay methods are available: geochemical and quantitative. Geochemical methods are semi-quantitative but have very low levels of detection and are generally used during the exploration drilling phase. Quantitative procedures are used during exploration, target analysis, and the sampling and analysis for ore reserve estimation and subsequent stages of development and operation. These may be by classical

volumetric and gravimetric methods, calorimetric methods or instrumental analysis, or fire assay methods.

Precision and accuracy are best established and maintained through the use of reference standard samples or replicates (3 of each 20). When the results from control samples do not agree within acceptable limits, the entire group of assays must be rejected until the differences are resolved.

Metallurgical testing of mineralized rocks is an essential step that must be carried out early in the investigation. Expenditures on a project should be curtailed when it becomes established that mineralization under investigation will not yield to current technology, or the treatment will result in unacceptable environmental problems.

3. DISCOVERY

Mineral deposits are detected by individuals, and the importance of the human resource cannot be overemphasized. Local knowledge, detection methods, and time and money expended are of little value if the explorationist fails to recognize or misinterprets favorable indications, fails to accurately record geological data, lacks accurate sampling data, or if management lacks the courage or economic or technical resources to proceed.

"Discovery" of valuable mineral is the foundation of the U.S. Mining Law of 1872. It is a prerequisite to mining claim validity. Initially, "discovery" was legally defined as the finding of sufficient quantity and quality of mineralization that a person with ordinary prudence, with reasonable hope of success, would be justified in further expenditure of labor and means. This was called the "prudent man" test. However, at present the Department of the Interior and the courts have modified their definition of discovery to a more stringent test, a "marketability" test. In order to establish discovery, the locator must demonstrate the existence of a mineral deposit that can currently be mined, treated, and marketed at a profit - a currently economic discovery. One cannot anticipate technology or the metal market fluctuations.

Lack of agreement by persons within the mineral industry as to the definition of "discovery" results from different objectives. What may be considered as a successful discovery for a small operation or company may not be acceptable to a large corporation.

An ECONOMIC DISCOVERY is achieved when 1) capital for development can be raised within a reasonable period of time; 2) tenure and ownership will be respected (the mining claims will qualify for patent); 3) a reasonable profit margin can be projected; 4) technology for mining and treatment exists or can be developed within a reasonable period of time; and 5) there is social and political acceptance of the mining activity. A geological discovery does not indicate an economic discovery.

4. TIME REQUIREMENTS

Lag time between discovery and development and operation of deposits influences capital investment decisions. Between the time of initial detection of base metal deposits and development is an average period of ten years. Gold and uranium deposits on an average require shorter preproduction periods and lower capital investments. Albers (1977) suggests an average of a seven year preproduction period from geological, geochemical or geophysical "discovery" for all mine types; ten years for copper deposits, five years for uranium deposits, and three years for gold deposits. Deposits with complex metallurgical problems, or permitting problems, may be delayed for 20 or more years.

A breakdown on time requirements for various exploration and development stages was proposed by (Allen, 1956):

Stage	*Cost*	*Time*
Reconnaissance	- 1 unit	1-20 years
Examination and evaluation	- 5 units	½ - 3 years
Mine development	30 units	2 - 5 years
Plant construction	80 units	2 - 3 years
Initiating production	7 units	1 - 6 months
Production with continuing exploration and development		

5. COST

An average target selection, lacking land or political complications, will cost in the vicinity of $150,000 to $250,000. To arrive at confirmation or rejection of the target will normally require an additional $500,000 to over one million dollars. Commonly it requires greater expenditure to arrive at a rejection conclusion than confirmation. In part this is psychological. The exploration manager or geologist in charge of the project may have become enamored with "his discovery" and is reluctant to abandon it. Also, in part it entails the difficulty in unraveling the complexities - geological, metallurgical, environmental, political and economic - of a deposit and the fear that another organization will discover an overlooked factor and make a major discovery.

Many companies change personnel and use outside consultants and mining and metallurgical engineers during the evaluation stage of a deposit to avoid the situation of "having a bear by the tail," and personnel afraid or embarrassed to let go. Some major mistakes can be avoided by having a mining engineer and a metallurgist assigned to the exploration team.

Some mineral deposits are more difficult and expensive to evaluate than others. Those deposits having good lateral continuity, such as base metal bedded deposits and mantos (iron, lead-zinc, uranium, industrial rocks), are relatively easy to evaluate. Those with spotty distribution of values, such as gold, silver, and tin deposits and many copper deposits, are very difficult to evaluate due to lack of correlation of values between test drilling and/or trenching.

A mineralized deposit should not be developed into an operating mine unless the estimated annual operating profit, after taxes, is judged to be sufficient to recover, with interest, the estimated capital and operating costs of developing the mine. The accuracy of estimation of capital and operating costs depends upon the quality of the technical assessment and knowledge of expected mining and mineral processing conditions.

EXPLORATION COSTS. Average costs of making a discovery range between 15% and 20% of the gross revenue anticipated from the deposit. Some companies consistently beat these averages, while others seldom achieve success despite substantial expenditures. This appears to be a function of management of exploration programs:

GROSS REVENUE FROM DISCOVERY ($)	*COST OF DISCOVERY (1984-86) ($)*
500 million	60-100 million
1,000 million	120-200 million
1,500 million	200-300 million

Distribution of exploration costs in the U.S. and Canada, 1980-1983 averaged:

Geological-Geochemical prospecting	35%
Geophysics	5-15%
Drilling	30-35%

6. LAND REQUIREMENTS

Size of various types of deposits and land requirements for mining and concentrating facilities, tailings ponds and dumps are shown on **Tables 12** and **13**, and range from 1/4 square mile to over 5 square miles. Land requirements are dependent upon whether mining operations are underground or open-pit, lateral extent of the orebody, and percentage of gangue within the ore that must be discarded as waste, and the topography.

7. RISKS

Records of exploration programs carried out in the U.S., Canada during the 1970s yielded the following results:

Location	*Favorable Areas*	*Target Areas*	*Mines*
U.S.	352	23	2
Australia	600	12	1
Canada	1000	70	7

TABLE 12:

NORMAL LAND AREAS IN MINERALS UTILIZATION IN THE UNITED STATES, 1968

Type of Deposit	Area of Mineralization (square miles)	Area Covering Orebody (square miles)	Area Required for Mining Facilities, Tailings Ponds, Dumps (square miles)
Disseminated (copper, molybdenum, gold silver	5 to 20	1/2 to 2	2 to 5
Flat-lying beds (phosphate, trona)	100 to 1000+	1 to 100	1 to 5
Inclined beds (phosphate, trona)	100 to 1000+	1 to 100	1 to 3
Vein (copper, lead, zinc, silver, gold)	1 to 20	1/10 to 1	1/4 to 2
Sand and gravel	1/2 to 100	1/10 to 5	1/4 to 5
Bedded replacement (copper, lead, zinc)	1 to 5[a]	1/10 to 1	1/10 to 1

[a]Excluding very large Missouri lead and zinc districts.

Source of Data: E. Wisser & Associates

TABLE 13:
COMPARATIVE LAND USE IN ARIZONA, 1966

Primary Use	Estimated Area (Acres)	Percent Of Total
Grazing (Minimum)	40,039,000	55.08
Recreation	23,092,000	31.76
High Density Recreation Areas	92,000	
General Recreation	3,000,000	
Natural Environment, Scenic Splendor, and Wilderness Areas	20,000,000	
Commercial Forestry	3,870,000	5.32
Military	3,134,000	4.32
Crop Agriculture	1,250,000	1.72
Water Surface Area	384,000	0.52
Inter-city Roads and Highways (Does *not* include 49,000 acres of roads in national forests and parks)	373,000	0.51
Urban (Residential, commercial, and industrial)	320,000	0.44
Mineral Industries	93,000	0.13
Public Utilities	60,000	0.09
Railroads	54,000	0.08
Burned-over Areas (1967 Only) (47,000 acres burned over in 1966)	19,000	0.03

Source of data: Division of Economic and Business Research, The University of Arizon and various other sources.

II. MINERAL LAND OWNERSHIP

Expenditures for mineral exploration and development are wasted unless secure tenure on surface and mineral rights is obtained on all parcels vital and necessary for a mineral project.

Mineral land ownership in the United States resides with the Federal Government (FEDERAL LANDS), the State Governments (STATE LANDS) or with private individuals and business entities (PRIVATE LANDS).

A. FEDERAL LANDS

The Mining Law of 1872 is being subjected to scrutiny and revision, and major questions may arise as to what permitting is required, who owns a particular type of mineral, and what type of surface and mineral rights can be transferred.

Federal lands can be categorized as: l) PUBLIC LANDS where both surface and mineral rights belong to the United States, and the Mining Law of 1872 governs acquisition by locating or leasing; 2) RESERVED or WITHDRAWN lands, which are permanently or temporarily withdrawn from mineral location and leasing; 3) ACQUIRED LANDS, acquired from state or private owners, are not available for location or leasing except by special provisions; and 4) SEVERED LANDS, lands for which the federal government has sold surface rights but retained mineral rights.

B. STATE LANDS

Each state has regulations which supplement federal mining laws, and should be consulted.

C. PRIVATE LANDS

Private lands are owned by individuals, trusts, corporations, mining operations, railroads, forest product companies, etc. Ownership may be in fee or consist of separate ownership of surface and mineral rights. The mineral rights may be further subdivided based upon the type of mineral or geological factors, such as depth of mineralization, or may be confined to specific stratigraphic horizons.

Where private lands are involved, a variety of approaches can be utilized to secure adequate tenure during exploration and development phases. The approaches vary dependent upon l) local customs and expectations, 2) risk involved, 3) the financial position of the owner and explorer, 4) technological capabilities of the explorer, etc. The most important factors include the sequence and timing of exploration and development stages, and the importance of reducing risk factors and establishing potential of the prospect before each major payment is required.

A good agreement requires knowledge and cooperation of a lawyer experienced in current mining law and pending legislation; an engineer and/or geologist who understands the practical aspects of scheduling exploration, testing and mining; a tax specialist who understands tax implications of the agreement; and a financial analyst. Commonly, however, the entire responsibility falls on the lawyer.

III. TRESPASS

Permission is required from land surface owners and owners of patented or operating mineral claims prior to conducting geological, geochemical or geophysical surveys, in order to avoid liability for trespass and to establish good relations with the owner. However, on inactive mining claims no trespass is committed by persons passing through the area on federal lands. Prospectors and geologists may examine the showing on a mineral claim without prior knowledge of its status as a mining claim. It is common practice to examine mineral showings and quickly map and sample the surface and underground geology of a prospect without contacting the owner of a claim. More extended investigations require inquiry as to ownership and owner permission.

In the situation of private lands and patented or operating mining claims, permission of the surface and mineral rights owners must be obtained to conduct geological, geochemical or geophysical surveys. When entry is made for these purposes without permission of the owner, or where permission is exceeded, courts have in some cases held the prospector liable for trespass damages on the basis that the landowner has the right to have the mineral potential of his land remain unknown unless he is paid a fee of gives permission to someone to enter and gather such information.

CHAPTER 4

EVALUATION OF MINERAL DEPOSITS

I. DEPOSIT EVALUATION

The terms "valuation" and "evaluation" in a mining context are often used interchangeably, but there are subtle differences. VALUATION has a narrow meaning of placing a monetary value on the worth of the project as a whole. EVALUATION has a much broader meaning of determining all variables that are important in assessing the feasibility and worth of a project: the assessment of relative viability of the project; estimates of ore reserves and resources; mining methods and rates; revenues; costs; expected returns; risks, cost/benefit analyses, as well as the monetary worth.

Evaluation at each stage of tactics employed depends upon the character of the deposit under investigation, topographic and geologic conditions, access, the commodity sought, the human and economic resources available, previous experience of the explorer, and results obtained in earlier stages of the exploration program.

A. EVALUATION OF EXPLORATION PROGRAM

Initial exploration drilling tests likely sites for the presence and extent of ore-grade mineralization by the tracking of evidence, hoping that it will lead to an orebody. If successful, delimiting and defining the orebody is then done with closely spaced holes. It is in this phase that the continuity of ore-grade mineralization (or lack of it) is determined. At this stage the determination of the shape of the orebody is modified from the outline inferred from initial drilling (**Figure 20**), and geological mineral resources can be computed, and decisions made as to continuing the program.

If the exploration manager terminates the project too early, he may have missed the orebody. On the other hand, continued drilling where no orebody is to be found will cost excessive money, time and manpower. He may have a "bear by the tail" and lack courage to let go, embarrassed by expenditures already authorized on a loser.

Guidelines for justifiable expenditure can be presented as:

$$\text{Expenditure} = (\ (\text{Present Value of Reward})\ (\text{Risk})) \div \text{Factor}$$

where "Factor" is 1 for governmental valuation, 2 or 3 for companies.

The evaluation is a continuing process applied to every step in the exploration and development process. Work continues so long as the risk of failure is progressively reduced.

FIGURE 20. A. Target Area examination.

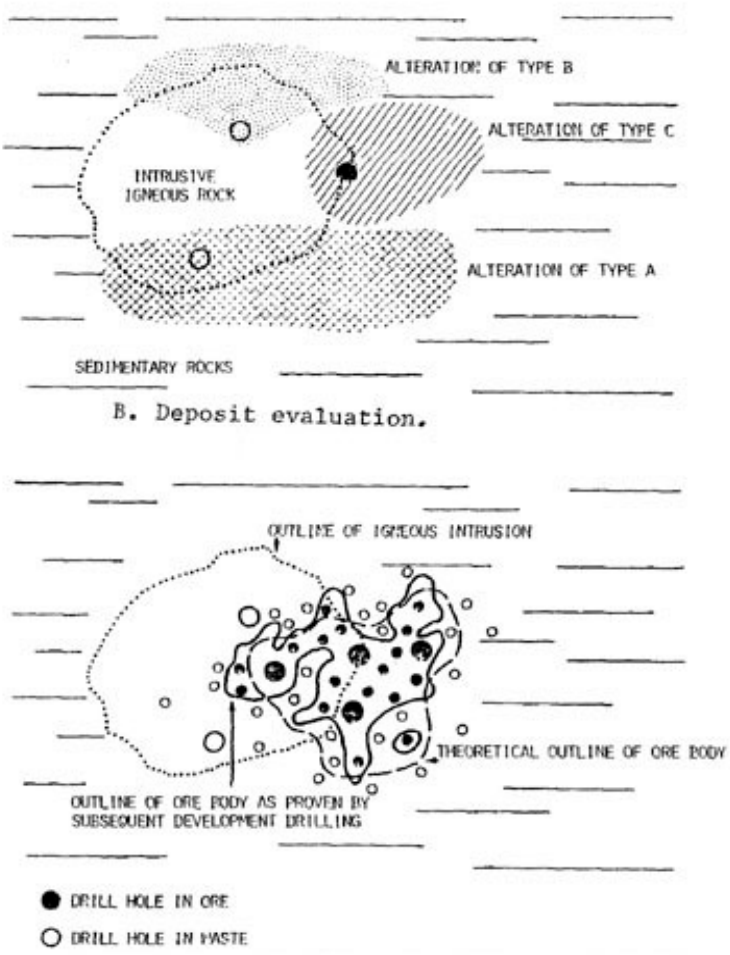


Figure 20: Target Area Examination and Evaluation -- EXPLANATORY NOTE.

A single drill hole in a mineralized body showing either "ore grade" values or "waste" values does not establish the presence or absence of a potential ore deposit. A favorable prospect must be sufficiently tested to establish geological conditions and controls in the distribution of economic values.

Once the existence of a mineral deposit of current or potential value is demonstrated, the project is normally turned over to the mining and metallurgical engineers. They conduct bulk sampling (through shafts or other excavations), metallurgical testing generally utilizing pilot mills, and feasibility studies as to various mining methods. They decide HOW, WHEN, and sometimes IF the deposit should and can be mined on the basis of a preliminary feasibility evaluation.

1. BENEFICIATION

Metalliferous minerals are not generally found in pure form; they are mixed with rock and gangue minerals, and are usually found as compounds of several elements. Physical separation of the various mineral compounds is the first of many beneficiation steps that eventually provide the degree of concentration required. Crushing and grinding ore used to achieve liberation of mineral grains; then, if required, grains must be classified to a pre-determined particle size that best suits the particular concentration process to be used. Then, separation of the ore mineral by gravity methods, froth flotation, hydrometallurgical techniques, etc., can take place.

During the exploration phase, tests should be carried out on a laboratory scale to determine feasibility of concentration, grinding size required for liberation of grains, percent recovery of metal values, etc. During development stage, testing generally needs to be expanded to bulk samples of various mineralization types in a pilot concentrator.

2. RISK

Mining is a high risk venture in view of the multitude of unpredictable factors in the finding, acquisition, extraction, treatment and sale of the product. Risks may be geological, technological economic, political and/or social.

GEOLOGIC RISKS. We have no way of seeing directly what variations or discontinuities occur in rock beneath the surface. We depend upon projection of surface indications with projection of rock types and structures and/or interpretation of geophysical responses, and/or widely spaced drill holes.

A diamond drill core, for example, has its limitations - it provides a cylinder of rock one to two inches in diameter which represents a sample half the distance to the next drill hole (usually 100 to 250 feet). There is no guarantee of continuity of mineralization, or lack of mineralization shown in adjacent drill holes. Expected continuity varies with the type of mineralized body. For example, there is a greater probability of continuity in base metal veins, stockworks and mantos than in precious metal veins, stockworks and mantos. There is better chance with silver than with gold (**Figure 21**).

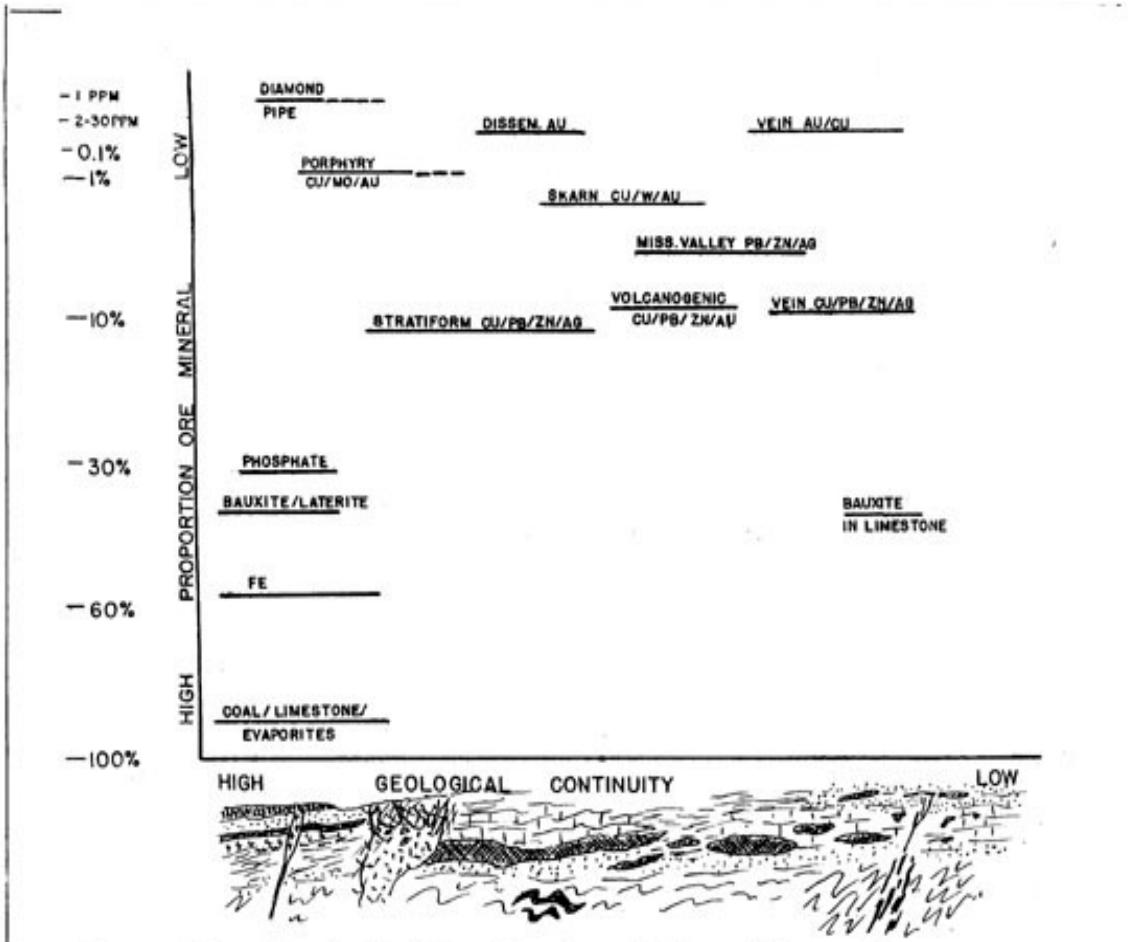


Figure 21: Geological Continuity of Mineral Deposits -- EXPLANATORY NOTE.

Different types of mineral deposits vary in their concentration of valuable mineral/metal content and in the continuity of values. Interpretation of drill intercepts and establishment of exploration and evaluation drill patterns will depend upon anticipated geological continuity of metal/mineral values.

A grid of drill holes, shafts or adits and cross-cuts may encounter high-grade mineralization or completely miss the mineralization as a consequence of local controls (**Figure 20**). Mining history is replete with examples where ore-grade was encountered in as many as 20 adjacent holes on a grid pattern, only to find that there were no values or only low-grade values between. On the other hand, barren drill holes have missed a major orebody by a matter of a few feet. Murphy's Law applies --"If anything can go wrong, it will." Hidden faults may disrupt continuity of mineralization (**Figure 5**), or variations in the character of mineralization may reduce recovery.

Groundwater conditions may be critical. Encountering an aquifer horizon, permeable fault zone or breccia, or cavernous limestone can flood underground workings making mining uneconomic, requiring excessive pumping or expensive drainage facilities. (The Tombstone Mine in Arizona is an example of a mine experiencing these problems).

METALLURGICAL RISKS. Mineral deposits are not uniform either in their physical character of the wallrock (hardness, toughness, stand-up time, required support), or in the nature of the ore and gangue minerals (intergrowths, variations in composition, intensity of oxidation and/or alteration processes acting on the ore minerals influencing their metallurgical behavior). Calculations of crushing and grinding characteristics, liberation size, metallurgical recovery, as well as variability of grade of mineralization may fail to meet expectations. Some portions of the mineralized body may contain deleterious elements (arsenic, mercury) that make them unacceptable to smelters, or they may contain unstable pyrite/marcasite that ignites spontaneously (PYROMORPHIC) within mine workings or during concentrate shipment.

Many of these risks can be anticipated with adequate geological logging of core samples and/or rock chip samples, and multiple metallurgical laboratory tests, but they are often overlooked.

ECONOMIC RISKS. Unlike most commercial products, prices of metals are generally set internationally and low-grade national products must compete for markets with higher-grade foreign products. Discovery and development of large and/or high-grade deposits elsewhere in the world may depress the market prices, or substitution of alternate material that will perform the function of a particular metal cheaper or better will diminish the market, or environmental or health influences of the product may result in its being banned or limited in its usage (mercury, arsenic).

Many governments view mineral deposits as belonging to the state and feel free to apply and increase taxes and royalty assessments at will, and change permitting regulations and restrictions on operations. The rules for operation change after investment has been made, often causing cut-off levels to rise; destroying ore reserves or, in some cases, the entire orebody.

There is no substitute for experience in the assessment of various risk factors.

B. COST/BENEFIT ANALYSES

BENEFITS comprise all of the nice things that will flow from any project (economic, social or political) financial or non-financial. COSTS comprise all of the undesirable things, financial or non-financial. Unfortunately, what is a cost to one person or group may be a benefit to another person or group. (Taxes are an example.) A balance must be achieved between present and future interest groups.

$$V(f) = \int_{t=0}^{\infty} \frac{[B(t) - C(t)]}{[1 - r(t)]}$$, where

B(t) = benefits accruing in time t.

C(t) = costs accruing in time t.

r(t) = the discount rate for period t.

V(f) = net present value for group f.

Evaluation of costs and benefits of any planned project, by anybody, requires forecasting - no matter how it may be dressed up in formulae or in computer language. However sophisticated the analytic techniques, forecasting remains a "guessing game". It can never be classified as "correct" or "incorrect". The forecasting techniques might be classified as "incomplete" or "biased". The forecasting of values for particular benefits or costs can be assessed as "unduly optimistic" or "pessimistic"; but, in the end, one can only assess a forecast as: "wildly improbable," "unlikely," "likely," "essentially dishonest," or "honest, but misguided".

It is possible to manipulate forecasts to conform with one's prejudices. A few deft manipulations will bring the desired answer -- bring the benefits in a bit earlier or later; add or subtract from the list of secondary benefits or costs; change the discount rate, etc. The use of good technique is no guarantee against abuse. Regrettably, much of this kind of analysis is prepared by activist groups with strong biases, and are often, if not generally, dishonest.

