Geologic course for fourth year students (Geology) of

ORE PETROLOGY

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Introductory Definitions

Ore: A metalliferous mineral, or aggregate mixed with gangue that can me mined for a profit, or can be treated at a profit . *Gangue* : associated minerals in ore deposit that have little value.

Protore : initial non-economic concentration of metalliferous minerals that may be economic if altered by Supergene enrichment or hydrothermal alteration.

Petrology: Branch of geology that deals with the origin, occurrence, structure and history of the rocks.

Economic Considerations

Grade: the concentration of a metal in an ore body is usually expressed as a weight % or ppm.

Ore assaying : The process of determining the grade of an ore.

Cut-off grade: after all economic and political considerations are weighed this is the lowest permissible grade that will mined. This may change over time. As ore deposits are mined the high-grade zones are developed first leaving low-grade ores for the future with hopefully better technology. Since mining proceeds to progressively lower grades the scale of mining increases because the amount of tonnage processed increases to remove the the same amount of metal.

Near-surface open pit mines are inherently cheaper than underground mines .
Other factors important to mining costs include transportation, labor, power,

equipment and taxation costs.

Classification of Ore bodies

Proved : ore body is so thoroughly studied and understood that we can be certain of its geometry, average grade, tonnage yield.

Probable: ore body is somewhat delineated by surface mapping and some drilling. The geologists is reasonably sure of geometry and average grade.

Possible: outside exploration zones the geologist may speculate that the body extends some distance outside the probable zone but this is not supported by direct mapping or drilling.

Geochemical Considerations: (Groups of Metal)

Precious Metals:gold (Au), silver (Ag), pt. group(Pt,Ir,Os,Rh,Pd).

Non-Ferrous Metals: copper (Cu), lead (Pb), zinc (Zn),tin (Sn), aluminum (Al) {1st four are known as base metals}.

Iron and Ferro-alloy metals: iron, manganese, nickel, chromium, molybdenum, tungsten, vanadium, cobalt.

Minor metals and related non-metals: antimony, arsenic, beryllium, bismuth, cadmium, magnesium, mercury, selenium, tantalum, tellurium, titanium, , etc.

Fissionable metals: uranium (U), thorium (Th), radium (Ra).

Concentration Factors

Metal	Crustal abundance Grade (%)	Average exploitable grade (%)	Cocentration factor
Aluminum (Al)	8	30	3.75
Iron (Fe)	5	25	5
Copper (Cu)	0.005	0.4	80
Nickel (Ni)	0.007	0.5	71
Zinc (Zn)	0.007	4	571
Manganese (Mn)	0.09	35	389
Tin (Sn)	0.0002	0.5	2500
Chromium (Cr)	0.01	30	3000
Lead (Pb)	0.001	4	4000
Gold (Au)	0.0000004	0.00001	25

Nature & Morphology of Common Ore Deposits

Syngenetic: ore body forms at the same time as the host rockEx. Fe-rich cement in stratigraphic interval.

Epigenetic: ore forms at some later time after the host rock body has Ex. Gold-bearing vein cutting across a granite pluton.

Description of ore deposit

Axis of ore body: line that parallels the longest dimension of the ore body.

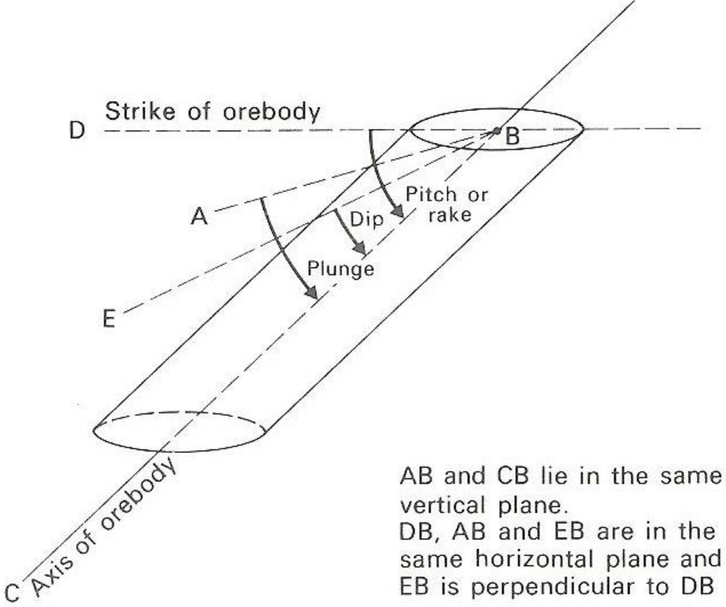
Pitch (Rake) of ore body: Angle between the axis and the strike of the ore body.