Nevertheless, a cost/benefit analysis can, if honestly prepared, focus attention on all aspects of present and future impacts.

C. ENVIRONMENTAL IMPACT

There is no question that development (extraction and processing) of mineral resources impacts the environment. However, with proper planning and precautions, these impacts can be minimized in terms of severity and duration. In the past there have been few environmental controls and there exists a legacy of environmental disturbances created by

mining and mineral processing (acid drainage, subsidence areas and unreclaimed open mine workings). Over 60 billion tons of solid waste have been produced by hardrock mining in the U.S.: 50% from copper mining; 24% from iron mining; and 16% from phosphate mining. Sites containing "hazardous waste" from metal mining and processing pose problems from soil and water contamination to dust and "toxic" gas emissions. Most of these adverse impacts predate environmental consciousness, laws and regulations, and technology that now enables greater control. In general, environmental priorities accompany economic affluence.

D. ORE RESERVE/RESOURCE ESTIMATION

A RESOURCE ESTIMATE is based on the prediction of the physical and chemical characteristics of a mineral deposit through collection of data, analysis of the data, and modeling of the predicted size, shape and grade of the deposit. Physical characteristics of the mineralized zone must be predicted and include: 1) the size, shape and continuity of the mineralized zone; 2) the frequency distribution of the metal grade; 3) the spacial variability of the metal grade, and 4) recoverability of metal values. These characteristics are never completely known, but are inferred from sample data which consists of one or more of the following:

1) Physical samples taken by drilling, trenching, test pitting and channel and bulk sampling of underground workings;

2) Measurement of the quantity of mineral or metal in the samples through assaying or other analytical procedures;

3) Direct observation, such as geologic mapping and/or drill core logging.

4) Analysis and synthesis of these data to develop a resource model.

This procedure will produce a GEOLOGICAL RESOURCE estimate.

A MINING RESOURCE estimation procedure must be made with some knowledge of the proposed mining method, since different mining methods may affect the size and shape and/or grade of the potentially minable reserves. These estimates must include:

1) The range of likely cut-off grades;

2) The degree of selectivity and the size of selective mining units; and

3) Variations in the deposit that affect the ability to mine and process the mineralized material.

The mining factors often determine the degree of detail that is required for the resource model, and thus the degree of difficulty in developing that model. For example, a

disseminated copper or copper/gold deposit may be continuous and regular in shape if mined by bulk, open-pit methods. The same deposit may be discontinuous and difficult to estimate, however, if mined by selective underground methods at a higher cut-off rate. Such large differences in deposit shape due to variations in cut-off grade and mining method may require different estimation procedures for different mining methods.

The geological interpretation of the orebody should be used in developing any resource model considering such features as:

1) Receptive vs non-receptive host rocks;

2) Alteration types that accompany mineralization and may create problems in beneficiation;

3) Faulting, folding and other structural modifications that may dislocate values, and/or may result in weakened rocks;

4) Multiple phases of mineralization that may modify mineral assemblages; and

5) Post-mineral deposition features processes such as oxidation, leaching, and enrichment which influence grade and amenability to beneficiation methods.

Estimated blocks should not cross geological boundaries, and a clear understanding of the genesis of the mineral body will give clues to the grade distribution. Estimations based on simple geometric forms, independent of geological units and structure can be misleading.

Compositing of assay data generally entails computing a weighted average over a mining unit.

RESOURCE ESTIMATES of different kinds of deposits all involve quality and quantity (tonnage and grade) of a usually concealed resource that must be amenable to profitable extraction. Estimates of resources are far from being precise: QUANTITY (tonnage) is generally the most precise because it is based mainly on measurement. GRADE to QUALITY is much more difficult to assess since it must consider not only variability in distribution, recoverable values, and greater probability of sampling errors. In general, the lower the proportion of the valuable constituent in the mineral body the greater the possible range of assay values and spottiness or variability in distribution **(Figure 21** illustrates the geological continuity of mineral deposit types.) In general sedimentary deposits have greater continuity than structurally controlled deposits. For example: coal, limestone, evaporite and laterite deposits have high lateral continuity; skarn deposits, Mississippi Valley type lead zinc deposits in limestone, vein gold, and vein copper, lead, zinc, silver deposits tend to lack lateral continuity. (**Figures 22a** through **22j** show the forms of vein deposits, irregular pockety deposits, high grade "bonanza" deposits, continuous high grade to low grade deposits, disseminated deposits, deep continuous high grade to low grade

deposits, bedded disseminated deposits, long vertical deposits, pockety disseminated deposits, and disseminated deposits with vertical veins.)

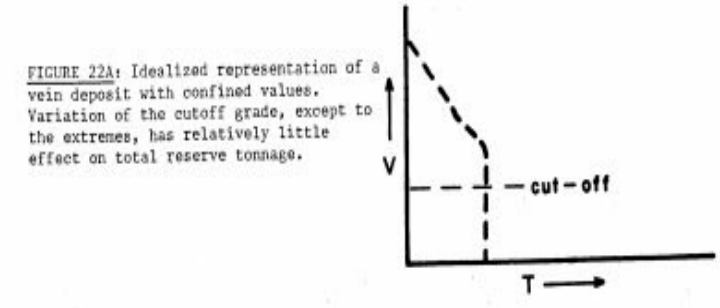
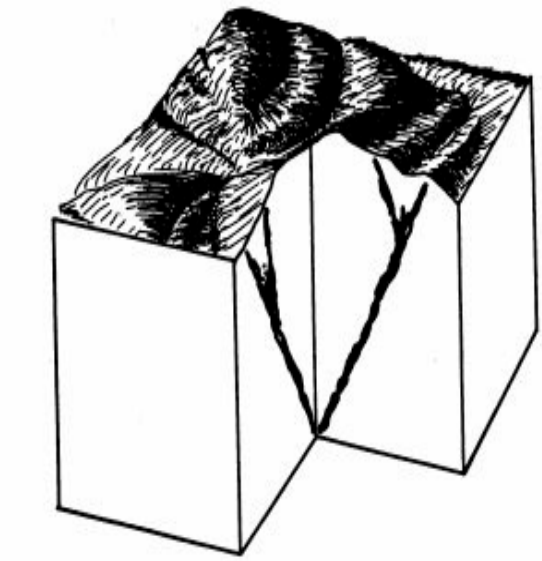


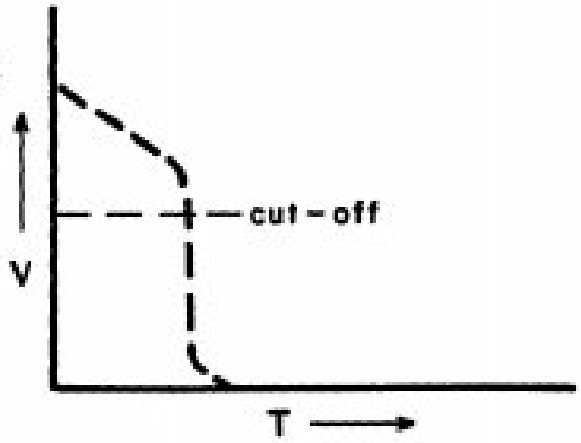
FIGURE 22A: Idealized representation of a vein deposit with confined values. Variation of the cutoff grade, except to the extremes, has relatively little effect on total reserve tonnage.



Figures 22A-22J: Value/Tonnage Relations -- EXPLANATORY NOTE.

Mineral deposits vary in shape, distribution of values, cost of extraction and concentration, etc. Variations in value and cost may create or destroy some deposits, or may have little effect upon profitability of others. Figures 22A to 22J show Tonnage/Value curves for a variety of deposit types. Each deposit must be analyzed to determine the effects of metal price changes, labor costs, taxes and royalties, etc.

FIGURE 22B: Idealized representation of an irregular, pockety deposit with confined values. The discontinuous nature of ore mineral occurrence results in higher mining costs and thus a higher cutoff grade.



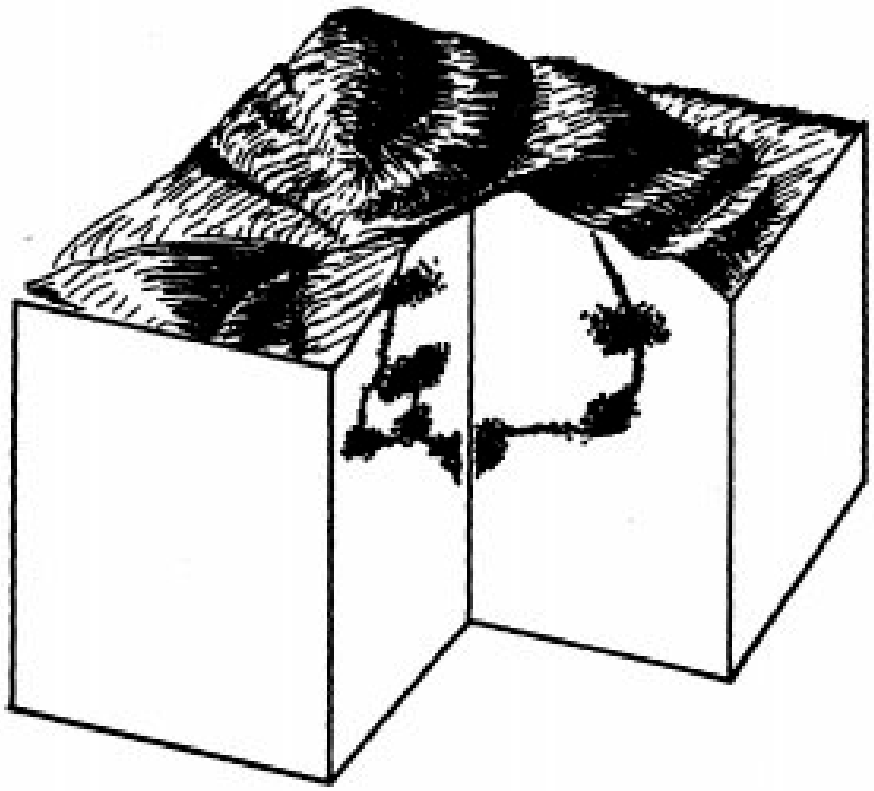
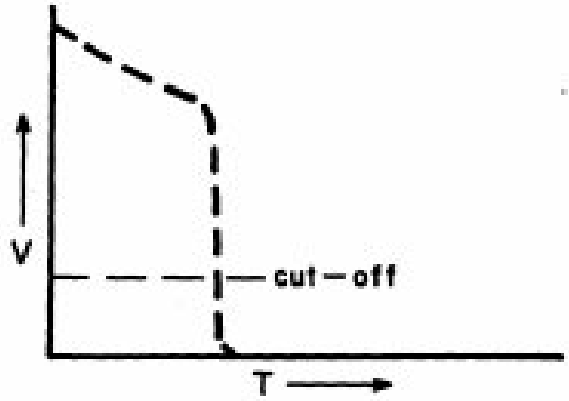


FIGURE 22C: Idealized representation of a relatively small, high-grade, "bonanza" type mineral deposit amenable to low-cost mining methods. Cutoff grade can be varied within a relatively wide range without affecting total reserves.



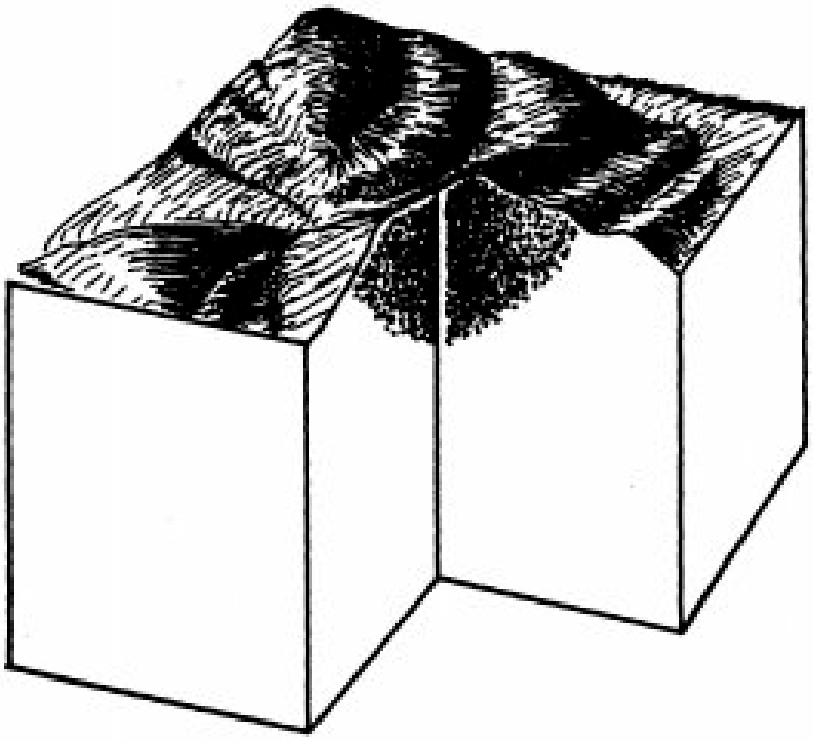
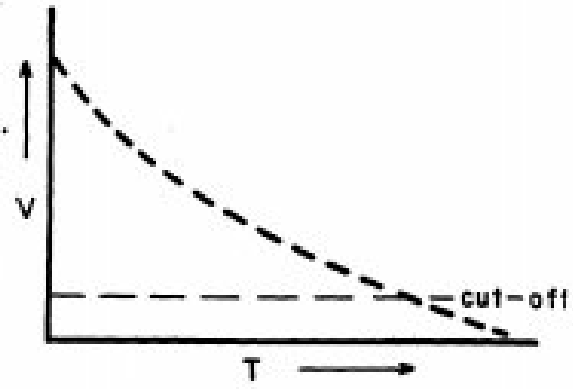


FIGURE 22D: Idealized representation of a mineral deposit with a high-grade center grading outward into lower-grade material. Exposure at the surface and continuity of values makes mining costs relatively low, lowering the cutoff grade and yielding a comparatively high reserve tonnage.



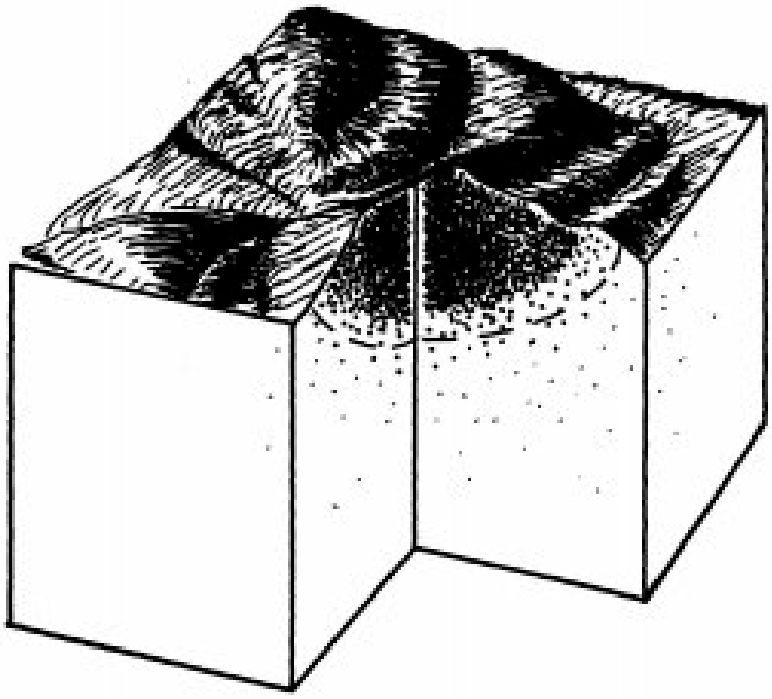
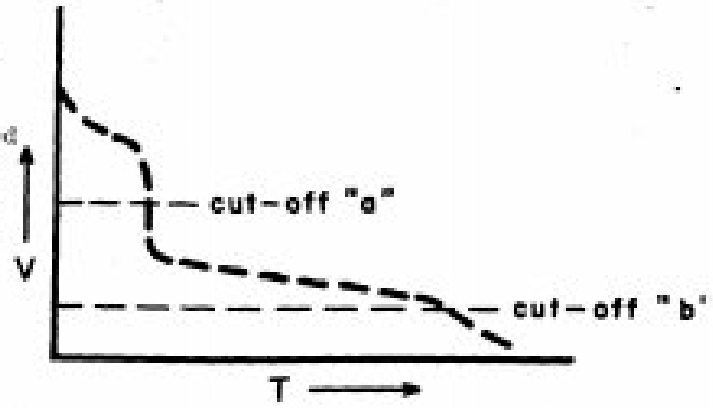


FIGURE 22B: Idealized representation of a disseminated low-grade mineral deposit with dispersed values but overlain by an enriched zone. Improved technology and/or rising metal prices may enable profitable extraction of the underlying, lower-grade resource. The reserve tonnage is thereby increased sunstantially.



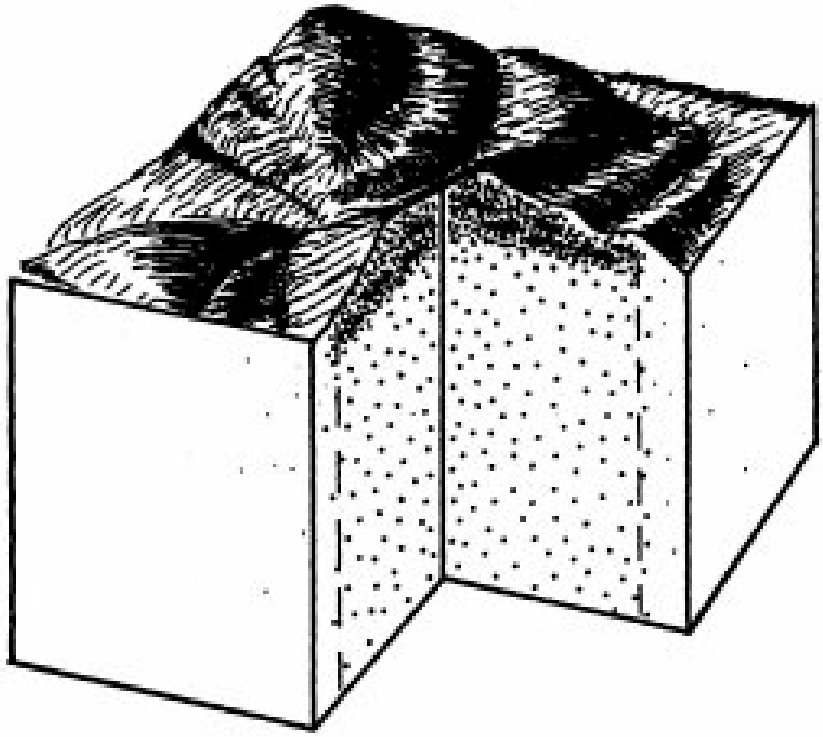
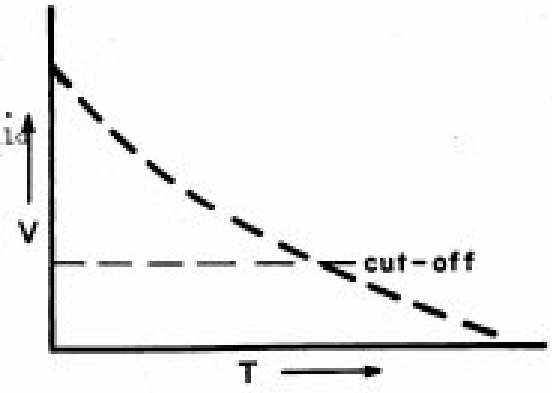


FIGURE 22F: Idealized representation of a mineral deposit with a high-grade center grading outward into lower-grade material. The position of this deposit at depth would increase mining cost and raise the cutoff grade resulting in smaller ore reserve tonnage compared to 22D.



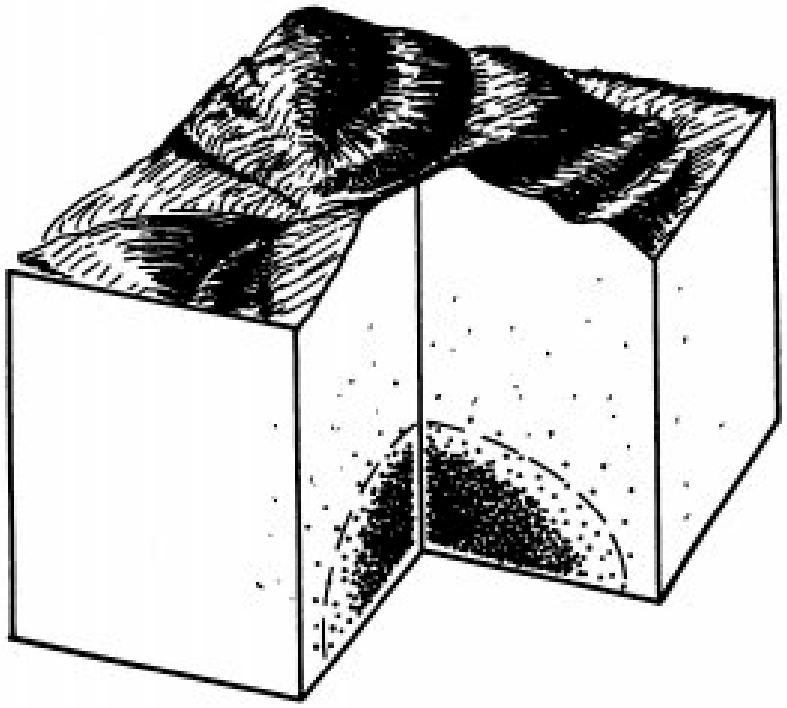
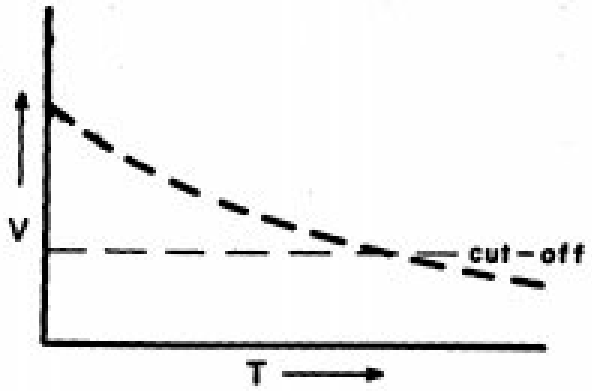
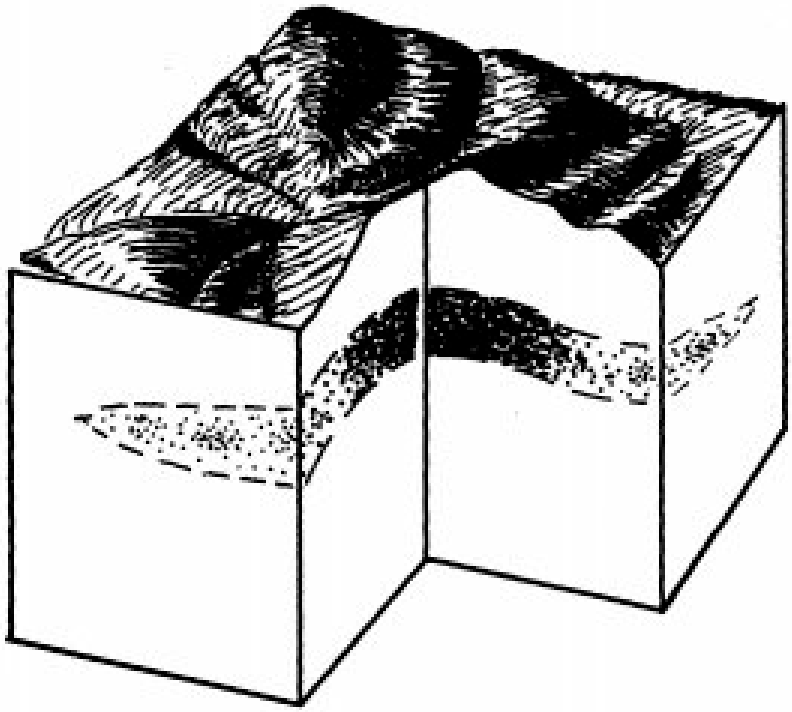


FIGURE 22G: Idealized representation of bedded ("manto") deposit with disseminated mineral values. Minor changes in cutoff grade could have relatively large effects on the total reserve tonnage.





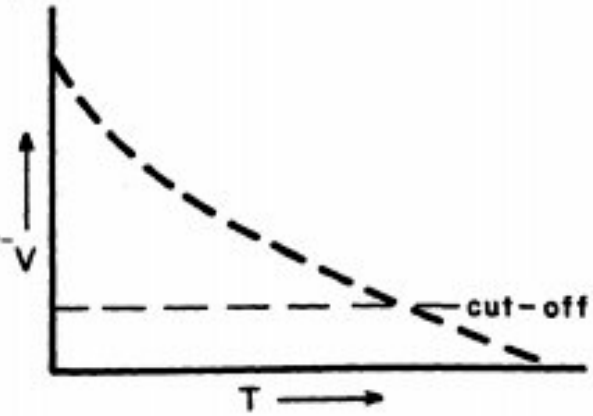


FIGURE 22H: Idealized representation of a disseminated mineral deposit with a long vertical axis and a higher-grade core grading laterally into lower-grade dispersed values. Small variations in cutoff grade could have large effects on the total reserve tonnage, particularly with rising mining costs at depth.

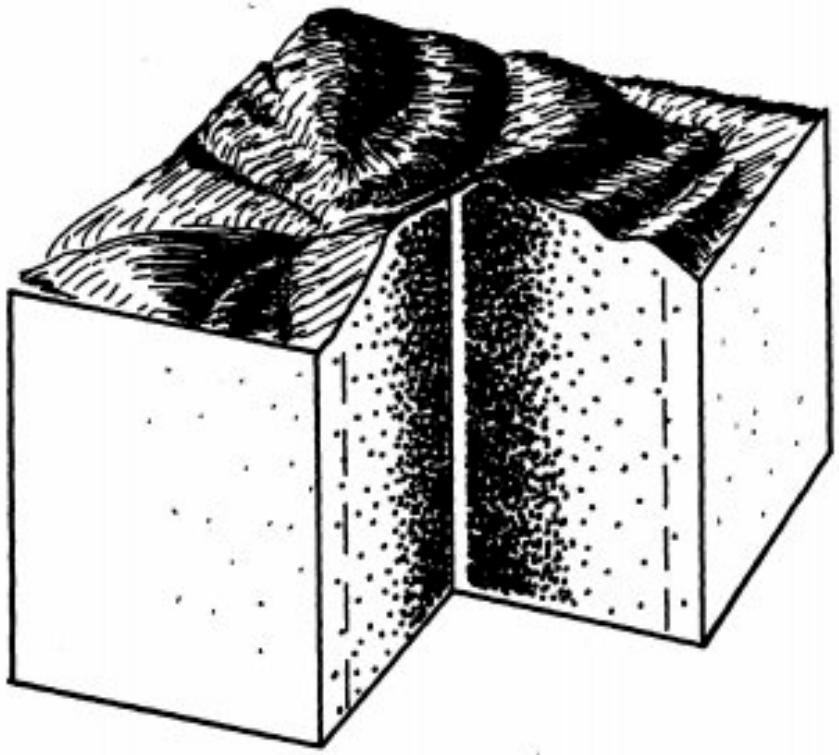
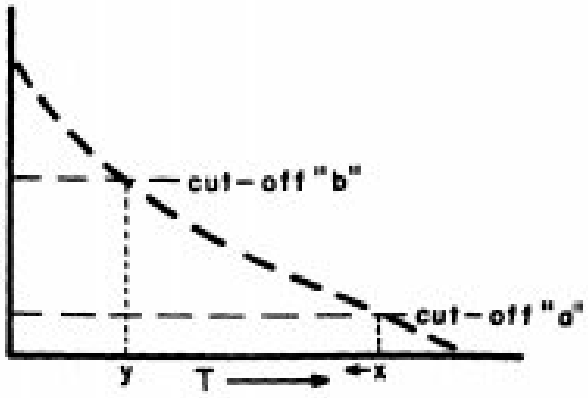


FIGURE 22I: Idealized representation of disseminated mineral deposit with higher-grade values in isolated pockets. Small changes in cutoff grade could cause major changes in both total reserve tonnage and mining methods. Many early "bonanza" type deposits were of this type. Improved technology and rising metal prices, by lowering costs and/or increasing values, turned the intervening low-grade rock into ore.



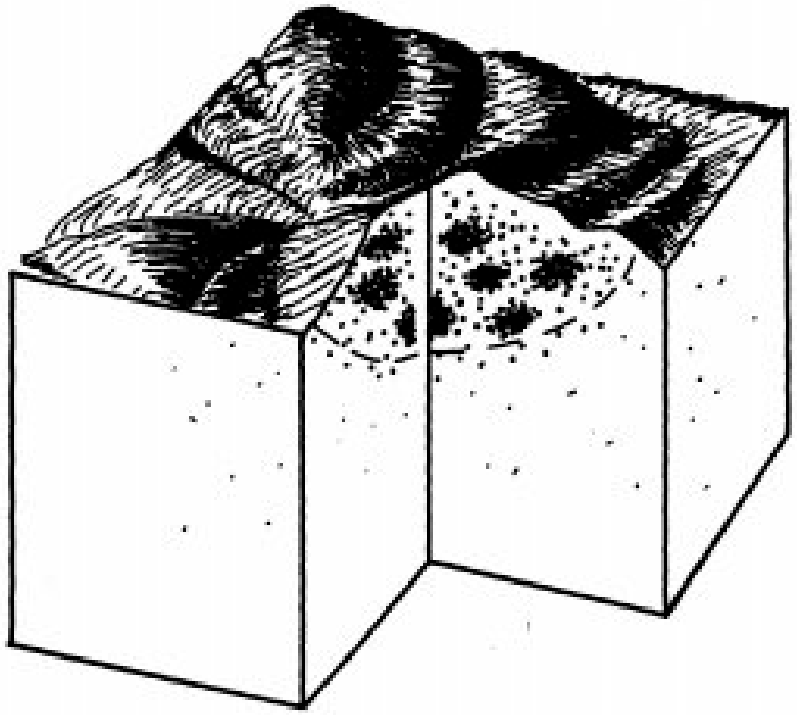
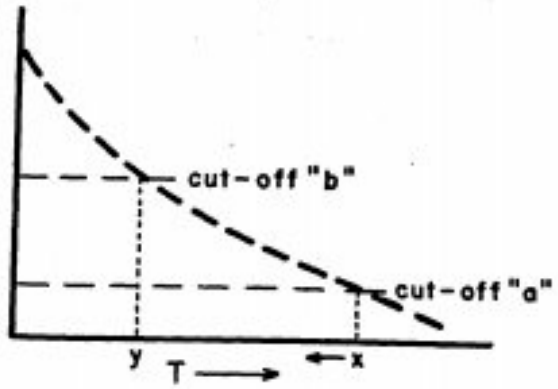
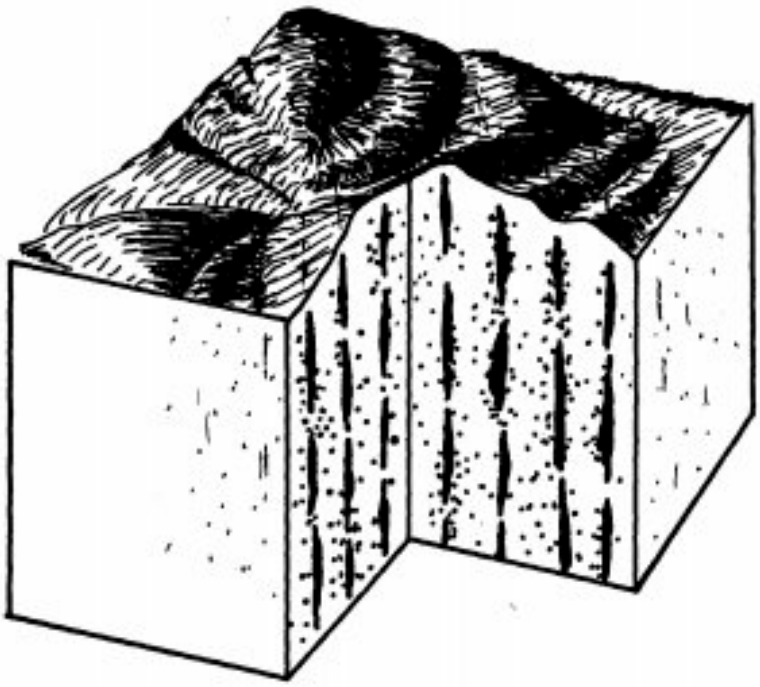


FIGURE 22J: Idealized representation of a disseminated mineral deposit with higher-grade values localized along vertical fractures with low-grade values between fractures. With a low cutoff the entire mass becomes a part of the ore reserves. An increase in the required cutoff results in severe loss of reserves.





Estimate procedures must adapt to the geometry of the mineralized body, to the pattern of the drill holes, adits and cross-cuts, trenches, etc. and to the continuity of values within the mineral body. A number of methods are in common use (**Table 14**):

a) AN OLD STYLE APPROACH (**Figure 23**) in which samples are all lumped together for calculating average grade and width from underground drifts, raises, etc. without weighting for spacing. In exploration or evaluation of data from old workings, this method may be used in early stages. It assumes that each sample represents grade and width halfway to the next sample. Regular spacing of samples is essential to avoid bias.

b) The POLYGONAL METHOD (**Figure 23c,d**) in which each drill hole is in the center of a polygon bounded by median lines or angular bisectors. Within the polygon, it is assumed for purposes of the estimate that thickness and grade are uniform. It is essential that the polygons not cross geological boundaries. Assay values from the sample are used only once.

c) The TRIANGULAR METHOD (**Figure 23e**) in which each hole is taken to be at one corner of a triangle, or a number of them, with a width and grade assumed to be the average of its three corner holes. Some samples in the fringe area may be used an unequal number of times, introducing a possible bias.

d) A SECTIONAL METHOD (**Figure 23f**) in which dimensions and grade between two drilled sections are assumed to be equal to the mean of the sections. It assumes continuity between sections.

e) A CONTOURING METHOD (**Figure 23g**) assumes continuity of values between drill holes or blocks of similar grade and basically means deriving a plan of grade distribution from vertical holes. Contouring may be accomplished by use of a traveling circle that averages all values within the circle. This smooths out irregularities.

f) A SPHERE OF INFLUENCE METHOD in which the grade of a portion of a mineral body is derived from samples within the surrounding blocks (in two or three dimensions) giving greater weight to near samples and less to distant samples. Samples are used repeatedly in a manner only feasible using a computer.

g) GEOSTATISTICS also uses surrounding blocks to estimate grade of particular blocks with weighting calculated from a 'variogram' representing a distance/value relationship between samples.

FIGURE 23: Resource estimation methods.

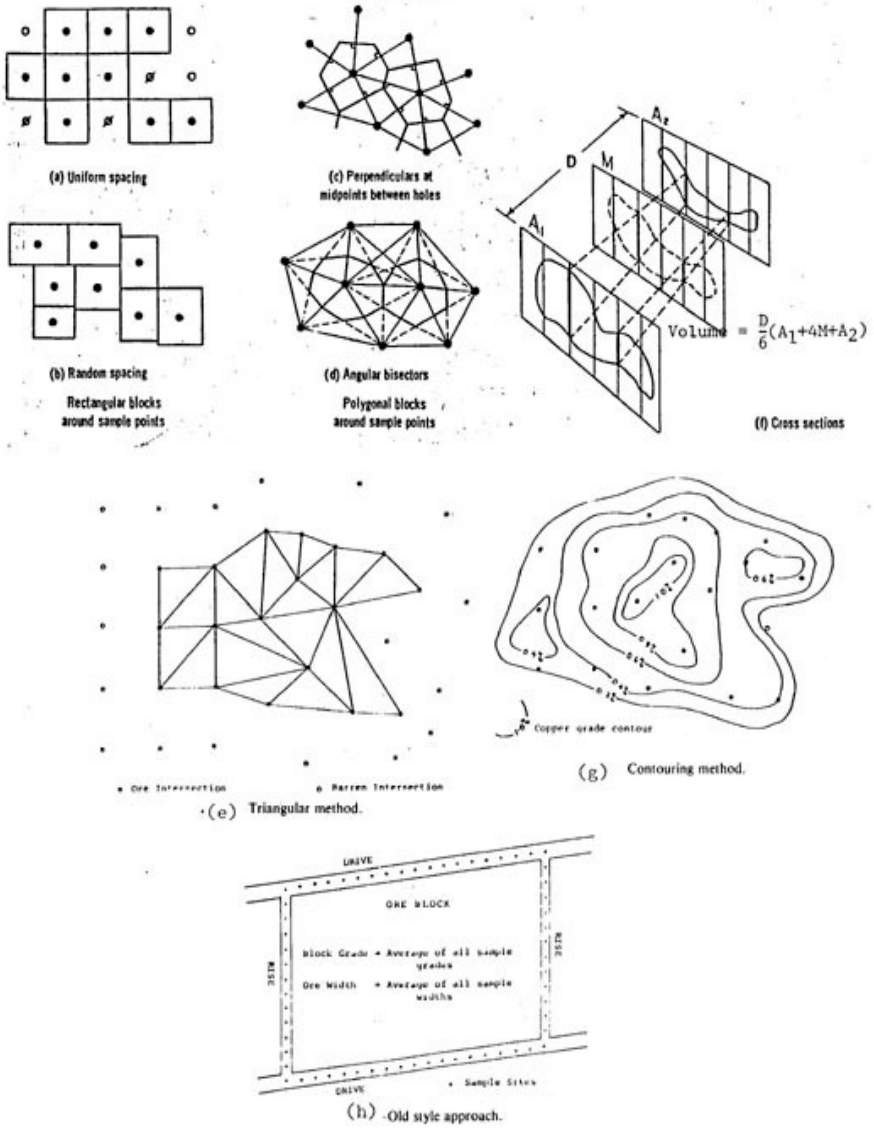


Figure 23: Resource Estimation Methods -- EXPLANATORY NOTE.

Methods of Ore Resource calculation will vary with anticipated continuity of values, the geology of the deposit, and available sampling information. Many mistakes have been made in resource estimations through failure to establish continuity of values.

In this progression from simple to complex mathematical procedures has both advantages and disadvantages:

a) It derives a grade for a particular portion of a deposit from more samples - in effect down-grading high assays and up-grading low assays.

b) One may become so wrapped up in computer mathematics and printouts that assumptions are lost sight of, and geological controls and characteristics and sampling errors are lost.

Computer-generated estimates must always be compared against geometric-generated block estimates superimposed on geological maps and sections and discrepancies explained.

E. COSTS AND COST ESTIMATION

The accuracy of estimation of capital and operating costs of a mining project is dependent upon the reliability and quality of data from exploration and development stages -the assessment and knowledge of expected mining and metallurgical conditions.

Estimates will need to be adjusted as more detailed information is acquired. Cost formulae can provide some guidance as to the order of magnitude of both capital and operating costs, but accurate estimation must be trusted to consulting engineering firms who employ civil, structural, mechanical, chemical, metallurgical and electrical engineers.

The most important factor affecting costs is the size of the mine and processing plant in terms of ore mined and milled per day of operation. Consequently, they are sensitive to the accuracy of ore reserve calculations - the size, shape, continuity, depth, and rock physical character. Uncertain forecasts of behavior of the metal market, equipment costs, future government actions and restrictions make estimates uncertain even with the best engineering.

Costs estimated in a preliminary feasibility study are unlikely to be more accurate than plus or minus 40%. These are usually based upon comparative costs with other operations of similar character, formulae and "rules of thumb". This degree of accuracy is not sufficient to provide a sound basis for major mine financing or assurance of a profitable mining operation.

Estimation of costs with an accuracy of plus or minus 10%, which is needed for a detailed feasibility study, requires completion of extensive technical work and studies on mine planning, general plant layout and design, environmental studies and assessment of supplies of labor, and equipment required for mining, milling and service operations (transport, housing, water and electrical, etc.). This type of feasibility study is normally required for obtaining long-term financing.

Table 14: Selection of Estimation Method Based on Deposit Geometry and Variability

	Low Variability, COV < 0.25	Moderate Variability, COV > 0.25 < 0.75	High Variability, COV > 0.75
Simple Geometry			
Deposit description	Tabular, continuous grade and thickness Flat or constant dip	Tabular, large ore pods Moderately variable grade	Tabular, small ore pods Highly variable grade
Example deposits	Evaporite Sedimentary Iron Limestone Coal	Stratiform copper Mississippi Valley lead Simple porphyry copper, molybdenum	Gold veins Gold placers New Mexico uranium Alluvial diamond
Estimation methods	Grade and thickness using any 2-dimensional method: polygonal, contouring, inverse distance, kriging. Geometric controls for boundaries of ore zone, faults, and fold axes	2-dimensional methods. Inverse distance or kriging. Polygonal or cross section with 5 to 15% dilution	2-dimensional methods. Inverse distance or kriging with recovery functions. Polygonal with 15 to 35% dilution
Moderately Complex Geometry			
Deposit description	Simple, bedded. Uniform grade but erratic thickness, gentle folding, or simple faulting	Simple three-dimensional geometry. Moderately variable grade	Simple three-dimensional geometry. Two-dimensional with smaller, more erratic ore pods. Simple folding, faulting
Example deposits	Bauxite (variable thickness) Lateritic Nickel (variable thickness) Salt Dome	Porphyry copper Porphyry molybdenum	Stockwork and Carlin-type gold Volcanogenic base metals
Estimation methods	Estimate grade, thickness and elevation using any 2-dimensional method Must define structural geology (faults, fold axes) Variability of thickness may be difficult to predict	Inverse distance or kriging with external controls to define the shape and grade trends. Polygonal and cross-sectional methods may be used but will require dilution/volume variance correction	Inverse distance of kriging with recovery functions. Polygonal or cross section with 15 to 35% dilution
Complex Geometry			
Deposit description	Otherwise simple deposits that have been severely folded and faulted	Complex geometry due to faulting, folding, or multiple mineralization controls. Moderately variable grade	Deposits with extremely variable grade and highly contorted, complex ore shapes. Typically little continuity between individual ore zones. General mineral envelope definable but with 50% or less ore
Example deposits	Talc Gypsum (deformed)	Tungsten skarns (folding/faulting). Base metal skarns (erratic shape). Copper porphyry combined with local skarns or replacements (multiple controls)	Archean gold deposits Roll front uranium
Estimation methods	Cross-section methods with detailed definition of structural geology. Difficult to define geometry for 3-dimensional block models and geostatistical methods	Cross-sectional methods with detailed input to describe structural geology and or zones. Geostatistical methods may be appropriate but difficult to implement because of geometric complexity	Estimation very difficult. Size, shape, and grade not locally predictable. Cross-section, area-outline methods, indicator kriging applicable. Errors of 50 to 100% typical. Tonnage often overestimated because of incorrect geologic model

II. FINANCING

The subject of mine financing is complex and varies with ownership, risk, market conditions, taxation and governmental policies, and the stage of mine development. As a project evolves from prospecting and exploration to target examination, then to evaluation, development and operation, the mode of financing changes (**Figure 41**).

During exploration by an exploration company/syndicate, risk monies are sought, and the promoters seek to retain as much of the equity and as little of the financing obligations as possible. In general there are two types of exploration companies or syndicates: those looking to find and develop a mine, and those whose objective is to develop a mineral deposit to a promising stage and then sell out.

The exploration or independent company at the exploration stage generally has a capital structure consisting largely of equity or tax-sheltered funds. Equity can be raised from individuals, companies stock issues, junk (high-yield) bonds, and some 30 to 40 other sources of funds.

Development companies may have one or two exploration successes which require financing for drilling and feasibility studies before actual mine development can be financed. Some junior companies may specialize in redeveloping defunct mines or restructuring troubled operations as a way to finance mine development.

The venture capitalist seeks high returns, as follows:

- Seed capital (exploration) 100-300%
- 2nd or 3rd stage (development) 30-45 %
- 4th stage (feasibility) 25-35 %

Returns can be in equity or loans converted into equity, or options/warrants or royalties.

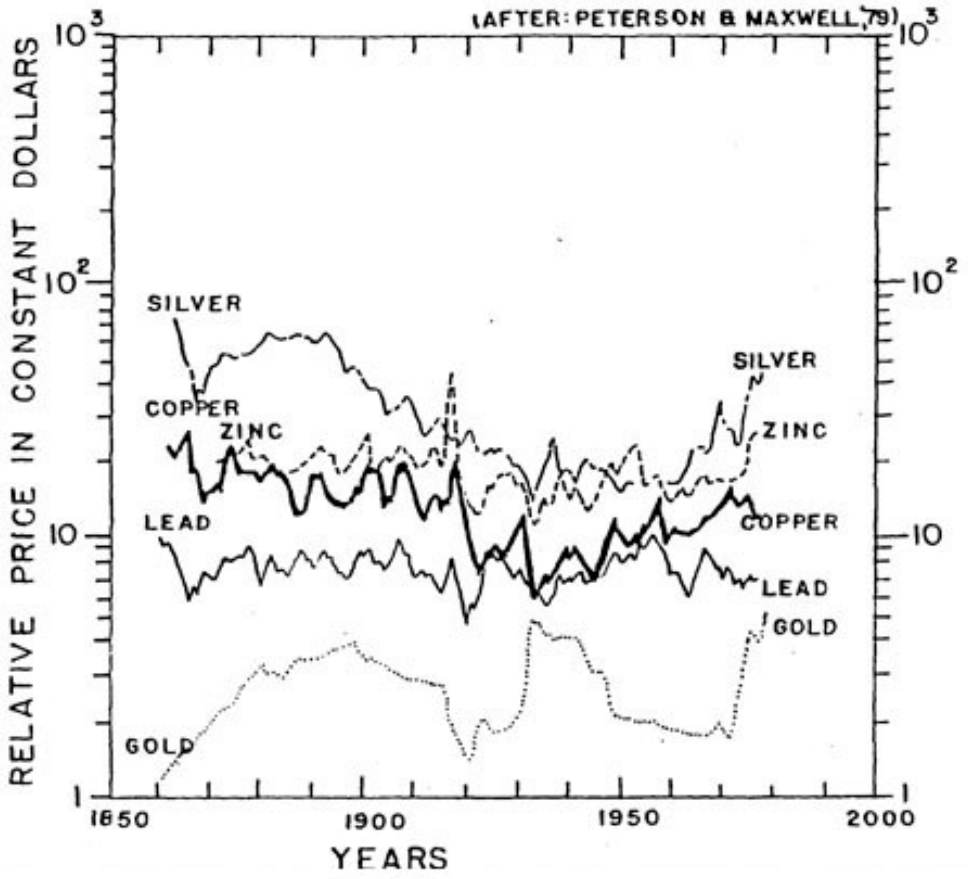
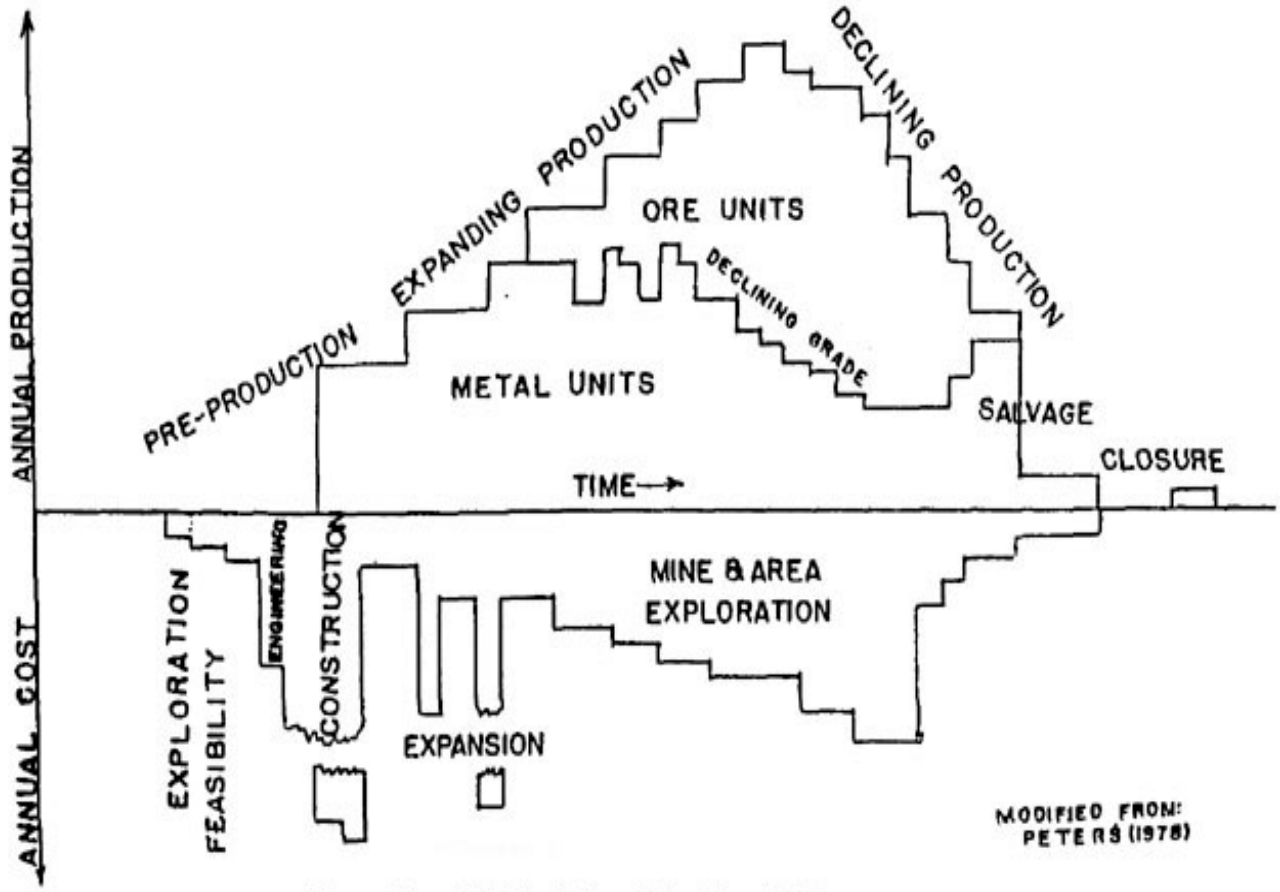


Figure 38: Historical Metal Price Trends (1850-1979) (after Peterson and Maxwell, 1979) --
EXPLANATORY NOTE:

The greatest economic risk to a mining operation is variation in metal prices. The plot by Petersen and Maxwell of relative prices in constant dollars from 1850 to 1979 illustrates this tremendous fluctuation. Gold and silver have been severely affected by controlled monetary policies where value failed to match inflation, and by divestment of monetary reserves. Copper, lead and zinc follow similar patterns affected by supply and demand.