* **Axis of ore body**:

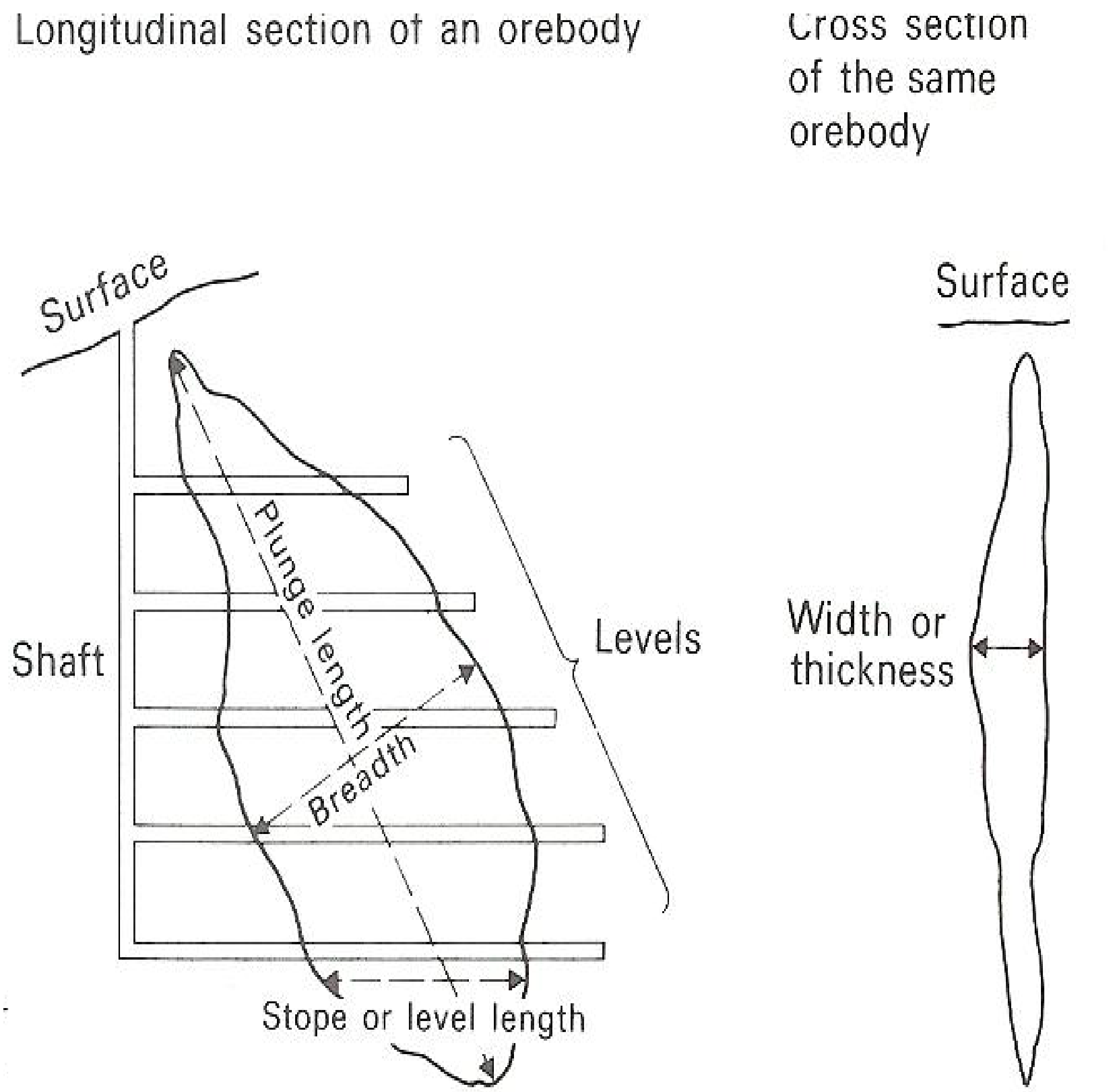
line that parallels the longest dimension of the ore body.

*** Pitch (Rake) of ore body**:

Angle between the axis and the strike of the ore body.



AB and CB lie in the same vertical plane.
DB, AB and EB are in the same horizontal plane and EB is perpendicular to DB



Discordant Ore Bodies

Regularly Shaped Bodies :