Figures 39 and 41: Mine Life and Mine Financial Life -- EXPLANATORY NOTE.

The birth and life of a mining operation begins with exploration, testing, feasibility and engineering studies, financing, and development. This generally entails a period of 7 to 15 years of spending with no financial return. Early years of mining, where higher grade ores are available, generally involve efforts to increase production over designed capacity to accelerate 'payback' of investment. As mining progresses, grade declines and in spite of production increases production ultimately declines to the point of mine unprofitability and closure and salvage -- unless mine and area exploration reveals additional resources and/or new technologies or higher metal prices enable conversion of 'waste' into 'ore' by reducing cost or increasing value. Figure 41 illustrates an idealized cash flow diagram at variable discount rates. It demonstrates that income not to be received for 20 years has little present value, and that any policy that increases pre-production periods detracts from the quality of a mining investment.

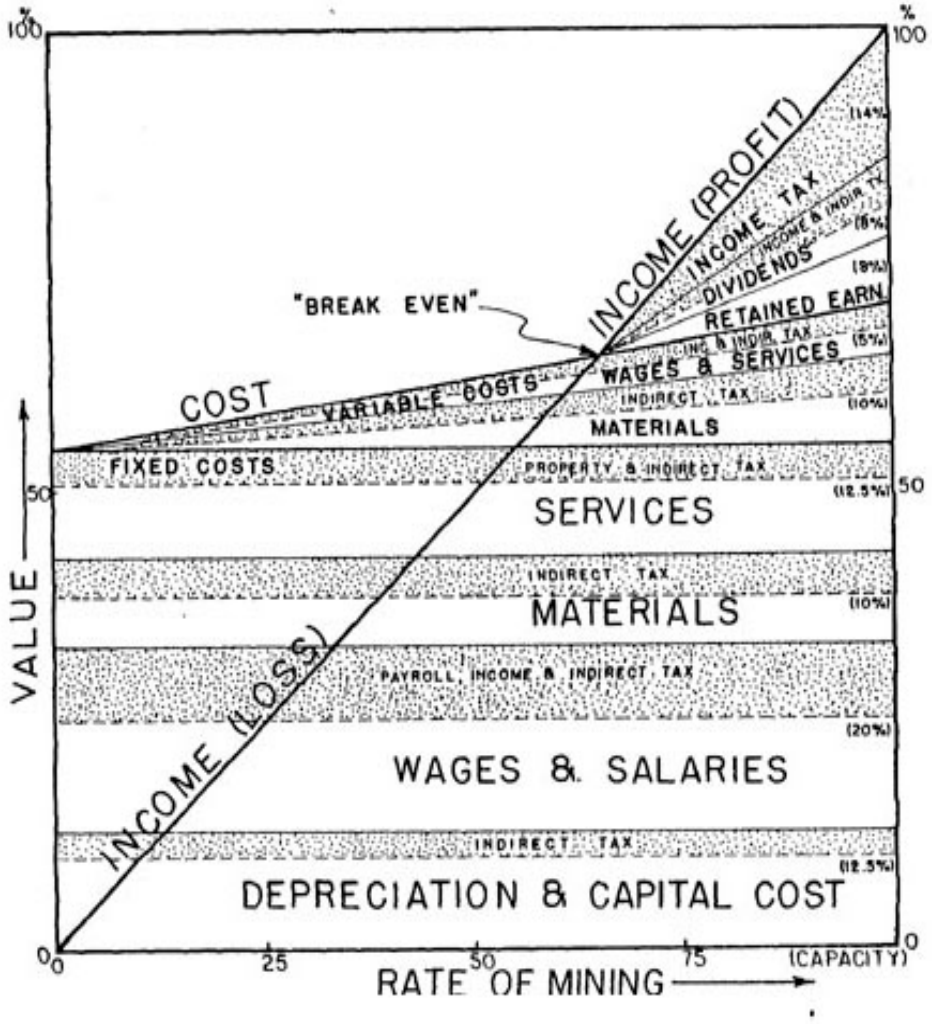


Figure 40: Value/Rate/Income of a Mining Operation -- EXPLANATORY NOTE.

Mining operations consist of fixed and variable costs, with fixed costs generally comprising over 50%. When interruptions to the rate of production occur as a consequence of labor difficulties, etc., losses are great. In most instances when production must be curtailed because of market surplus, mines must continue operations at a reduced rate, since fixed costs will continue.

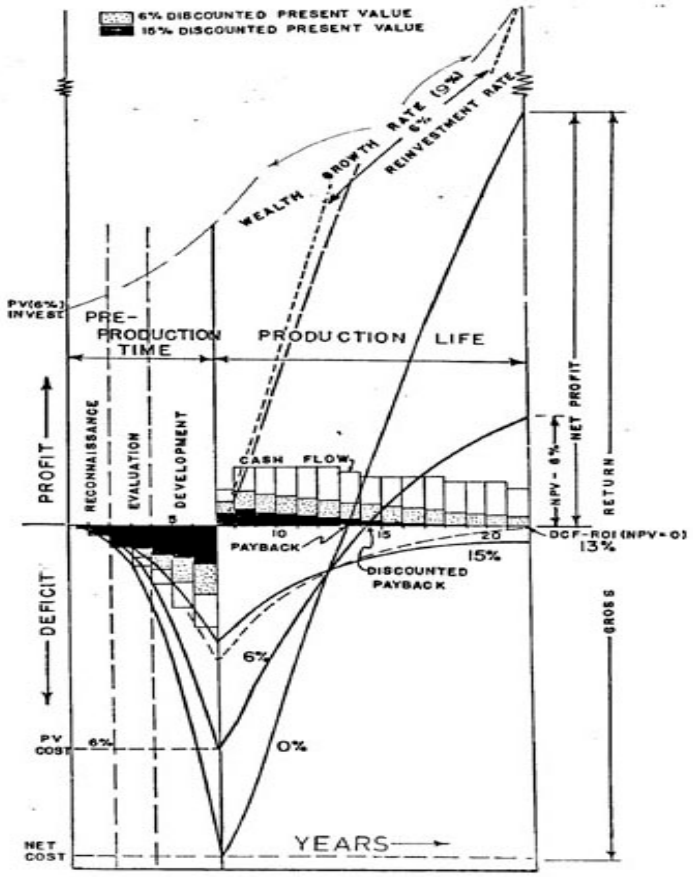


Figure 41: Mine Financial Life --
EXPLANATORY NOTE (This note contains the same text as the note to Figure 39.)

The birth and life of a mining operation begins with exploration, testing, feasibility and engineering studies, financing, and development. This generally entails a period of 7 to 15 years of spending with no financial return. Early years of mining, where higher grade ores are available, generally involve efforts to increase production over designed capacity to accelerate 'payback' of investment. As mining progresses, grade declines and in spite of production increases production ultimately declines to the point of mine unprofitability and closure and salvage -- unless mine and area exploration reveals additional resources and/or new technologies or higher metal prices enable conversion of 'waste' into 'ore' by reducing cost or increasing value. Figure 41 illustrates an idealized cash flow diagram at variable discount rates. It demonstrates that income not to be received for 20 years has little present value, and that any policy that increases pre-production periods detracts from the quality of a mining investment.

Development funding may come from a variety of sources and the cost of capital will depend upon tax laws which allow deduction of interest payments, but not dividend payments. For example, the following is an approximation of the cost of capital for a project:

Finance Source	*% New Capital*	*Cost %/Annum*	*After Tax Cost*
Bank Loans, unsecured	15.0%	16.0%	9.6%
Mortgage Bond	20.0%	14.0%	8.4%
Equipment Leases	15.0%	16.0%	9.6%
Preferred Shares	4.0%	17.0%	17.0%
Common Shares	41.0%	19.0%	19.0%

Operating companies often fund exploration from internally generated cash flow or they may joint venture development of a new project. They generally have very different sets of financing objectives. Increasingly, new developments must stand on their own in financing and operations, rather than being carried by the mother corporation.

As a "rule of thumb," the objective of most mining developments is to achieve a capital structure of 50% equity and 50% debt financing. A project with a highly predictable cash-flow, based on strong sales contracts can move leverage to 90 to 100%, while a mine with cash-flows difficult to predict, as with most industrial minerals (mercury, etc.) can expect to attract very little traditional debt financing. However, as the ratio of borrowed money to equity money increases, the interest payments and the rate of interest may become so large that profits may disappear.

(After C.R.Tinsley.)

CHAPTER 5

FINANCIAL ANALYSIS

I. FEASIBILITY ANALYSIS

(After E.S. Frohling, N.C. Hario, 1971) (TABLE 19)

A feasibility study entails a review of costs and potential earnings of a proposed mining venture. Throughout mining history, low-cost mines continue to be developed regardless of the impact of new production or technology on price, and, in times of oversupply, low-cost producers replace marginal producers. It is essential for new producers to know where their prospects stand economically, relative to other producers.

After a potential orebody has been discovered, a decision must be made as to specifically, what is to be produced and marketed (ores, concentrates, refined metals) and the cost of such production? A feasibility study must, for example, determine what production costs are required to upgrade the product and determine the additional investment required.

A. OBJECTIVES

The first objective is a market survey. Prediction of demand/price, political atmosphere and regulations (taxes, royalties, risk of expropriation, etc.) is an assessment of risk. Comparative cost analysis is appropriate. After the capital cost estimates are determined, estimates can be made of operating costs, and these can be compared.

Companies use different internal criteria to determine basic viability: Net Present Value (NPV), Rate of Return on Investment (RRI), Payback Period, Project Life, etc. In politically unstable areas it is important to recoup investment as quickly as possible (perhaps 4 years), while in stable areas one might stretch the amortization period to 8-9 years or more (**Figure 41**).

B. DETERMINATION OF CAPITAL COSTS

Capital cost estimates may be required for a number of purposes. The purpose of the estimate dictates the accuracy required:

- whether more capital should be spent to develop more definitive data and the allocation of additional funds;
- information for private financing from individuals, banks, or other mining companies;
- to furnish data to go for public financing through stock issues;
- to obtain funds from governmental agencies (AID, EXIM, etc.).

The greater the degree of accuracy required, the higher the preparation cost and time required. For example, people experienced in estimating certain types of plants have data on relative capital costs depending upon ore grade and proposed feed rate. With minimal information of this type, accuracy might not be better than 40%.

Where a flow-sheet is established, with equipment lists, price of equipment, etc.; building costs based upon consumption of concrete, steel, etc.; electric costs based upon cost per horsepower; piping as a percentage of equipment costs, etc, the estimate might not be better than 30%. This could be refined to within 15%.

Finally, when about 40% of the final engineering is complete and the project is well defined, estimates should be within 10%.

C. RISK ANALYSIS

Risk analysis entails a review of the sensitivity of the proposed venture to production market conditions, cost of production, selling price of products, grade variations, geological variations, etc.

II. MARKETING AND FINANCING

(After B. Nolk, 1992)

Sales and marketing of mineral products varies with individual companies. The entire system of exploration, discovery and evaluation, mining and processing depends upon sale of the product at a profit within a long preproduction and production time frame. Most major mining companies have their own marketing division, and marketing strategies can help compensate for the risks inherent in any mining venture (**Figures 38**, **39**, **42**).

Mineral material is frequently sold at several stages in its development. Copper, for example, may be sold as ores or concentrates, intermediate metal (BLISTER copper anodes), refined metal (electrowin or electrolytic copper cathodes), alloyed metal, semi-finished products or finished products, or, finally, as scrap. At each step the material is bought and sold, or if processed internally, at least priced for that purpose.

A copper company will need to know the market for concentrates as well as blister copper to determine whether it is economically worthwhile to build or up-grade smelter facilities.

Internal selling of ore to concentrator, concentrator to smelter, blister copper to refinery, etc., is a valid marketing exercise. It serves to evaluate economic efficiency of the system and guides marketing strategy to avoid gluts or bottlenecks in the chain.

Increasing internationalism of the minerals commodity market causes a shortage or surplus in one part of the world to influence the market worldwide.

Transactions include: 1) sales contracts at fixed prices and tonnages, or 2) multi-year contracts with periodic pricing linked to exchange price formulae for various tonnages.

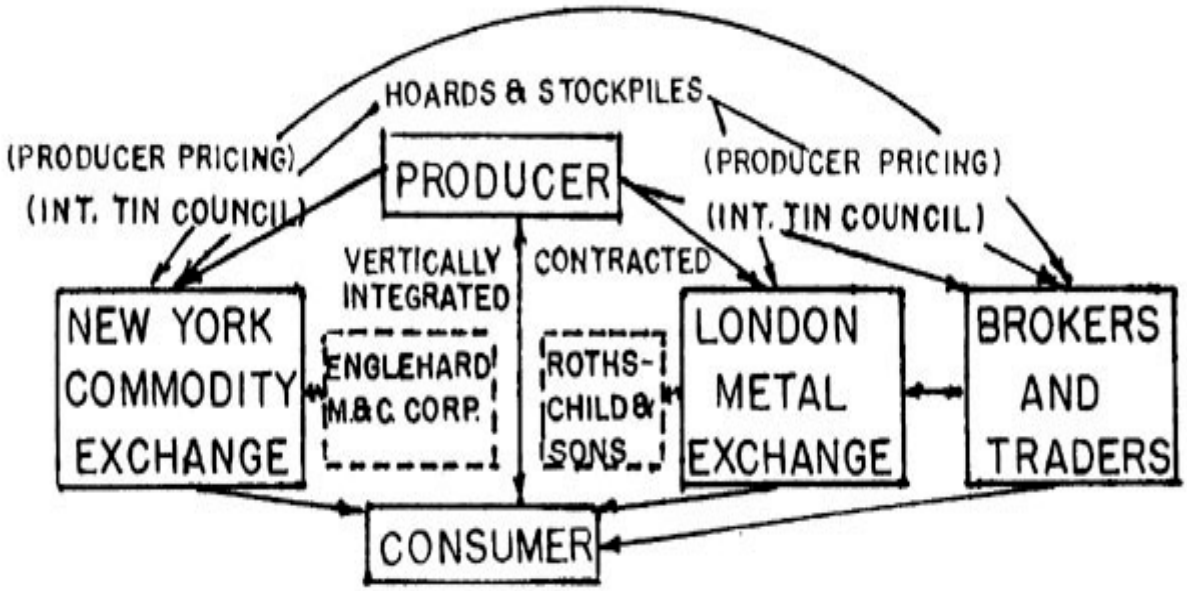


Figure 42: Metal Marketing -- EXPLANATORY NOTE.

On occasion, sales contracts may be arranged directly between producer and consumer, or utilized within a vertically integrated corporation, but generally sales are arranged and prices set by the New York Commodity Exchange or the London Metal Exchange. This international pricing of metals places competition on an international basis.

A. PRODUCER PRICING

Producer pricing is a straight forward approach by which the producer establishes a reasonable and competitive price for his product by announcing to key customers and media a fixed price for the day (or month or quarter). Consumers can contract set amounts of product in increments for delivery. It is possible for producers to maintain pricing control of their product when there are few competitors for the product or the quality required.

Today, much of the production of major metallic mineral commodities is integrated vertically, so that the large miner of metallic ore has considerable control over the sale of the finished metallic product. However, for the alloying metals only a small proportion of the production is carried through to the refined metal products. Ores and concentrates of these are generally sold either by the miners to the industrial consumer or through dealers. For the minor metals, dealers are important in marketing.

B. EXCHANGE-BASED PRICING

In times of price volatility, the producer may wish to tie pricing to a free market indicator, such as the London Metal Exchange (LME) or the New York Commodity Exchange (Comex) futures contract, or even to free market quotes, such as those published monthly in the Engineering and Mining Journal (E&MJ).

Both buyers and sellers must choose the same pricing mechanism.

Trading in futures and options contracts has become increasingly important and offers an opportunity for HEDGING. A futures contract enables producers to guard against the risk that prices will fall and protects the buyers from the risk that prices will rise. The need for hedging is important when several foreign currencies become involved. Hedges may involve metal commodities, currencies, or interest rates.

Most companies do not like to hedge 100% of their production, in hopes that they can take advantage of price spikes that take place periodically. A 'rule of thumb' for hedging is (C.R. Tinsley):

1) Cover 100% of mine operating cost as far forward as possible on the downside production profile and be sure local currency costs are matched in that currency.

2) Cover loan repayments by at least 50% where currency hedging is required. Change the percentage hedged progressively by roll-overs and perhaps leave unhedged from time to time.

3) Cover forward price volatility with floor-price programs and PUT options designed to insure a minimum cash position, after debt repayment and exploration costs.

4) Match debt obligations where possible by commodity-linked programs, e.g. gold loans, especially for volatile commodities.

Exchange trading of metals serves to establish PRICE DISCOVERY for commodities traded and, by extension, to the comparable materials both up and down the materials chain, by use of premiums and discounts from the exchange traded price.

C. INDUSTRIAL MINERALS

Marketing of industrial minerals and rocks is normally local to regional, except for potash and sulfur. Marketing is done by the producers or through use of sales agents, and, in many instances, the producer is the seller of the finished product (i.e. gypsum as wallboard, asbestos, phosphate, etc.).

In the marketing of industrial minerals and rocks, the factors of primary concern are the location and size of the particular local markets (existing and potential), the chemical and physical specifications of the product, unit value and transportation costs. The product generally must be "sold" to the potential consumers. It will not normally "sell" itself, as is true of metal commodities (**Table 4**).

D. MINERAL PRICES

(After S.D. Strauss, 1992)

In any feasibility study for a metals or mineral project, an assumption must be made as to the prices at which the projects products can be sold. Forecasts of prices must cover the extended period of pre-production and production until investment is recouped.

Among virtually all the metallic minerals prices are highly volatile, although there have been some periods of relative stability for the published prices of some commodities.

III. FINANCING MINE DEVELOPMENT

(After C.P. Tinsley)

Post-feasibility study mine development funding offers a wide variety of options international in character. Once exploration has resulted in a viable mining project, the financial requirements for funding change in emphasis. Factors such as cash flow, impact of taxation policies, net income, etc. become dominant considerations.

A great variety of financing opportunities are available and selection of the optimum combination often determines the profitability of the project. Financing possibilities include: 1) equity financing, 2) commodity-linked financing, 3) contract mining, 4) supplies/buyers credits, 5) governments, 6)joint ventures, 7) institutions/insurance companies, etc. (**Figure 43**).

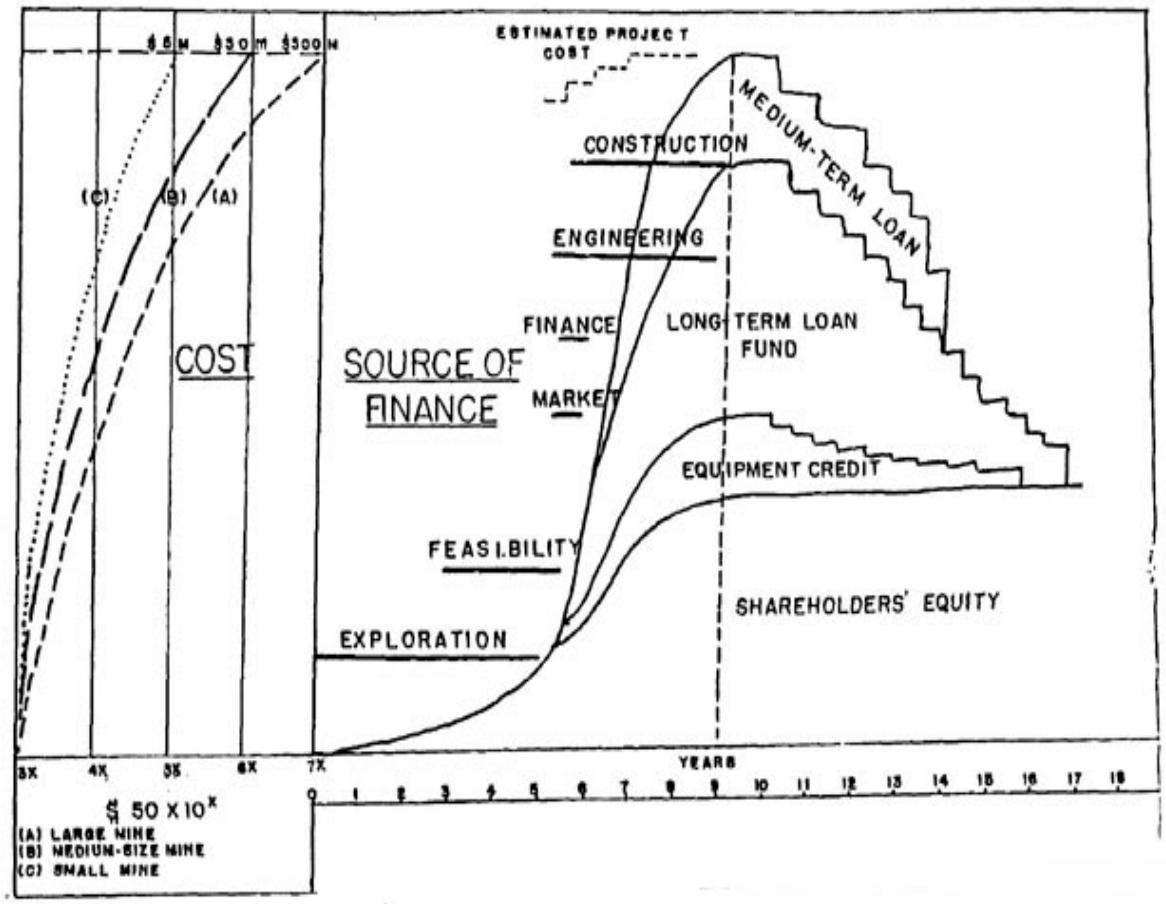


Figure 43: Financing of a New Mine -- EXPLANATORY NOTE.

The risk of failure and the possibility for great reward varies during the development and life of a mine. Few lending institutions are willing to risk loans during the exploration phase, until a feasibility or engineering study has been completed. During this early phase financing is generally through the issue of equity shares. Financing becomes easier as market and engineering studies establish the economic viability of the project.

Present corporation financing policies tend toward PROJECT MULTI-LAYERED FINANCING rather than internal corporate financing, with each development standing on its own merits. Although project financing is usually more expensive than borrowing on the strength of the corporation's balance sheet or the issue of additional stock, and involves more rigorous examination of projects by financial institutions, it does offer the advantage of making financing available to joint ventures. Project financing permits companies to leverage their assets beyond what would otherwise be possible. With increased debt financing (increased leverage) the net proceeds are related to a smaller base and a higher return on equity is expected.

Until about 1960, 90% of capital requirements were met by equity financing. However, growth of inflation and income taxation policies made it more attractive to utilize debt financing which had the advantage that it served as a hedge against inflation because debts are repaid in cheaper dollars.

Multilayered financing may entail commercial bank and institutional financing mixed with financing from suppliers, export incentive institutions, international development institutions, metal purchasers and merchants, and others.

Political and project risks can be reduced by placement with organizations such as Eurobank syndicates. And in Third World international developments, for example, a host government can borrow, say from the World Bank, funds for the infrastructure required by a new mining community at a lower rate of interest and for a longer term than can be obtained by the investors.

Operating mines may secure credit in bank loans, trade financing, or by hedging on the commodities market.

CHAPTER 6

METHODS OF MINING AND MILLING

I. MINING METHODS

Basically all mining methods entail two fundamental tasks regardless of scale: breaking the ore, and transporting it to the beneficiation or processing plant (**Figure 24**).

Ore breakage historically has been a drill and blast cycle. Continuous breaking is used in "soft" rock using mechanical rotating cutters or chain-saw type devices. Large machines are now capable of boring through hard rock continuously and are used for drilling mine shafts and underground workings.

A. SURFACE MINING

Methods of surface mining can be subdivided into various classes and subclasses (E. Bohnit, 1992):

Class	*Subclass*	*Method*
Mechanical		Open Pit Mining
		Glory Holing
		Quarrying
		Strip Mining
		Auger Mining
Aqueous	Placer	Dredging
		Hydraulic Mining
	Solution	Surface Techniques
		In Situ Leaching

OPEN PIT MINING is a term properly applied to a surface mining method in which reclamation is deferred until all, or nearly all, of the deposit is removed within economic limits.

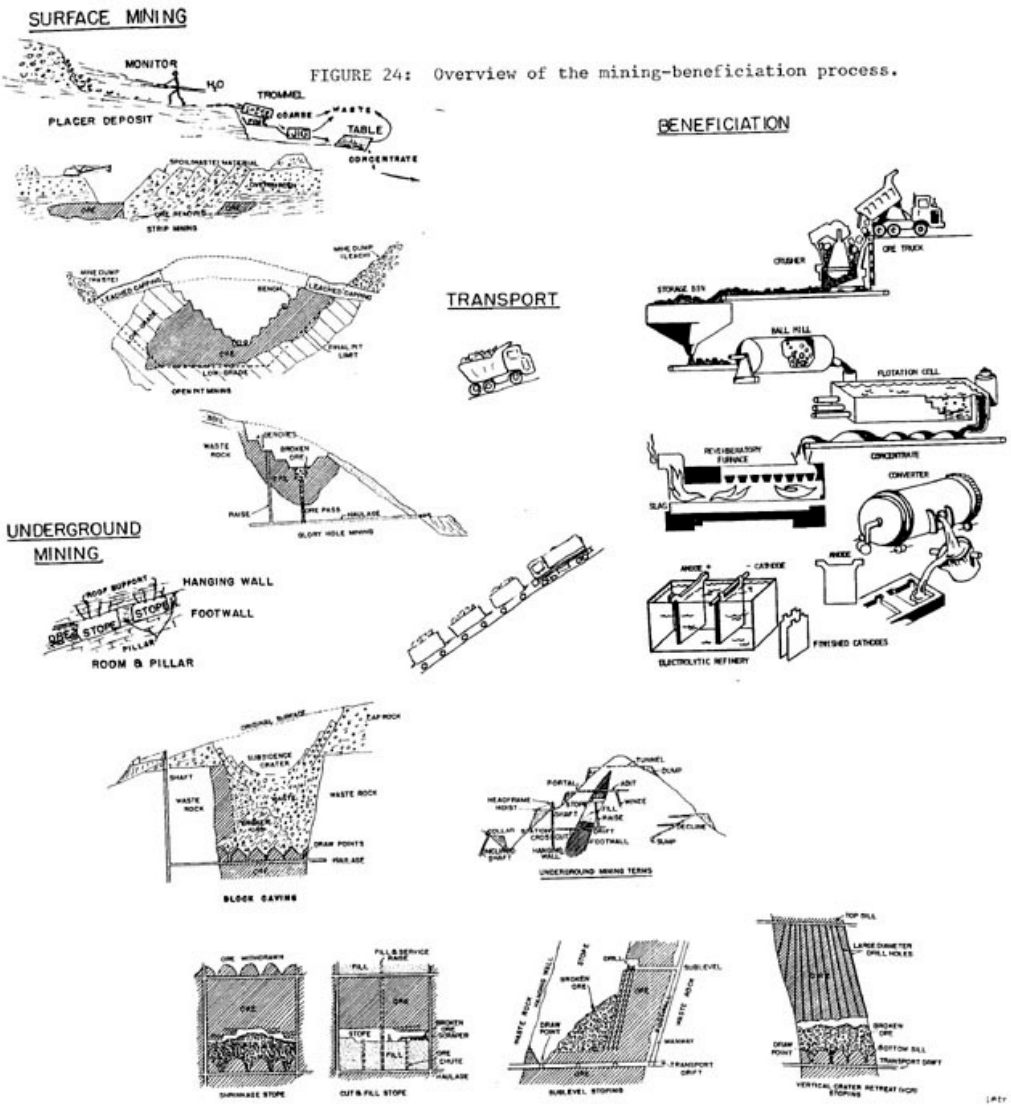


FIGURE 24: Overview of the mining-beneficiation process.

Figure 24: Mining/Beneficiation Process Overview -- EXPLANATORY NOTE.

Ease and costs of mining will vary with the shape of the mineralized body, its proximity to the surface, physical characteristics of the rock/soil host, as well as distribution of values. Beneficiation of ores will vary with the character of the ore minerals, liberation size, amenability to gravity, flotation, magnetic or electrostatic methods of separation, etc. Figure 24 is oriented principally to mining and processing of sulfide copper ores, but is generally applicable to other types of deposits.

The concept of open pit mining is simple, but planning for development is complex and costly. It may be necessary to blend different ore types to maintain character and grade of the mill feed, or it may be necessary to ship different ore types separately - oxide must be treated separately from sulfide ores, and low-grade ores may go to leach dumps, or gold-bearing oxide capping to special leach pads. (**Figure 31.**)

Grade and tonnage of material available will determine pit limits and how much waste rock can be stripped. The ultimate limit to the pit is determined by the economics of removing overburden (STRIPPING RATIO [ORE/WASTE]). Deposits generally decline in grade outward, so cut-off and pit limits may vary greatly with economic parameters. Slight variations in cost/value may have a great influence upon ore resources.

GLORY HOLING involves a mine opening at the surface from which ore is removed by gravity through raises connected to adit haulageways beneath, and tramming the ore to the surface. It is suited to mining on a hillside, and irregular deposits can be mined without dilution by waste wallrock. Mining can be quite selective and little waste rock accumulates on the surface. However, reclamation is difficult (**Figures 24**, **30**).

QUARRYING or Quarry Mining is usually restricted to mining dimension stone - prismatic blocks of marble, granite, limestone, sandstone, slate, etc. that are used for primary construction of buildings or decorative facing materials for exterior and interior portions of buildings.

Quarries generally have benches with vertical faces from a few feet to 200 feet in height. Blocks are drilled and wedged free in a highly selective manner using time consuming and expensive methods.

Planning of the excavation is based primarily on geological factors such as the direction and attitude of bedding and joint systems.

STRIP MINING is surface mining in which reclamation is contemporaneous with extraction. AREA MINING or strip mining is generally carried out on a large scale, and consequently is low-cost. It essentially involves removing the overlying strata or overburden and extracting the valuable mineral deposit. It is applicable to shallow, flat-lying deposits of coal, oil-shale, clay, sand, gravel, and some uranium, phosphate and placer deposits (**Figure 24**).

As the overburden is removed from one portion of a mineral deposit, it is used to fill in the trench left by the previous removal. Deposition of waste is, thus, much less of a problem and reclamation can readily be accomplished.

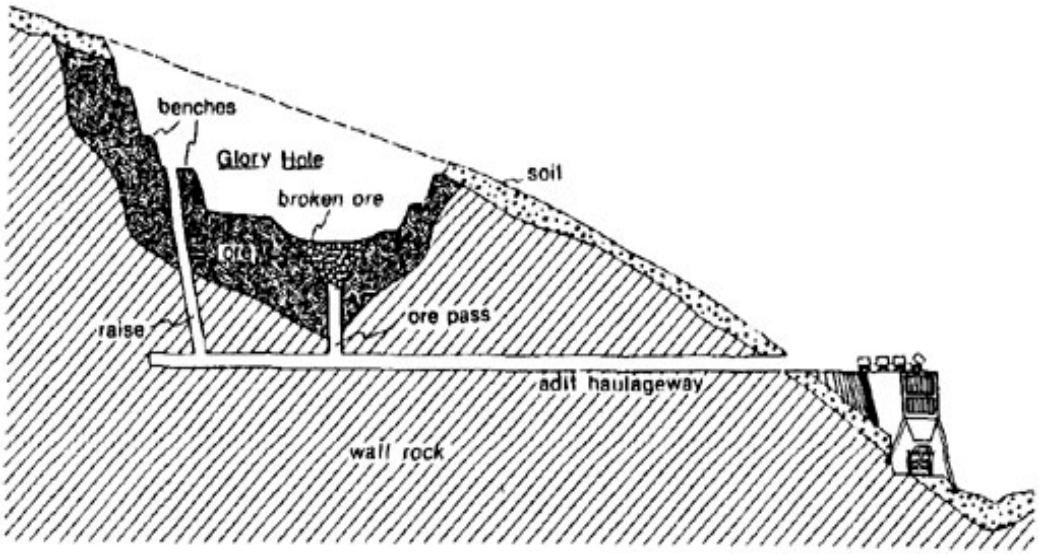


Figure 30 :The glory hole mining method.

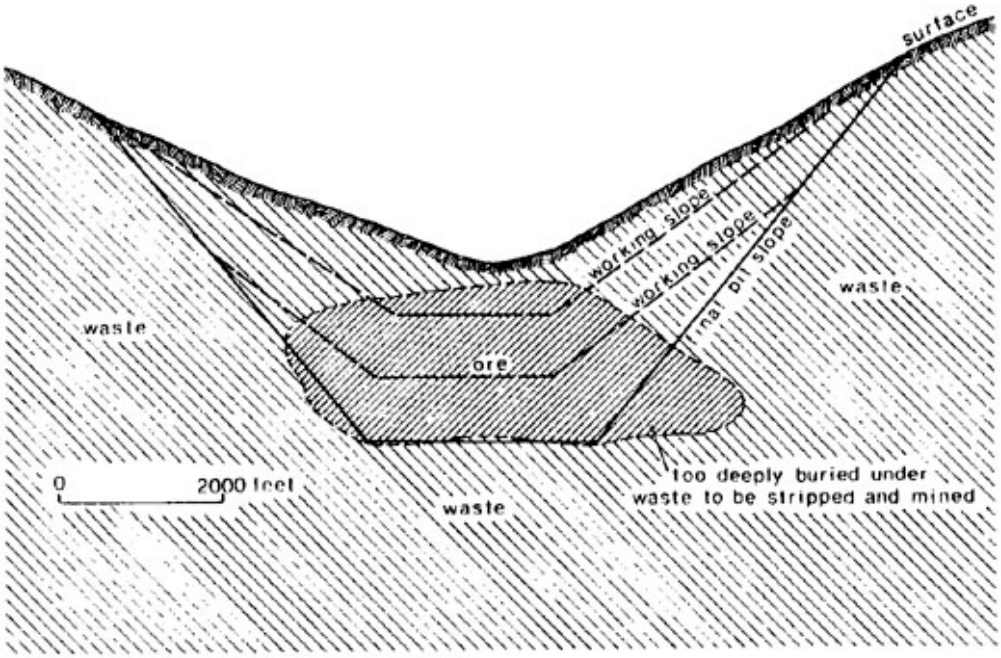


Figure 31: -Open pit mining.

AUGER MINING refers to a method of removing coal, clay, phosphate, oil-shale, etc. from thin seams exposed in deep trenches or high-walls in strip mines.

The auger consists of two principal pieces. The first is a cutting head, generally from 1.5 to 8 feet in diameter. It may be single or multiple. The second is a prime mover, usually a skid mounted carriage, providing a mounting for the engine, drive head, and controls. As coal arrives at the surface it is transported via a conveyor belt or a front-end loader to a waiting truck.

Operations are usually low-cost and highly productive, but recovery ranges from 40 to 60%. It can be implemented with relatively low capital costs.

PLACER MINING or ALLUVIAL MINING (C.A. McLean, 1992). Placering is a method for the recovery of heavy minerals using water to excavate, transport, and/or concentrate the mineral.

Placers are deposits of detrital material containing valuable mineral liberated as discrete grains through weathering and erosion processes, usually occurring as unconsolidated sediments. Rich placers usually result from several cycles of erosion and reconcentration in one place. Ore bodies can be very large and low-grade, but low-cost. Most high-grade surficial placer deposits which historically supporting the small prospector have been exhausted.

Placer mining affects large surface areas for the volume of material mined, is highly visible and has serious environmental problems with surface disturbance and stream pollution.

A variety of placer deposit types exist. RESIDUAL PLACERS or SAPROLITES are composed of mineralized rock weathered in place, and are common in tropical countries. HILLSIDE SLOPE PLACERS form a transition between source and stream, with less liberation of mineral grains than in stream placers. STREAM or FLUVIAL PLACERS (creek, river, bench, terrace, gravel plain or swamp, and delta) are formed by running water which carries away lighter minerals and concentrates heavy minerals in areas where current is reduced or on steam rock bottoms or on top of clay seams. DRY or BAJADA PLACERS are formed in arid climates as a result of violent storm and wind action. There is less sizing and liberation of mineral grains than in stream placers. GLACIAL TILL or GLACIO-FLUVIAL PLACERS are usually poorly sorted with poor liberation of grains. They are difficult to evaluate because of lack of uniformity and lack of continuity of values unless subjected to stream action. BEACH PLACERS are formed by bottom currents and/or beach wave action on pre-existing placers, deltaic deposits, and coastal mineralized bedrock.

Economically, the three most important placer types have been fluvial, beach, and off-shore marine placers.

PLACER MINING METHODS vary greatly as a consequence of the great variability in size and characteristics of placer deposits. They consist of the following.

PANNING and SLUICING. The traditional prospectors gold pan is an efficient device for washing and separating the heavy minerals in placer deposits and is commonly used as a prospecting and testing tool for evaluating placer deposits. However, as a production device it is slow, and even in the hands of a skilled operator only a small volume of material can be processed. Most surface deposits rich enough to be economically mined and concentrated by panning have long since been mined. However, it is still used as a recreational tool.

In SLUICING the placer gravel is shoveled, along with a stream of water, into the head of an inclined elongated sluice box with RIFFLES positioned across the bottom. These trap the heavy minerals and the lighter minerals are washed over the top and out as relatively barren waste. Sometimes fine gold is trapped as an amalgam when mercury is placed within the riffles or on a copper plate at the exit of the sluice box. The gold in the amalgam is recovered by retorting off the mercury.

HYDRAULIC MINING involves directing a high-pressure stream of water, via a MONITOR or nozzle, against the base of the placer bank. The water caves the bank, disintegrates the ground and washes the material to and through sluice boxes, and/or jigs, and/or tables situated down-slope. Hydraulic mining totally disturbs large areas and puts much debris into the drainage system. Presently, hydraulicing is used primarily in Third World countries. It is closely controlled or prohibited in the U.S.

DREDGING involves floating washing plants capable of excavating gravel, processing it and stacking the tailings away from the dredge pond. Several types of excavation methods are in use.

DRAGLINE and BACKHOE PLANTS. Dragline use in placer mining with washing plants is limited to shallow digging depths. Its bucket is less controllable on the bottom than the backhoe, and it is less able to dig into the bottom to clean up all the ore that may be there. However, it has the advantage of a longer reach. The digging reach of the backhoe extends to as much as 70 feet below the surface. It has the advantage of relatively low first cost, excellent mobility, and an ability to excavate hard material.

BUCKET WHEEL HYDRAULIC DREDGES are becoming more popular for underwater excavation, except where a high content of soft clay exists or where excessive oversize material occurs. It is dependent upon flooded pump openings that convey the material mined to the washing plant, and therefore it cannot work above water level. Placement of the pump suction is critical.

SUCTION CUTTER DREDGES are similar to the Bucket Wheet Dredge except the digging device consists of a series of cutting arms rotating in a basket about a suction intake. The rotating arms break up the bank material, slurrying it so it can be drawn into the dredge

suction. It has proven to be successful in mining unconsolidated beach sands and offshore placers.

BUCKETLINE DREDGES are capable of continuous excavation and are very efficient. They mine, process, and discard tailings to waste in one continuous stream. However, no storage opportunities exist, and the stream moves through the system by the force of gravity. Buckets, supported by a LADDER, dig the mine face. Material moves up the ladder and dumps into a hopper that feeds the washing plant. They are capable of high excavation rates. Various methods are used to position the dredge --anchored by wire ropes or piling (SPUDS) at the rear of the dredge. Boulders can cause serious problems.

PLACER MINING COSTS. Capital Cost of Bucketline Dredge (1990):

Bucket Capacity (cubic feet)	*Cost ($U.S x M)*
10	9
15	16
20	23
30	50

Operating Costs (1990):

Metal	*Cost ($/cubic yard)*
Malaysian Tin	0.60
Peruvian Tin	0.67
California Gold	1.20
Australian Titanium	0.32

Because large placer deposits can be thoroughly explored before floating a dredge, such operations can lend themselves to thorough planning, and it is possible to carry out reclamation as mining progresses at only a slight increase in operating costs.

IN SITU LEACHING is an alternative to mechanical mining that is growing in popularity because of low capital and labor costs, short preproduction time, and low surface environmental impact. Sub-surface groundwater contamination can pose a problem. For example, promising tests carried out at Miami, Arizona by Occidental Minerals were discontinued on the basis of being a threat to Miami's water supply.

It is applicable to a wide variety of commodities that are soluble in water or an aqueous lixiviant. Three general area of application include, first, extraction of water soluble salts, such as potash, trona, and common salt (NaCl). Second, in situ leaching is used in the FRASCH PROCESS, in extraction of sulfur from salt domes using hot water injection to supply heat to melt the sulfur and allow it to be pumped to the surface. Finally, hard rock in

situ mining using a lixiviant. It is applicable to extraction of uranium, copper and gold. Permeability, innate or induced, within the rock is critical, as is the distribution of metal values relative to the flow channels. Various methods are used, or proposed, to enhance permeability, including hydrofracing, use of explosives, undercutting and caving.

In situ mining of hardrock ores has been successfully utilized in extraction of uranium in Texas **Figures 25**, **26**),Wyoming, and Nebraska. It has been utilized in leaching oxide copper values from fractured rock adjacent to caved areas in Arizona. Tests continue in undisturbed mineralized rock in Arizona and New Mexico, but results have been disappointing.

The pattern and spacing of injection and production wells is critical and varies with rock conditions (**Figure 26**).

Amenability of a deposit to in situ leaching is a function of: 1) The pattern and character of value distribution (depth, shape, grade, mineral type and distribution, and structural and/or stratigraphic features; 2) fluid flow characteristics of the rock (permeability, porosity, natural groundwater flow, fracture character, frequency and orientation; 3) solvent effectiveness (rate of mineral dissolution, reactions with host and gangue minerals and the effects of reactions upon permeability) and 4) recovery of values from the leach solutions.

Evaluation requires both qualitative and quantitative determinations, with particular attention directed to controls to avoid groundwater pollution.

Deposits in hard rock that favor in situ leach fall generally into six categories: 1) stratiform sandstone deposits, 2) stockwork deposits, 3) breccia bodies, 4) fault zones, 5) shattered irregular bodies, and 6) surficial deposits.

B. UNDERGROUND MINING METHODS

Underground mining methods are illustrated in Figure 28.

1. SELF-SUPPORTED METHODS:

Small orebodies are often completely mined out, leaving no pillar of ore in place to support the walls of the stope. In situations with stable rock (generally limestone), it may be possible to mine out huge open stopes which remain stable and stand open for years. Sometimes, after open stoping of a mine, any pillars remaining are removed prior to abandoning that portion of the mine, allowing it to collapse. Often, narrow veins can be open-stoped, placing an occasional wood STULL, POST or BEAM between the two walls for minor support of the walls and/or to support a platform on which workers can stand (**Figure 27**).

2. SUPPORTED METHODS

ROOM AND PILLAR MINING is used in flat or gently dipping bedded ores or mantos. Supporting pillars are left in place, generally in a regular pattern, while the rooms are mined out. Where possible areas of waste or low-grade mineralization are used as pillars. Where pillars are of ore grade, they are mined out prior to abandoning the stope, starting at the farthest point from the mine haulage exit, allowing the roof to collapse.

Figure 25: In Situ Leach

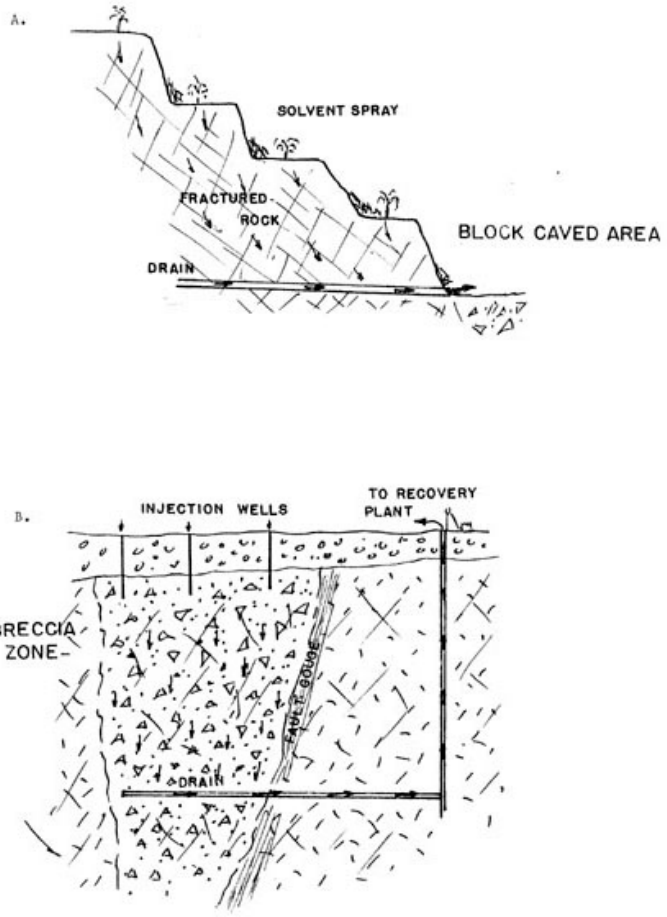


Figure 25: In Situ Leach -- EXPLANATORY NOTE.

Oxide/sulfide copper, gold and uranium deposits may be amenable to in-situ leaching of values by circulating leachants. This method of extraction enables low-cost removal of values with minimal disturbance of the surface and permits multiple land use.

Deposits subject to in-situ leaching must have permeability to leaching solutions, lack reactive minerals that will react with and/or poison the leachant, and must have enclosing impermeable barriers that prevent groundwater contamination.

Removal of salt and sulfur from salt domes in the Gulf Coast area of the Southwest U.S. by in-situ leaching methods has long been in use.

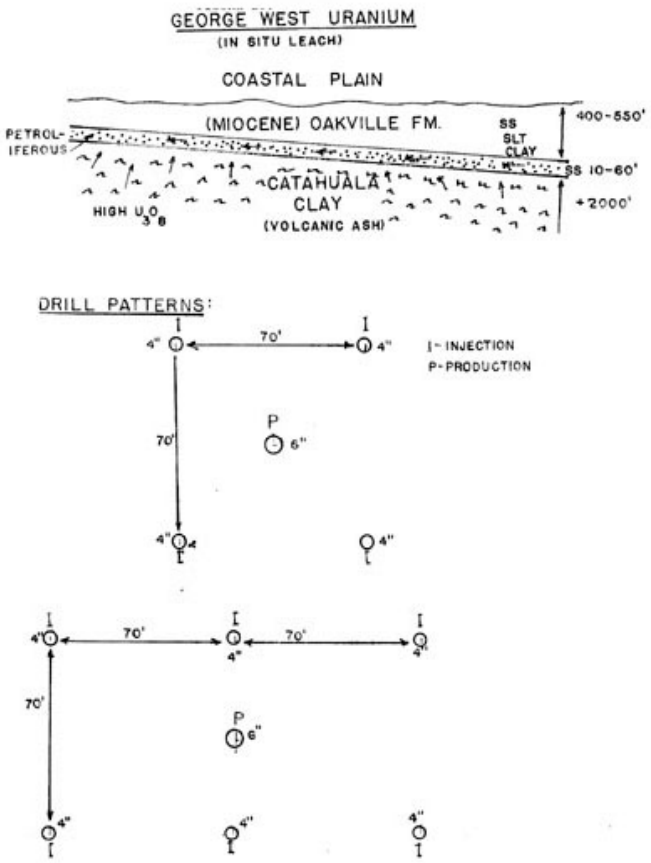


Figure 26: In Situ Leach -- EXPLANATORY NOTE (This note contains the same text as the note for Figure 25.)

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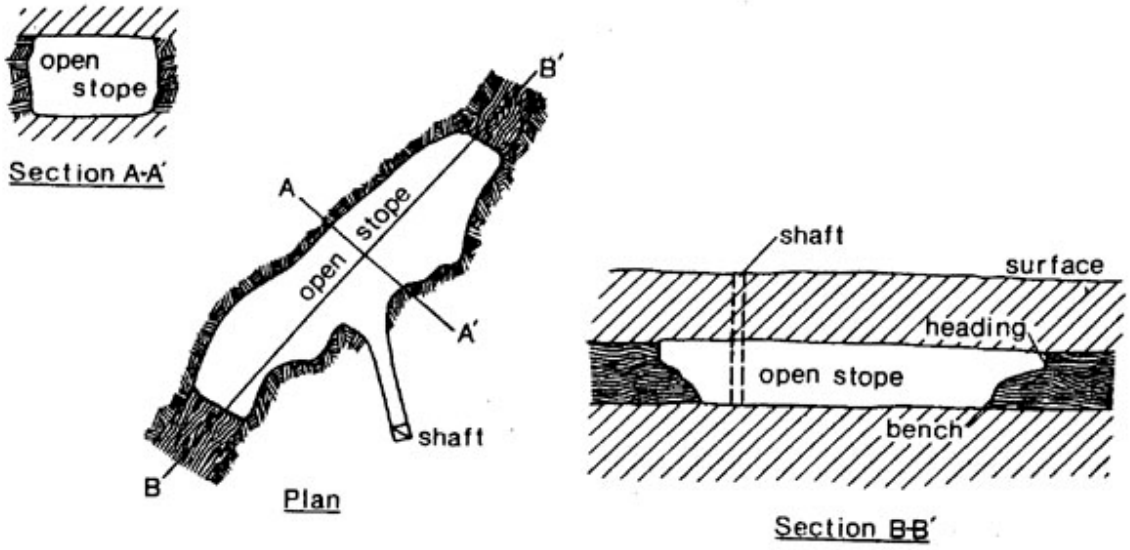


Figure 27: --Open stope mining method.

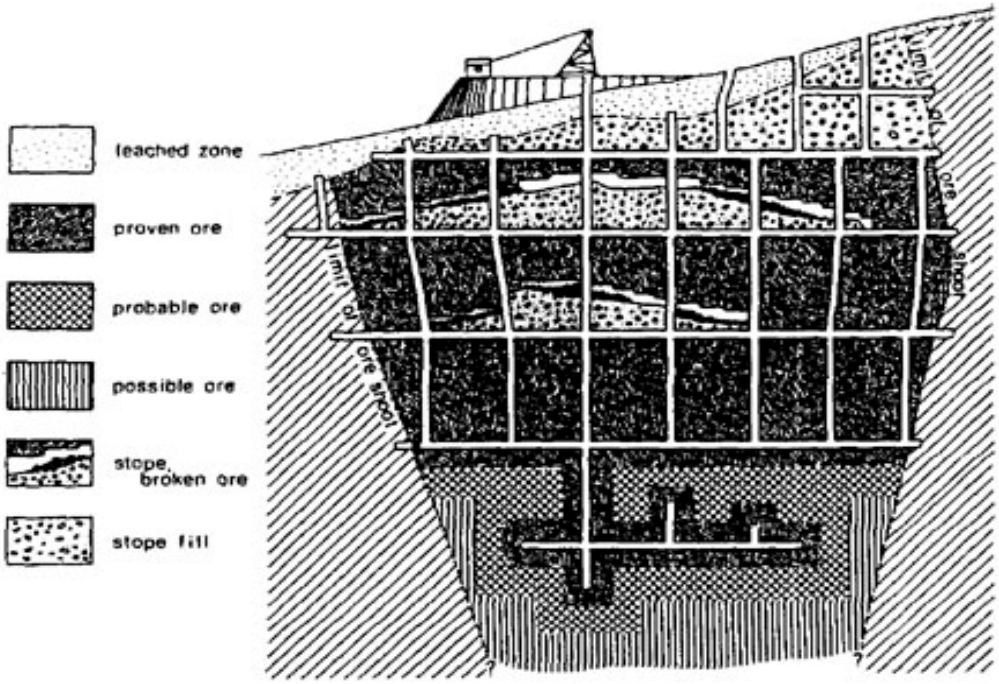


Figure 28: -Partially developed vein, three ore categories.

Room and pillar methods are well adapted to mechanization, and are used in deposits such as coal, potash, phosphate, salt, oil-shale, bedded uranium, and base-metal deposits (**Figure 24**).

SQUARE-SET STOPING is slow and expensive and requires skilled workers. It is generally used only for the extraction of high-grade ore bodies where rock walls are not strong enough to support an opening. In square-set stoping, one small block of ore, roughly 8'x8'x8', is removed and immediately replaced by a SET or framework of timber composed of a CAP (perpendicular to vein), a GIRT (parallel to vein) and a POST (vertical). The timber sets interlock and are filled with broken waste or sand fill after a tier of sets or stope cut is made (**Figure 30**).

SHRINKAGE STOPING is usually employed in the extraction of steeply-dipping veins where the walls are sufficiently strong to support themselves during the mining. It is done by stoping the vein or orebody from beneath, allowing broken ore to support the stope walls, but leaving a space above the broken ore sufficient for the miners to stand and drill overhead for the next break. Broken ore is drawn out through CHUTES on the HAULAGE LEVEL as necessary to maintain working room for the miners. The rock mass expands when broken, roughly by 30% (**Figure 24**).

After the complete block of ore has been broken, all broken ore is removed and the walls are permitted to collapse. If the walls are insufficiently strong to support the opening during mining and cave into the opening or into the broken ore, dilution of the ore grade will take place.

CUT AND FILL STOPING is used in vein structures where the vein is moderately dipping, and/or where one or both walls lack the strength to stand up during mining of the ore block. It is similar to shrinkage stoping except that each cut of ore is removed and replaced with layers of waste - either waste rock from mine headings or sand-size portions from mill tailings (HYDRAULIC FILL), with or without cement addition (**Figure 24**).

3. CAVING METHODS

Underground caving methods are characterized by high productivity, relatively low cost, as well as a high percentage of extraction of ore bodies with various shapes. The method lends itself to a high degree of mechanization and a continuous flow of ore from the extraction areas. Caving methods include: LONGWALL MINING, SUB-LEVEL CAVING and BLOCK CAVING. The method selected is dependent upon the shape of the orebody, and the strength of the ore and enclosing rock.

LONGWALL MINING is used primarily in the extraction of coal, but may be used in extraction of flat-lying oil shale, salt, phosphate, or sedimentary metalliferous beds. It might be considered as a modification of room and pillar mining, but offers better opportunity for mechanization. Extraction is from long panels, with widths up to 1000 feet where roof conditions are favorable.

Mining of coal or ore is accomplished by cutting machines or SHEARER-LOADERS or PLOWS, which cut the coal or ore along the longwall face. The mine is protected by a shield which supports the roof and separates the mining operation from GOB fill. One disadvantage of the method is the time required to move to the next longwall position.

SUBLEVEL CAVING is a mass mining method based upon gravity flow of blasted ore and caved waste rock. Its major advantage is safety, since all mining activities are conducted from relatively stable openings. Mining entails a) drifting and reinforcing, b) fan drilling, c) production blasting (fragmentation), d) ore drawing, loading and transport. Mining activities can be standardized and mechanized (**Figure 24**).

Disadvantages include the following. There is relatively high dilution of ore by caved waste. All ore must be drilled and blasted in order to obtain a coarse material suitable for extraction by gravity flow. Some ore is lost in passive zones between those of active flow. A large amount of development is required. Finally, mining generates progressive caving in overlying rock, resulting in subsidence.

Analysis of gravity flow characteristics of broken ore in each type of rock is essential.

BLOCK CAVING is the lowest cost of all underground mining methods. It is a mass mining method where the extraction and breaking of ore depends largely on gravity. It is used when large orebodies have good vertical dimensions, but have a barren or low-grade cap too thick to strip for open pit mining, or a cap which extends to depths where stripping ratios make open pit mining uneconomic. By removing a thin horizontal layer at the mining level of the ore column, the support of the ore column is removed, and the ore caves by gravity. As broken ore is drawn from DRAWPOINTS at the mining level, the ore above continues to break and cave by gravity (**Figures 24**, **32**).

Most mines use a panel system, mining panels sequentially, or by establishing a large production area and gradually moving it forward as the first area becomes exhausted. This is in contrast with earlier methods of mining blocks on a checkerboard fashion.

There are three major systems of recovering the broken ore from the block cave. The GRIZZLY SYSTEM is a full gravity system wherein ore from the drawpoints flows directly to TRANSFER RAISES after sizing at the grizzly. Sledge hammers are used to break oversize. The ore is then gravity loaded into cars for transport to the concentrator. The SLUSHER SYSTEM uses a slusher scraper for the main production unit. It is used where rock breaks into moderate-sized fragments. Finally, LHD (Load-Haul-Dump) SYSTEM is used where rock breaks into relatively large fragments.

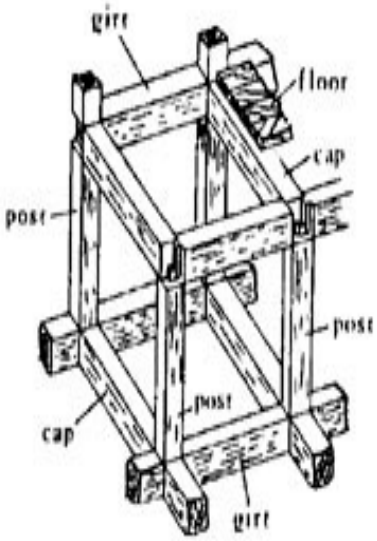
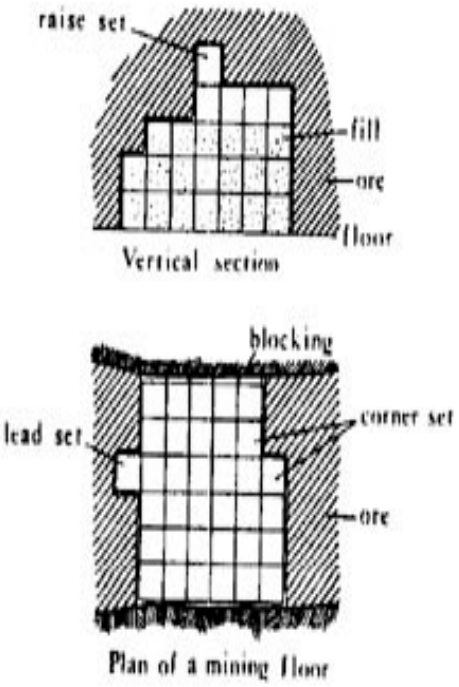


Figure 29 : Square-set timbering



Square-set stoping.

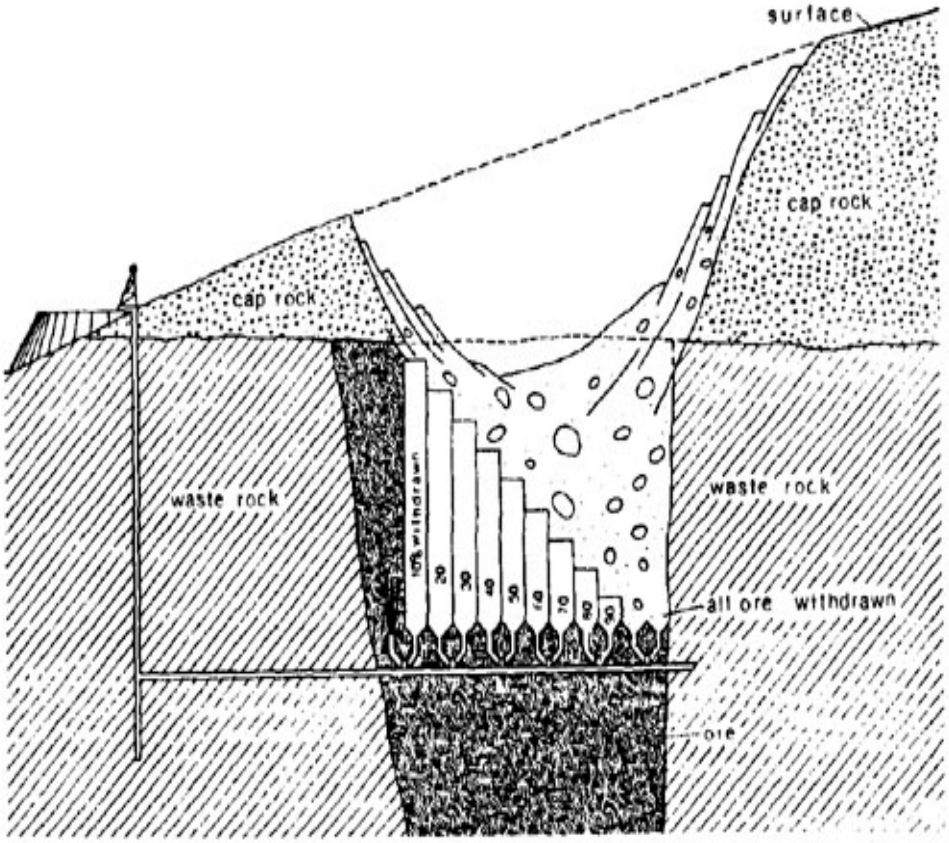


Figure 32: -Block caving underground.

The surface over the drawn panels subsides, ultimately forming an immense collapse crater larger in diameter than the are actually caved, but not as deep as the withdrawn ore, due to the swell factor of the broken capping rock. This crater may be used to enable open-pit mining of mineralization exposed on the fringes of the collapse crater, and by leaching of the collapsed column of capping rock and low-grade mineralization around the periphery of the collapse crater.

The height of the ore columns varies. The higher the ore column is, the cheaper the development cost per unit mined. Ore columns mined by block caving range from 100 feet to as much as 1000 feet or more.

VERTICAL CRATER RETREAT mining is a variation of sublevel caving, using a spherical charge to break the ore. Blasting is carried out at the base of vertical holes, making horizontal cuts and advancing upward. The shrinkage technique can be used for wall support. This method can be used where the orebody is well defined between steeply dipping walls and broken ore will flow to drawpoints under the influence of gravity (**Figure 24**).

It is a high capacity mining method with good recovery and offers good wall support during mining. It is safe, since miners work under a fully supported roof. However, it requires extensive pre-stope drilling, and planning and development lead time. In addition, much ore is tied up in the stope until final draw-down. This delay may result in oxidation of some of the ore minerals, causing metallurgical problems.

4. COSTS (Table 15):

Mining Method	*Direct Mining Costs ($ per ton of ore) (1989)**
Open Pit Mining	
Large Mines (+20 Mt/yr)	0.51 - 0.64
Medium Mines (2-20 Mt/yr)	0.39 - 1.19
Small Mines (-2 Mt/yr)	1.01 - 4.20
Phosphate Strip Mining With Hydraulic Transport	6.00 - 12.50
Room and Pillar Mining (Shaft)	2.10 - 3.83
Stope and Pillar (Diesel)	4.10 - 9.81
Cut and Fill (-10 foot vein, slusher)	34.10 - 68.00
Cut and Fill (+10 foot vein, LHD)	20.82 - 26.36
Shrinkage Stoping	30.00 - 40.00
Block Caving	2.50 - 8.00
Vertical Crater Retreat	20.00 - 25.00

* Direct mining cost includes drilling, blasting, loading, haulage, but does NOT include administration, development, processing, and services.

Table15: Relations between ground conditions, mining method, explosive consumption and costs (Modified from Boshkov and Wright, 1973, p. 12-9).

Mining Method	Ground Condition	g Explosive per tonne	$ Cost per tonne	Labour % total cost
Square set	weak	150 - 540	6.22 - 18.72	71
Cut-and fill	medium	250 - 615	3.07 - 14.73	57
Sub-level stoping	strong	165 - 300	1.06 - 4.71	57
Room and pillar	strong	335 - 570	1.16 - 2.41	44
Block caving	weak	40 - 95	1.15 - 2.00	50
Block caving	medium	115 - 235	2.00 - 2.25	55
Open pit		50 - 265	0.21 - 1.15	36

Table 16.: Relations between rock character, compressive strength, bit requirements and expected rate of advance (modified from Bluekamp and Beinlich, 1973, p. 10-91).

Rock Classification	Compressive Rock Strength (k/m^2)	Bit Type -(1) Cost (Fig.3)	Expected Rate of Advance (m/hr.)
Soft	500 max	Milled tooth, Kerf, Disk, Drag, Scraper.	3 - 6
Medium	500 - 1000	Milled tooth, Kerf, Disk.	1 - 3
Medium-hard	1000 - 2000	Tungsten-carbide-button, Roller or Kerf.	.5 - 1
Hard	+ 2000	Tungsten-carbide-button	.3 - .5

(1) Disk: protruding V-shaped ridge around a cylinder roller; Kerf: composed of 3 or 4 ridges on a roller, of hard steel of tungsten-carbide; Milled tooth: face hardened long steel teeth miller out of a tapered roller; Tungsten-Carbide-insert: tungsten-carbide-buttons inset in tapered rollers.

II. BENEFICIATION

Success in any mining project cannot be achieved without a thorough knowledge of the characteristics of the ore to be treated. The geologist must establish close liaison with the metallurgist to correlate metallurgical behavior with detailed distribution patterns of the mineralogical, structural, textural and grade variations with the ore deposit. Plant design and production scheduling will be based upon this information.

The fundamental principle in mineral beneficiation is to reduce the crude ore to a size that will permit optimum liberation of the ore minerals and allow their subsequent separation from associated gangue minerals by gravity, magnetic, electrostatic, froth flotation, etc.

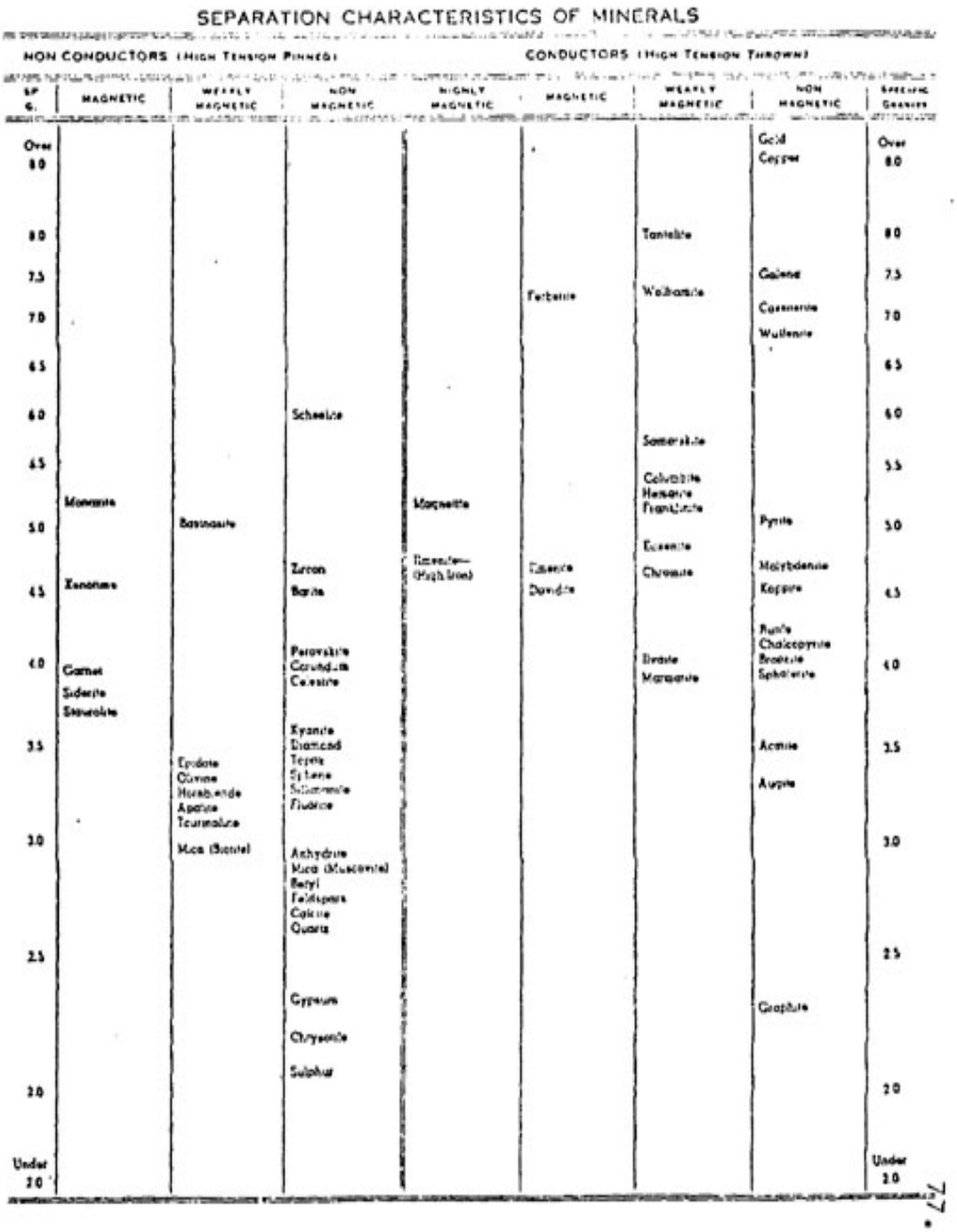
Information is gathered through chemical analyses, X-ray determinations, mineragraphic examination, probe analyses, and geomechanical testing. Data sought will be: 1) tensional and uniaxial compressive strength of the ore/rock; 2) range of grain-sizes of ore and gangue minerals; 3) percentage of 'free' ore and gangue minerals at various size fractions; 4) states of oxidation, hydration, leaching and replacement in minerals; 5) presence of surface coatings which might influence flotation, cyanidization, etc.; 6) presence of exsolution phenomena and recognition of solid solution states; and 7) any special physical or chemical properties which might interfere with separation, or cause environmental problems. These characteristics may vary within the orebody and must be continuously monitored. This information will enable decisions to be made regarding separation methods or modification to existing procedures.

Mineralogical investigation is essential for determination of proper beneficiation methods. The most important factors for determination are: 1) identities of all minerals present in the ore and gangue: 2) observations on grain size, texture, alteration, coatings, etc.; and 3) nature of locking and liberation factor (**Table 17**, **Figure 33**).

A. SIZE REDUCTION - CRUSHING AND GRINDING

COMMINUTION, the reduction of ores to small particles, is generally the most expensive phase of mineral beneficiation (50%). It is advantageous to remove ores from the crushing and grinding circuit as soon as an optimum size has been achieved and before sliming of the ore minerals causes loss in metal recovery. It is often advantageous to stage comminution, e.g. grind only ore material, separating out freed ore minerals at a coarse grind, with only the MIDDLINGS fraction being recirculated for regrind. In some instances color/magnetic/gravity sorters or even pickers on a conveyor belt remove obviously waste material before it goes into the grinding circuit (**Figure 34**).

TABLE 17: Separation characteristics of minerals.



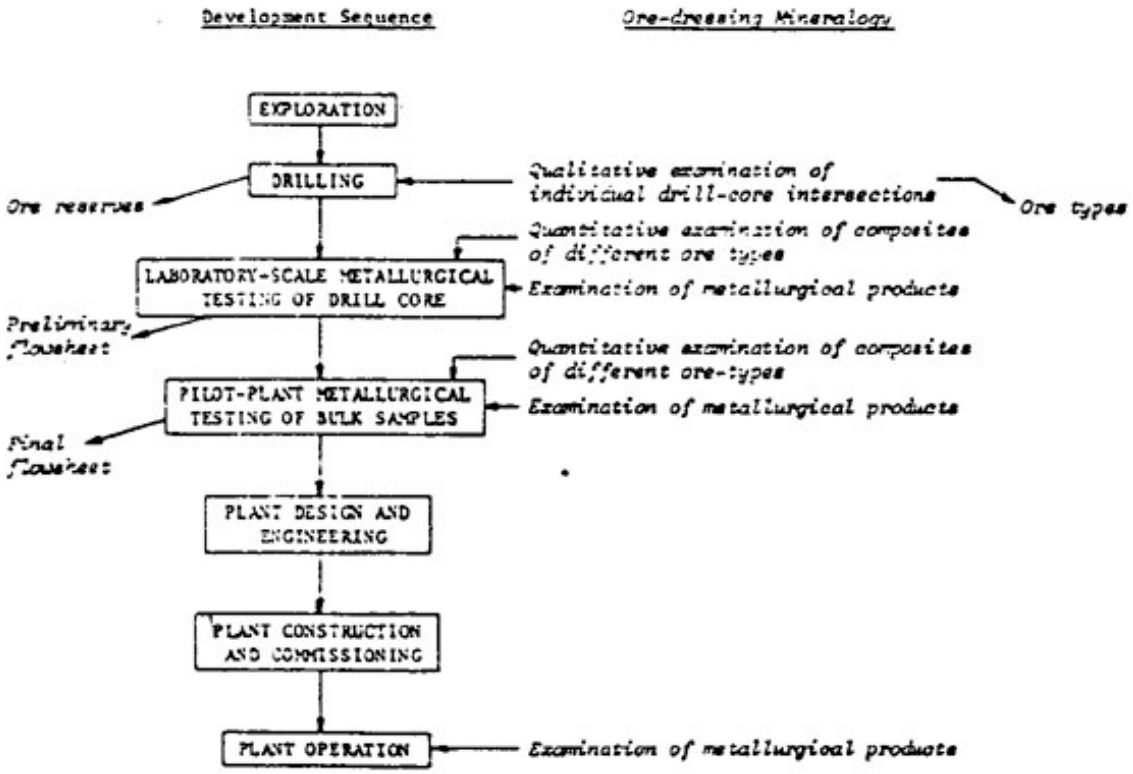


Table 17a — Development sequence of ore dressing mineralogy

PRINCIPAL EXPLOITABLE CHARACTERISTICS

Selective Mineral Characteristic	*Type of Separating Force*	*Operation*
Colour, Lustre.	Visual, manual, automated.	Hand-sorting of graded ore, to remove detritus, waste rock, special constituents. May use fluorescent lighting, or impulses triggered by reflected light.
Specific Gravity.	Differential movement due to mass effects, usually in hydraulic currents.	"Gravity" separation of sands and gravels by D.M.S., jig, sluice, shaking table, spiral.
Surface Reactivity.	Differential Surface Tension in Water.	Removal of relatively aerophilic mineral as froth from aerated pulp by froth-flotation. Widely used process.
Chemical Reactivity	Solvation by appropriate chemicals.	Hydrometallurgy. Ore exposed to solvating chemicals, perhaps with heat and pressure, then filtered. Dissolved element/s recovered from filtrate, chemically, electrolytically or by ion exchange.
Ferro-Magnetism.	Magnetic.	Magnetic devices remove the preferred mineral. Also used to remove "tramp" iron.
Conductivity.	Electrostatic charge.	Particles pass through high-voltage zone. Rate of dissipation of induced charge influences subsequent deflection. Differential conductivity.
Radio-activity.	α or β rays.	Emissions are signalled by G.M. Valve which also activates a separating or "picking" device.
Shape.	Frictional.	Sliding force is opposed by "cling" of particle, resultant movement depending on cross-section and area, hence on shape.
Texture.	Crushing. Screening. Classifying.	Characteristic shapes and surfaces are developed during comminution.

Table 17b — Development sequence of ore dressing mineralogy

By Dr. G. C. Amstutz,

FIGURE 33:
Geometric Classification of Basic Intergrowth Patterns of Minerals

Type 1a: Simple intergrowth or locking type; rectilinear or gently curved boundaries. Most common type, many examples.

Type 1b: Mottled, spotty, or amoe- -type locking or intergrowth. ple, common pattern; many examples.

Type 1c: Graphic, myrmekitic, or "eutectic" type. Common; examples: chalcopyrite and stannite; quartz and feldspars; etc.

Type 1d: Disseminated, emulsion-like, drop-like, buckshot or peppered type. Common; examples: chalcopyrite in sphalerite or stannite; sericite, etc. in feldspars; tetrahedrite in galena; etc.

Type 2a: Coated, mantled, enveloped, corona-, rim-, ring-, shell-, or atoll-like. Common; examples: chalcocite or covellite around pyrite, sphalerite, galena; etc.; kelyphite rim, and other rims.

Type 2b: Concentric-spherulitic, or multiple shell-type. Fairly common; examples: uraninite with galena, chr -yrite, bornite; cerussite-li- mo-...e; Mn- and Fe-oxides; etc.

Type 3a: Vein-like, stringer-like, or sandwich-type. Common; examples: molybdenite-pyrite; silicates; carbonates; phosphates; etc.

Type 3b: Lamellae-layered, or polysynthetic type. Less common; examples: pyrrhotite-pentlandite; chlorite-clays; etc.

Type 3c: Network, boxwork, or Widmanstätter-type. Less common; examples: hematite-ilmenite-magnetite; bornite or cubanite in chalcopyrite; millerite-linnaite; metals; etc.

Between most of these nine common locking types there are naturally gradational transitions with regard to both, pattern and size. Particle or grain size data are a prerequisite of any accurate study of rocks and mineral deposits and enhance the value of this chart.

Figure 33: Mineral Intergrowths -- EXPLANATORY NOTE.

In the concentration process the grade and purity of the concentrate and the percentage recovery of values will depend upon the intergrowth of ore/gangue minerals. Many mineral concentrates, despite fine grinding, are unable to attain liberation of the ore minerals, and values may be lost, encased in the gangue.

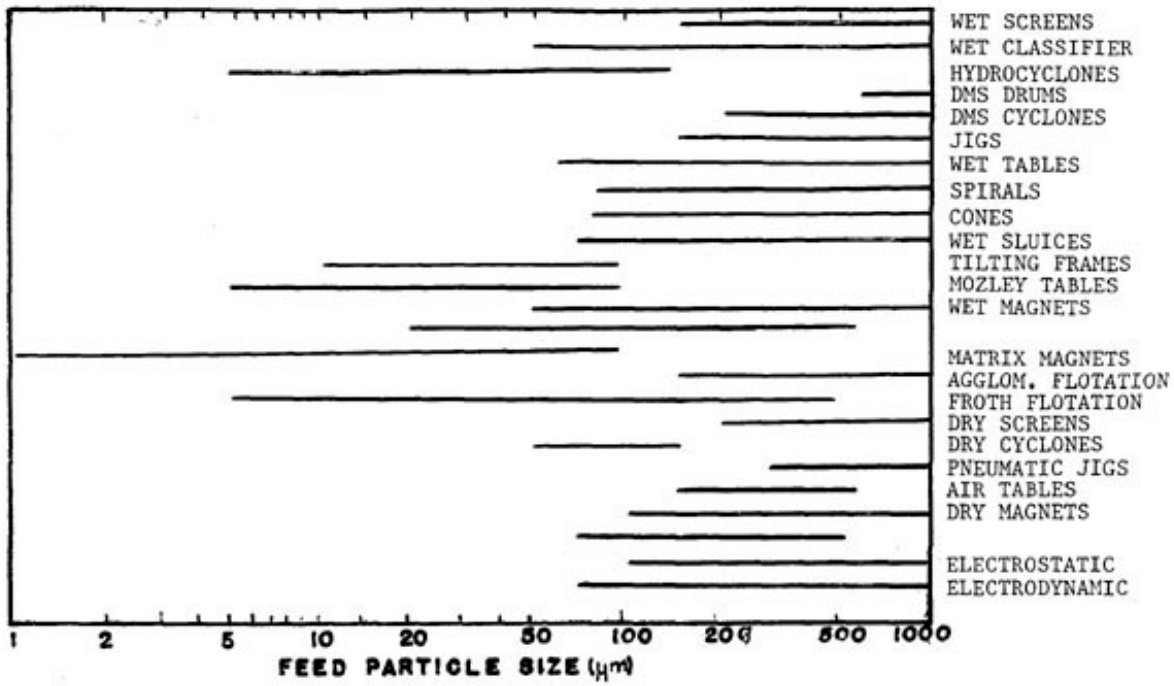


Figure 34: Size Range Applicability for Beneficiation Processes -- EXPLANATORY NOTE.

Liberation size and physical character of ore minerals, as well as specific gravity differential, and chemical reactivity will control beneficiation processes. Since grinding requires high-energy (high-cost) input, it is advantageous to remove the ore minerals at the maximum liberated size. Different separation methods are available that depend upon specific gravity differential, magnetic or electrostatic properties, etc. as well as liberation sizing.

FIRST STAGE CRUSHING is generally by JAW, GYRATORY or CONE CRUSHERS, depending upon the tensional strength of the rock. Crushing capacity can be predicted from testing data from BRAZILIAN TESTS and UNIAXIAL COMPRESSIVE TESTS, or SCHMIDT HAMMER tests. It is important that all rock types that will be fed through the concentrator are tested. Many new beneficiation plants have found themselves to be short of crushing and grinding capacity because they tested an average grade ore and paid little attention to the rock type, or failed to recognize a siliceous cap that dominated production for the first several years.

SECOND STAGE GRINDING, a high energy input stage of processing, is limited to an optimum rather than a minimum size because: 1) cost increases rapidly as fineness increases; 2) grinding efficiency decreases with increasing fineness; and 3) production of slimes increases metallurgical losses. Resistance to grinding is a function of ore and gangue minerals properties, including hardness, cleavage, grain size, bonding, etc.

SCREENING AND/OR CLASSIFICATION entails removal of mineral grains from the grinding circuit as soon as they are reduced to an optimum size. Screens are generally used for making the separation when coarser sizes are involved, whereas CYCLONES and CLASSIFIERS are used when fine sizes are involved.

SCREENING, usually 20 mesh or coarser, may be dry or wet, stationary or vibrating. This sizing method is particularly effective when gravity methods of separation will be used, since the classification is purely on the basis of size.

CLASSIFICATION uses water or air currents as the suspending medium in which particles settle at different rates. The settling rate is influenced not only by the size of the particle, but also by its specific gravity and grain shape.

Classifiers may be mechanical, usually classifying grains in the 100 to 400 mesh range. Sizes larger than the desired size settle out and are gathered by a rake or and returned to the mill for additional grinding. The finer sizes overflow from the classifier and pass on to the next stage of beneficiation.

In hydrocyclones, the separation takes place as a consequence of differential flow rates out of the top and bottom of a cone. Larger and heavier particles sink and are recycled, whereas the lighter and smaller particles go into the overflow and move along the circuit.

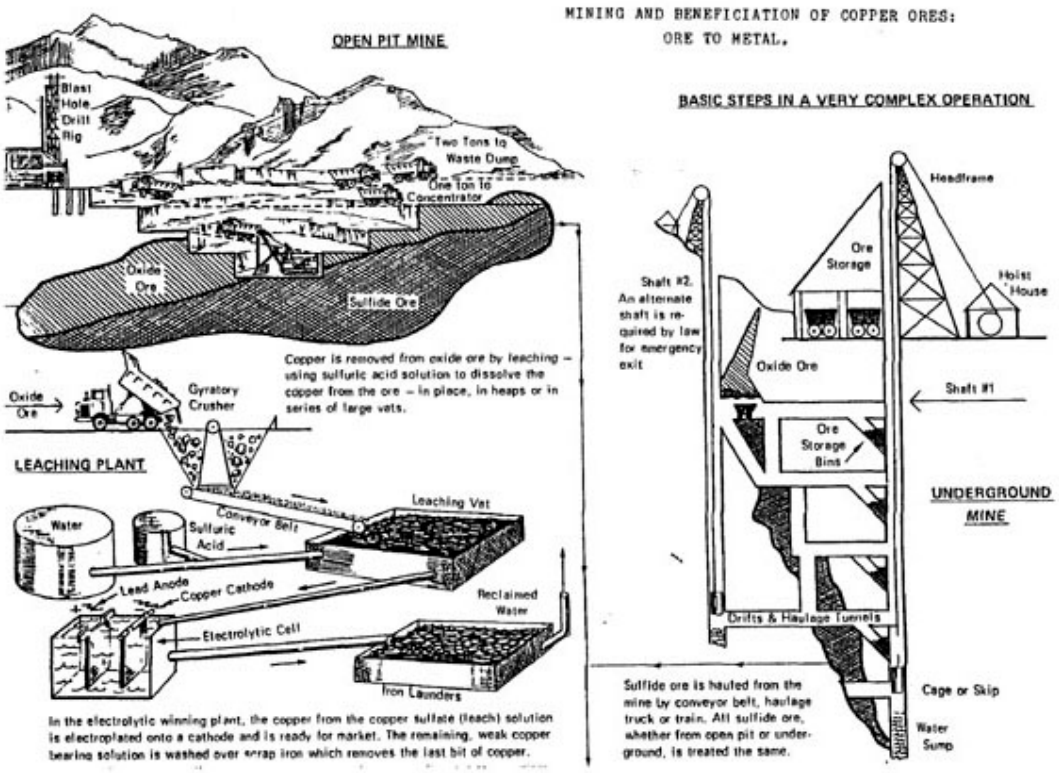
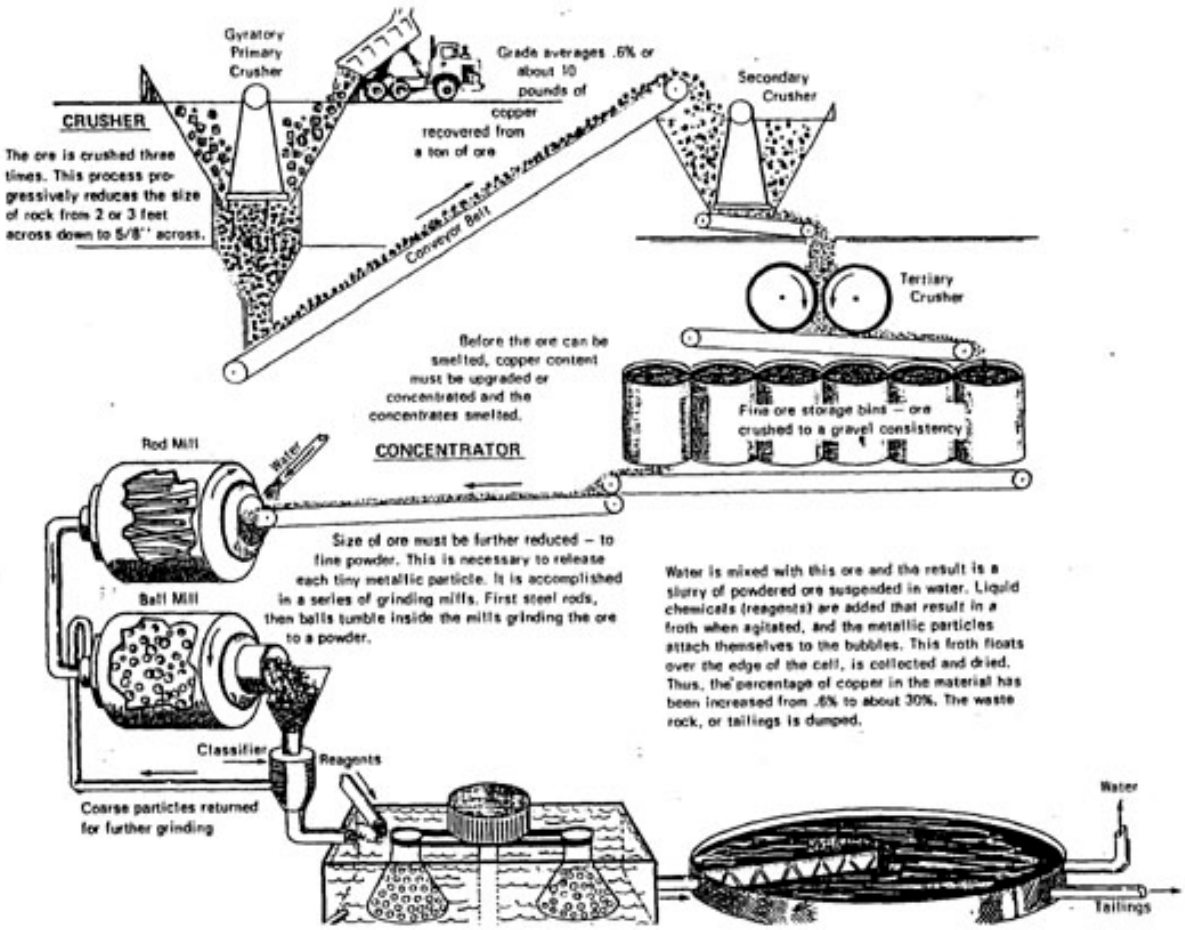


Figure 35: Mining and Beneficiation of Copper Ores -- EXPLANATORY NOTE

Many deposits contain ores that require separate treatment. Copper deposits illustrate this where oxide, coarsely crushed, low-grade ores amenable to hydrometallurgical leaching cap sulfide ores that require fine grinding and froth flotation to achieve concentration. One may be mined by open pit, the other from underground workings.

Figure 35 (cont.)



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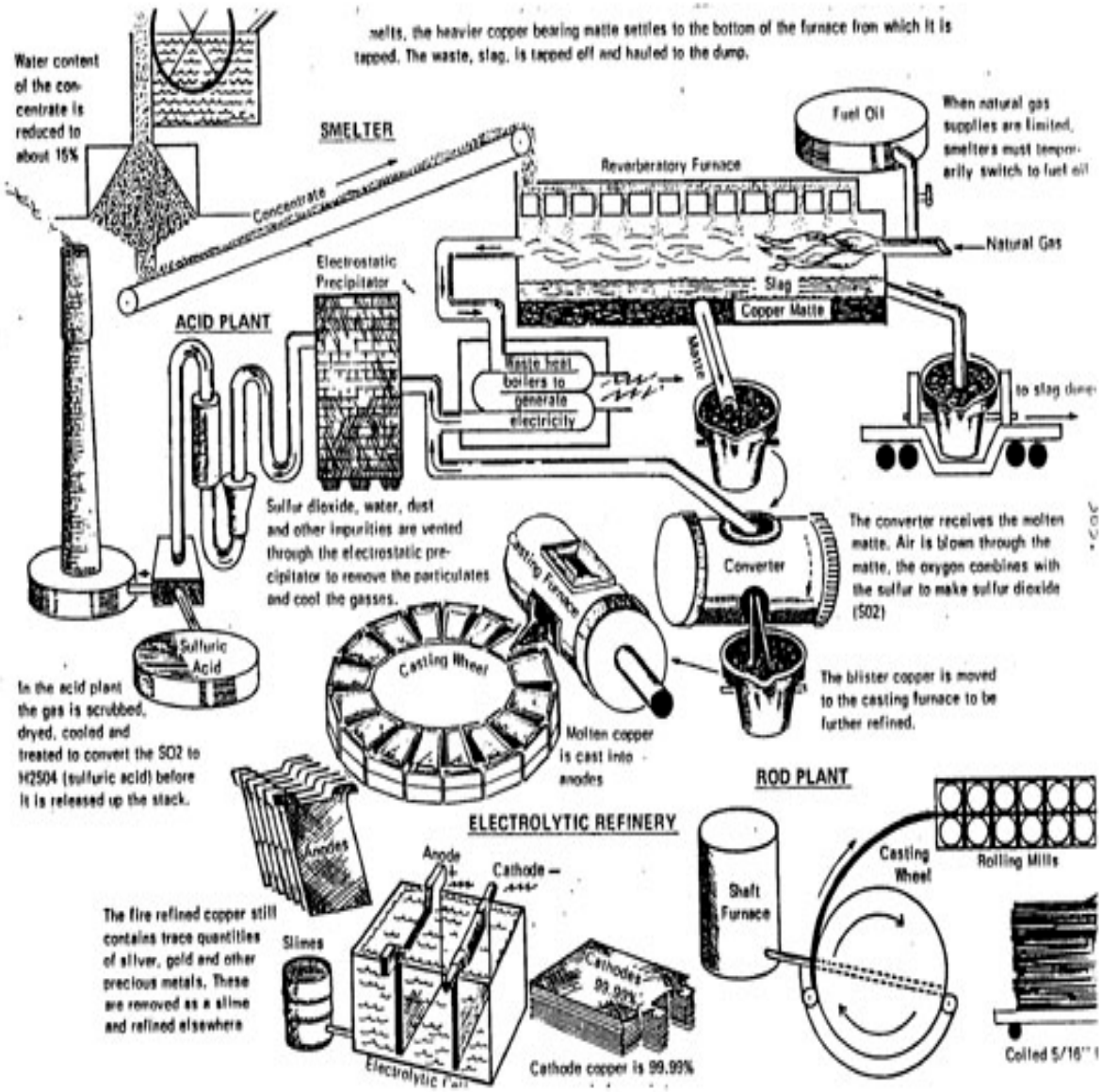
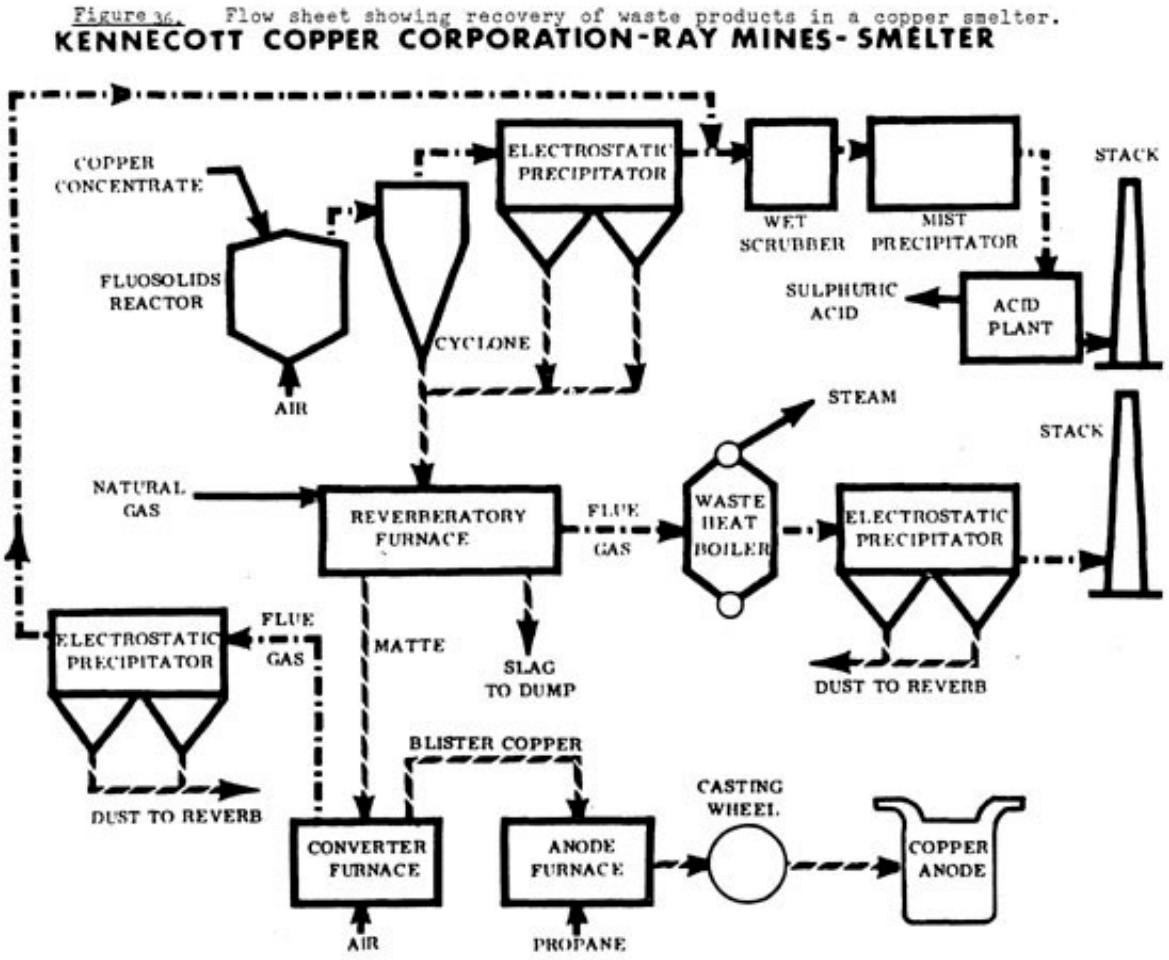
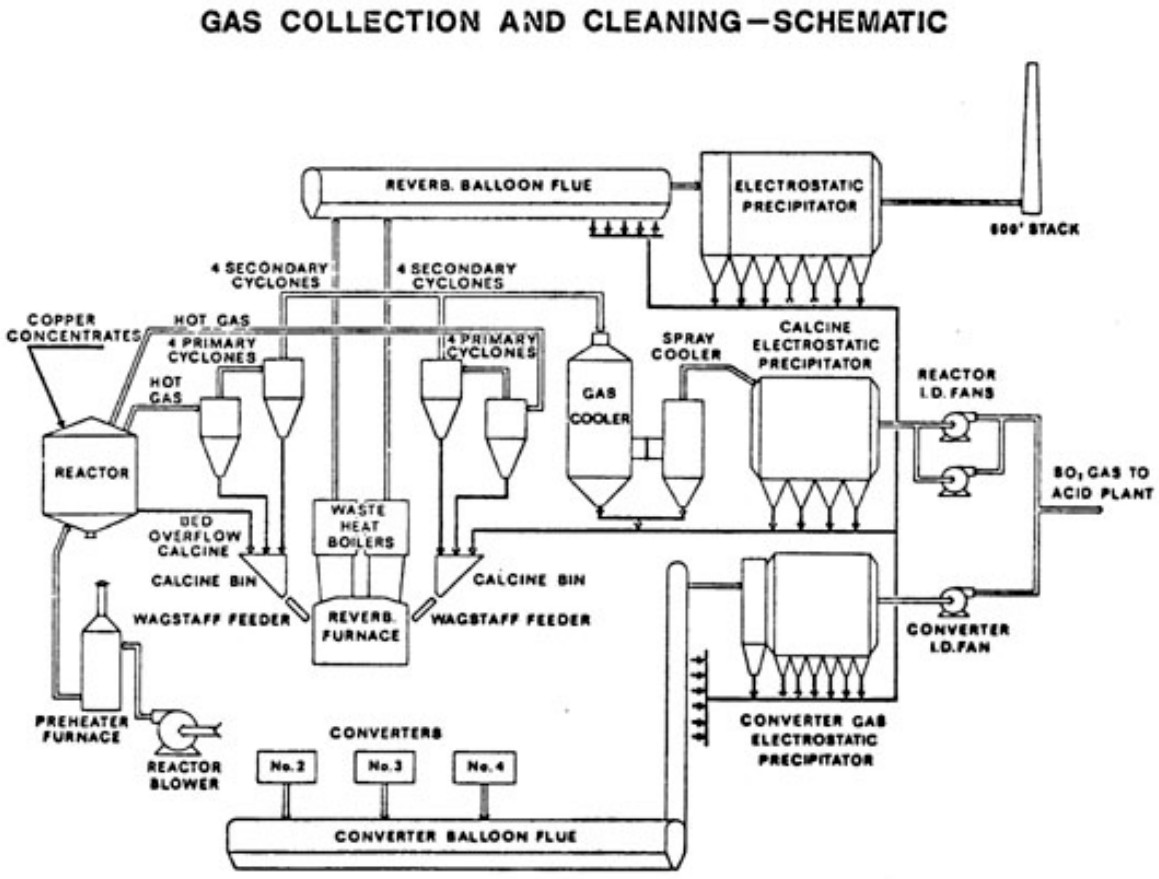




Figures 36 and 37: Copper Smelting Operations -- EXPLANATORY NOTE.

The copper smelter has the objective of extracting and purifying copper from the copper concentrate, but also controlling dust and gas emissions. Some of these environmental precautionary measures are shown.

Figure 37: Scrubbing of stack gases.



B. GRAVITY SEPARATION

HEAVY MEDIA SEPARATION is most effective in coarse sizes (between 1 cm and 20 mesh, but workable in the 150 mesh or 100 microns). Specific gravity of ore and waste may differ by as little as 0.2, though 0.5 is desirable. Pieces as large as 30 cm in diameter have been effectively separated. The heavy media is generally finely ground magnetite or ferro-silicon in a water suspension. The magnetite can be recovered magnetically.

SHAKING TABLES are generally used for coarsely ground ore, above the size limit for flotation. Suitability is based upon size, shape, and specific gravity of grains and the specific gravity difference between ore and gangue minerals. For gold, shaking tables can be used above 200 microns, sulfides, above 400 microns, and for silicates, above 1000 microns.

SLUICE, PINCHED SLUICE, HUMPHREY SPIRALS, and REICHART CONES are all modifications of a simple sluice, where stratification of heavy and light minerals takes place in running water. The heavier fraction can be trapped by riffles or separated by splitters.

JIGS were among the earliest mechanical concentrating devices, with alternating upward and downward water currents acting on a bed of mineral particles. Stratification of mineral particles by their settling rate (size, shape and specific gravity) permits separation. Maximum size is generally 2 cm, minimum 10 mesh.

DRY CONCENTRATORS have presented a continuing challenge in desert country. Various forms have been devised: pneumatic jigs and tables, where air takes the place of water in supplying the suspending medium; and the Haultain infrasizer which has 7 cones, each with half the cross-sectional area of adjacent cones, giving separation according to air speed from 7 to 56 microns. Use of dry concentrators is very limited for minerals, though it is used extensively in cereals and food products.

Mineralogical factors affecting gravity separation:

- identity and specific gravity of all minerals in the ore;
- porosity and degree of leaching in individual minerals;
- replacement and exsolution intergrowths of minerals;
- grain shapes resulting from grinding and cleavage; and
- magnetic properties that may cause agglomeration aggregates of mineral grains.

TABLE 18:

COMPARATIVE SOLID WASTE PRODUCTION FOR UNDERGROUND AND SURFACE COPPER MINES

	Open Pit Mine	Large Underground Mine (block caving)	Small Underground Mine (square set stoping)
Grade of ore			
(1) in percent copper	.75	.75	4.0
(2) in pounds of copper per ton of ore	15	15	80
Material mined per day			
(1) tons of ore	40,000	40,000	2,500
(2) tons of waste[a]	100,000	3,200	200
Tons of concentrator tailings per day	39,000	39,000	2,167
Total tons per day of waste material produced	139,000	71,000	2,367
Average tons per day of copper produced[b]	300	300	100

[a]Assumes a 2.5:1 stripping ratio for the open pit mine, and waste rock production at eight percent of ore production for the underground mines.

[b]Assumes a concentrate grade of 30 percent copper and a recovery rate of 100 percent. Actual recoveries are usually less than 100 percent.

Source of data: U.S. Bureau of Mines, *Minerals Yearbook, 1966.*

C. MAGNETIC SEPARATION

MAGNETIC SEPARATION has proven to be economical and efficient, acting on either wet or dry particles, such as: hematite, limonite, siderite, magnetite from gangue; sphalerite from pyrite; sphalerite from rhodonite, garnet, etc.; rutile from apatite; and rutile, garnet, monazite from each other (**Table 17**).

Magnetism can be induced in iron sulfides, oxides, hydroxides and carbonates by flash roasting.

D. ELECTROSTATIC SEPARATION

Mineral mixtures to be separated by electrostatic methods are subjected to a charge in an electrostatic field then passed over oppositely charged rolls. Some particles will cling to the rolls, and others will not. The following main groups exist:

- good conductors - native metals and most sulfides, except sphalerite;
- poor conductors - most silicate minerals;
- variable - good to poor conductors - garnets, sphalerite/marmatite, amphiboles.

(**Table 17**)

E. FROTH FLOTATION

Flotability of a mineral is determined by it ability to adhere to air bubbles which form a froth in a flotation cell. The ability to adhere differs with mineral surface properties. Various agents are added:

- frothing agents - to produce and maintain the froth;
- collecting agents - to induce specific minerals to adhere to froth bubbles; and
- modifying agents - to induce or depress adhesion of specific minerals to the bubbles.

Flotation is by far the most important and most widely used method of mineral separation of sulfides, oxides and native metals from silicates and of the separation of specific minerals.

Flotation is applied to finely ground ores - the upper size is determined by what an air bubble will lift. Thus, it depends upon the specific gravity of the minerals. The following upper limits are illustrative:

- gold, galena: 200 microns (65 mesh)
- pyrite, sphalerite: 3-500 microns (48-28 mesh)
- silicates: 1000 microns (10 mesh)

- coal: 2500 microns (8 mesh)

The efficiency of flotation decreases toward both the upper and the lower size limits. The process is most efficient in the 10 to 50 micron range. Below 10 microns colloidal gangue material may also be carried mechanically and ore minerals fail to attach to bubbles effectively. Therefore, slimes of ore and gangue minerals must be avoided.

F. AMALGAMATION

Concentration by amalgamation consists of passing ground ore pulps over a mercury-coated copper plate. Free gold particles amalgamate with mercury and the amalgam can periodically be scraped off and the gold recovered. Unfortunately, other minerals react with the surface layer of mercury to form mercury sulfides - poisoning the amalgam. The most toxic minerals include: stibnite, enargite, realgar, tetrahedrite; the least toxic include pyrrhotite, marcasite, pyrite, arsenopyrite.

Also, certain gangue minerals, such as clay, graphite, sericite, talc and serpentine may adhere to the mercury, reducing its effectiveness in attaining contact with the gold particles.

G. HYDROMETALLURGICAL PROCESSES

Hydrometallurgy includes a diversity of processes featuring dissolution of metals from ores and concentrates and recovery of relatively pure compounds or metals. Except for in situ leach operations, ores must be crushed, and usually ground and sized prior to leaching in order to permit effective contact between ore minerals and solvent. Sulfide minerals are on occasion broken down by roast in air or with chlorides to produce soluble salts; silicate and insoluble oxides may be roasted with chlorides, sulfur or soda ash to produce soluble compounds.

Agitated tank, vat, heap and dump leaching are most commonly used to win copper from oxidized copper ores using sulphuric acid leach solutions, or to extract gold using alkaline cyanide solutions or, acidified thiourea solutions.

Heap and dump leaching requires careful hydrological examination of the leach site prior to placement of the crushed ore materials. Generally, an impervious pad must be laid down.

Application of leach fluids to heaps or dumps may be through flooding, sprays, or injection wells. In the case of sulfide copper ores the dump is alternatively leached and permitted to drain and oxidize to promote faster extraction.

Agitation leaching, using dilute solvent on finely ground amenable ore usually will achieve extraction of over 95%, whereas vat and heap leaching of coarser ore will require a much longer time to attain extraction of no more than 80%.

Most leach processes feature recovery, regeneration and recycling of solvent solution.

CYANIDATION is the most effective way of extracting fine gold from ores. However, it is subject to failure or low recovery under certain mineralogical or textural conditions that must be determined through careful mineralogical studies.

- The ores most amenable to cyanide leach contain gold along grain boundaries and cleavages of host sulfide or gangue minerals. Difficulties occur where gold is contained as fine inclusions or in solid solution in host minerals.
- Many of the minerals frequently found in gold-bearing ores may 1) react with the NaCN to form cyanogen complexes and give unacceptable rates of reagent consumption; 2) absorb the oxygen supply required for the cyanide-gold reaction (pyrrhotite, marcasite); 3)influence the precipitation of gold by the zinc plates; 4) react with the cyanide solution (copper minerals, antimony/arsenic minerals, some zinc minerals); 5) have iron oxide coatings which can interfere with cyanide attack.

Gold may be recovered from cyanide solutions by addition of zinc powder, or by the use of activated carbon added in-line in the beneficiation.

BASE METAL LEACHING processes have made great progress during the past several decades, but are not in general use. They include Anaconda's Arbiter process for dissolution of copper, and the CYMET Process for conversion of base-metal sulfides into pure metals.

ION EXCHANGE RESINS AND LIQUID ION EXCHANGE (LIX) have come into universal usage for the concentration of metals from low-grade leach solutions to a level suitable for electrowinning or chemical precipitation. These methods are now in general usage in the recovery of leach uranium, copper, zinc, tungsten. For example, 98% of tungsten was removed by ion exchange from Searles Lake brine in which it was present at 70 ppm.

III. SMELTING

A. PYROMETALLURGICAL

Smelting is the most important pyrometallurgical process by which metals are recovered from ore and concentrates to produce semi-refined metals. It entails high temperature processing during which gangue minerals are chemically altered - fluxed and reduced to form low-density molten slag, which separates from one or more heavier liquid metals or metallic compounds.

Feed to the smelting operation often goes through preliminary preparation, including drying, roasting, calcining, sintering, agglomeration and/or pelletizing.

Because of the high energy input required, only relatively high-grade ores or concentrates can be economically smelted. This is usually by one of two processes:

- the smelting of metal oxide ores, concentrates and calcines, which involves reduction of the oxide to metal with coke or carbon monoxide, and less frequently iron, in blast furnaces or occasionally reverbatory or electric arc furnaces using a mixture of coarse ore, coke and fluxes and/or a sinter of these.
- matte smelting of sulfide ores and concentrates takes place in a neutral or slightly oxidizing condition to form a matte (an alloy of several metal sulfides) in a reverbatory furnace using concentrates and fluxes.

Products produced by either of the above methods require further treatment and refining:

- PIG IRON (blast furnace) requires removal of carbon, sulfur and phosphorus by oxidation smelting with steel scrap, fluxes and air in reverbatory or basic oxygen furnaces;
- LEAD BULLION (blast furnace) must be drossed and softened. Impurities are removed by oxidation, sulfidization, alloying or electrolysis;
- COPPER and NICKEL MATTE (reverbatory furnace) require oxidation of sulfur and slagging of iron with silica flux to produce BLISTER.

All pyrometallurgical operations produce large quantities of vaporized metals, dust and fumes.

B. DISTILLATION

Because of their relatively high vapor pressure at elevated temperatures, some metals are recovered from ores, fumes and slags by distillation or fuming. Nearly all primary mercury is recovered and refined by relatively low temperature distillation of low-grade cinnabar ores using rotary kilns, hearth furnaces and retorts. Zinc fuming or distillation in Imperial Smelting type furnaces is common. It entails sintering to remove sulfur, blast furnace smelting at high temperatures to volatilize the zinc and recover lead bullion, and condensation of the zinc in a spray of molten lead followed by cooling the zinc-saturated molten lead by skimming. Arsenic, antimony and cadmium can also be recovered by distillation techniques.

C. LIQUATION

Liquidation is a method by which metals or metallic compounds are separated on the basis of differences in melting points. For example, stibnite, which has a melting point of 550 degrees C., is recovered as pure Sb_2S_3 for subsequent reduction, by heating coarsely

crushed stibnite ores. Liquation techniques are important in the refining of lead. The blast furnace produced lead contains copper, arsenic, antimony, tin, gold and silver that must be removed and refined to saleable products.

Copper, arsenic, antimony and tin are removed by cooling the lead bullion, adding elemental sulfur and blowing with air. When sulfidized and/or oxidized these impurities become insoluble in the molten lead and are skimmed off as DROSS floating on the molten lead. Gold and silver are removed by adding metallic zinc to form insoluble alloys that can be skimmed from the surface.

Liquation is also an important unit process utilized to separate copper-rich matte from heavier nickel-rich matte prior to subsequent processing.

IV. REFINING

Refining varies with the metal. Copper serves to illustrate. Fire-refined copper (BLISTER) in most instances still contains trace quantities of silver, gold and other metals. These are removed as ANODE RESIDUE and as slime on the bottom of electrolytic tanks. The copper precipitated on the cathodes is + 99.99% pure. This is then fabricated into wire, tubing, etc.

Table 19. Salient Factors Requiring Consideration in a Mining Project Feasibility Study

I. Information on Deposit
- A. Geology
  1. Mineralization: type, grade, uniformity
  2. Geologic structure
  3. Rock types: physical properties
  4. Extent of leached or oxidized zones
  5. Possible genesis
- B. Geometry
  1. Size, shape, and attitude
  2. Continuity
  3. Depth
- C. Geography
  1. Location: proximity to population centers, supply depots, services
  2. Topography
  3. Access
  4. Climatic conditions
  5. Surface conditions: vegetation, stream diversion
  6. Political boundaries
- D. Exploration
  1. Historical: district, property
  2. Current program
  3. Reserves
     a. Tonnage-grade curve for deposit, distribution classification; computation of complete mineral inventory (geological and mining reserves) segregated by ore body, ore type, elevation and grade categories
     b. Derivation of dilution and mining recovery estimates for mining reserves.
  4. Sampling: types, procedures, spacing
  5. Assaying: procedures, check assaying
  6. Proposed program

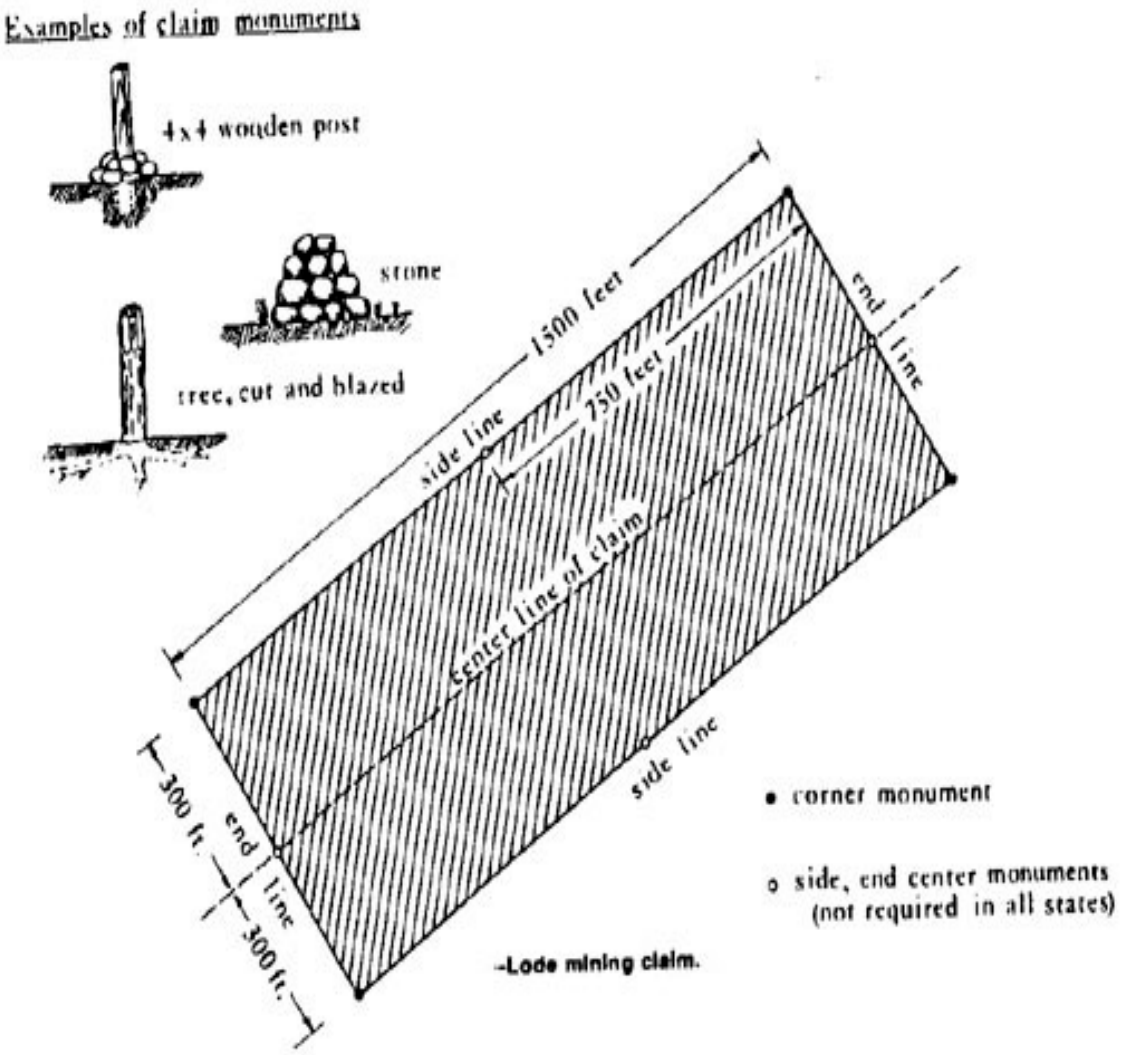
II. Information on General Project Economics
- A. Markets
  1. Marketable form of product: concentrates, direct shipping ore, specifications, regulations, restrictions
  2. Market location and alternatives: likely purchasers, direct purchase vs. toll treatment
  3. Expected price levels and trends: supply-demand, competitive cost levels, new source of product substitutions, tariffs
  4. Sales characteristics: further treatment, sales terms, letters of intent, contract duration, provisions for amendments and cost escalations, procedures/requirements for sampling, assaying, and umpiring.
- B. Transportation
  1. Property access
  2. Product transportation: methods, distance, costs
- C. Utilities
  1. Electric power: availability, location, ownership right-of-way, costs
  2. Natural gas: availability, location, costs
  3. Alternatives: on-site generation
- D. Land, Water, and Mineral Rights
  1. Ownership: surface, mineral, water, acquisition or securement by option or otherwise, costs
  2. Acreage requirements: concentrator site, waste dump location, tailings pond location, shops, offices, changehouses, laboratories, sundry buildings, etc.
- E. Water
  1. Potable and process: sources, quantity, quality, availability, costs
  2. Mine water: quantity, quality, depth and service, drainage method, treatment
- F. Labor
  1. Availability and type: skilled/unskilled in mining
  2. Rates and trends
  3. Degree of organization: structure and strength
  4. Local/district labor history
  5. Housing and transport of employees
- G. Government Considerations
  1. Taxation: federal, state, local
     a. Organization of the enterprise
     b. Tax authorities and regimes
     c. Special concessions, negotiating procedures, duration
     d. Division of distributable profits
  2. Reclamation and operating requirements and trends: pollution, construction, operating and related permits, reporting requirements
  3. Zoning
  4. Proposed and pending mining legislation
  5. Legal issues: employment laws, licenses and permits, currency exchange, expatriation of profits, agreements among partners, type of operating entity for tax and other purposes.
- H. Financing
  1. Alternatives: sources, magnitudes, issues of ownership
  2. Obligations: repayment of debt, interest
  3. Type of operating entity: organizational structure
  4. Division of profits: legal considerations

III. Mining Method Selection
- A. Physical Controls
  1. Strength: ore, waste, relative
  2. Uniformity: mineralization, blending requirements
  3. Continuity: mineralization
  4. Geology: structure
  5. Surface disturbance: subsidence
  6. Geometry
- B. Selectivity
  1. Dilution, ore recovery estimates
  2. Waste mining and disposal
- C. Preproduction Requirements
  1. Preproduction development or mining requirements: quantity, methods, time
  2. Layout and plans: schedule
  3. Capital requirements
- D. Production Requirements
  1. Relative production
  2. Continuing development: methods, quantity, time requirements
  3. Labor and equipment requirements
  4. Capital requirements vs. availability

IV. Processing Methods
- A. Mineralogy
  1. Properties of ore: metallurgical, chemical, physical
  2. Ore hardness
- B. Alternative Processes
  1. Type and stages of extraction process
  2. Degree of processing: nature and quality of products
  3. Establish flowsheet: calculation of quantities flowing, specification of recovery and product grade
  4. Production schedule
- C. Production Quality vs. Specifications
- D. Recoveries and Product Quality
  1. Estimate effects of variations in ore type or head grade
- E. Plant Layout
  1. Capital requirements
  2. Space requirements
  3. Proximity to deposit

V. Capital and Operating Cost Estimates
- A. Capital Costs
  1. Exploration
  2. Preproduction development (may also be considered operating costs)
     a. Site preparation
     b. Development of deposit for extraction
  3. Working capital
     a. Spares and supplies (inventory)
     b. Initial operations
     c. Financing costs (when appropriate)
  4. Mining
     a. Site preparation
     b. Mine buildings
     c. Mine equipment: freight, taxes and erection costs, replacement schedule
     d. Engineering and contingency fees
  5. Mill
     a. Site preparation
     b. Mill buildings
     c. Mill equipment: freight, taxes and erection costs, replacement schedules
     d. Tailings pond
     e. Engineering and contingency fees
- B. Operating Costs
  1. Mining
     a. Labor: pay rates plus fringes
     b. Maintenance and supplies: quantities, unit costs
     c. Development
  2. Milling
     a. Labor: pay rates plus fringes
     b. Maintenance and supplies: quantities, unit costs
  3. Administrative and supervisory
     a. Overhead charges
     b. Irrecoverable social costs

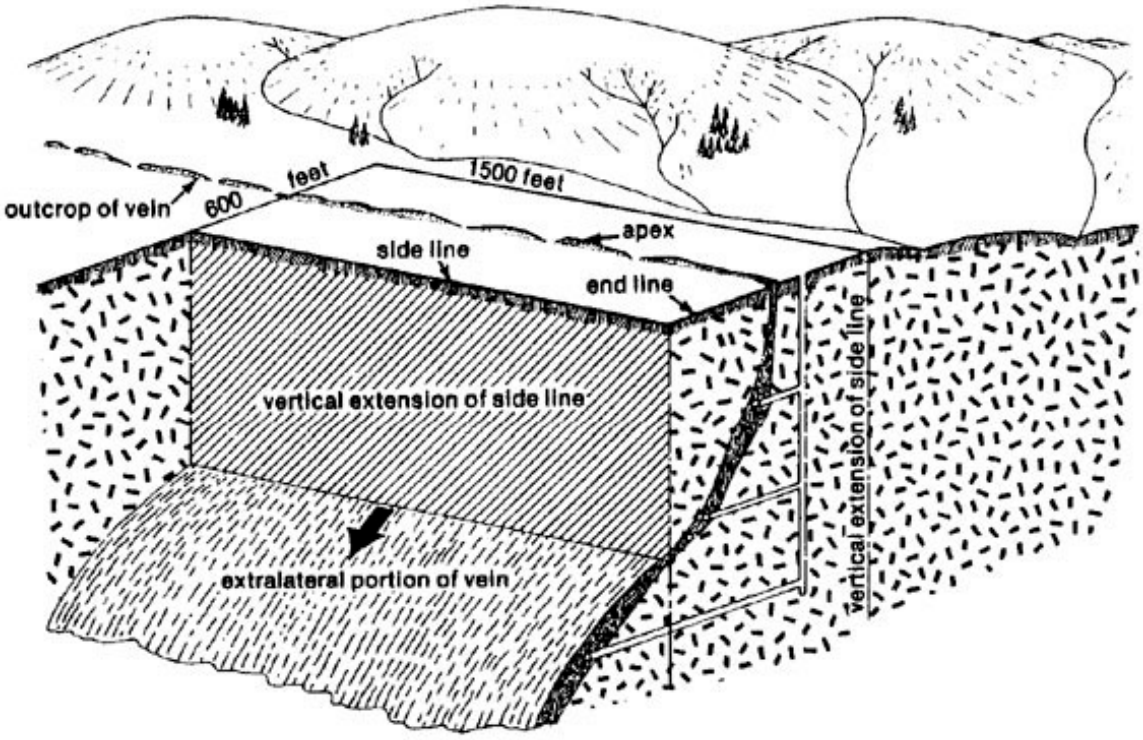
Source: Gentry and Hrebar, 1978; Taylor, 1977.



Figures 44 and 45: Lode Mining Claims -- EXPLANATORY NOTE.

With satellite positioning, it is now easy and advisable to position mining claims accurately tied to Public Land Surveys.

Because of difficulties in the interpretation of complex branching vein systems, and the diversity in shapes of ore deposits, extralateral rights are generally waived in mining claim agreements.



--Extralateral rights of a lode mining claim.

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