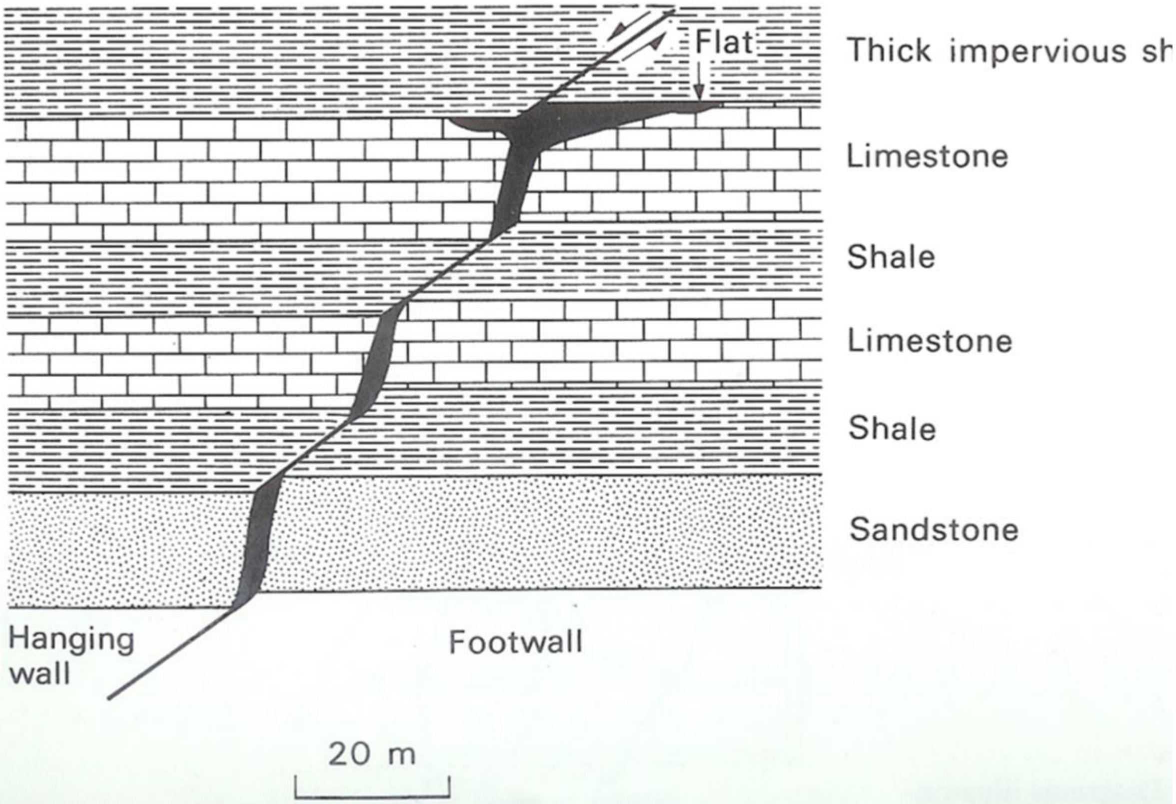
- Tabular ore bodies: extensive in 2 dimensions and restricted in the 3rd
- Tubular ore bodies: short in 2 dimensions, extensive in the 3rd.

Irregularly Shaped Bodies :

- Disseminated deposits: ore minerals are dispersed throughout the host rock
- Replacement deposits: develop from contact metamorphism; termed “Skarn”.

Tabular ore bodies :

These bodies arc extensive in two dimensions, but have a restricted development in their third dimension (Veins). Veins are often inclined, and in such cases, as with faults, we can speak of the hanging wall and the footwall. Veins frequently show pinch and swell. (Fig.3). When movement occurs producing a normal fault then the less steeply dipping sections are held against each other and open spaces (dilatant zones) form in the more steeply dipping sections. Then, should minerals be deposited in these cavities, a vein will be formed.

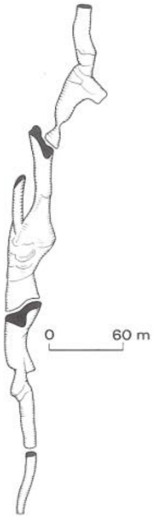


g. 2.2. Vein occupying a normal fault and exhibiting pinch-and-swell structure, giving ris
bon ore shoots. The development of a flat beneath impervious cover is also shown.

Fig.3

Tubular ore bodies

These bodies arc relatively short in two dimensions but extensive in the third. When vertical or subvertical they are called pipes or chimneys, (Fig 4) when horizontal or subhorizontal, 'mantos'.In eastern Australia, along a 2400 km belt from Queensland to New South Wales, there are hundreds of pipes in and close to granite intrusions. Most have quartz fillings and some are mineralized with bismuth, molybdenum, tungsten and tin. In some tubular deposits formed by the sub-horizontal flow of mineralizing fluid, ore grade mineralization may be discon- tinuous, thus creating pod-shaped ore bodies as with the McClean deposits, Saskatchewan. These pods undulate along the unconformity between a <u>regolith</u> and the overlying Proterozoic Athabasca sediments. The mineralizing fluid removed much quartz from both the regolith and the overlying sediments and deposited new minerals including a considerable amount of pitchblend in its place.



Disseminated deposits:

In these deposits, ore minerals are peppered throughout the body of the host rock in the same way as accessory minerals are disseminated through an igneous rock, eg.

1- **Diamonds in Kemberlites:**

In south africa, and the orthomagmatic nickel-copper deposits, of La Perouse Layered Gabbro, Alaska which contains disseminated sulphide mineralization throughout its entire thickness of about 6 km. This deposit has over 100 Mt grading about 0.5% nickel and 0.3% copper.

2- Disseminated Stockworks

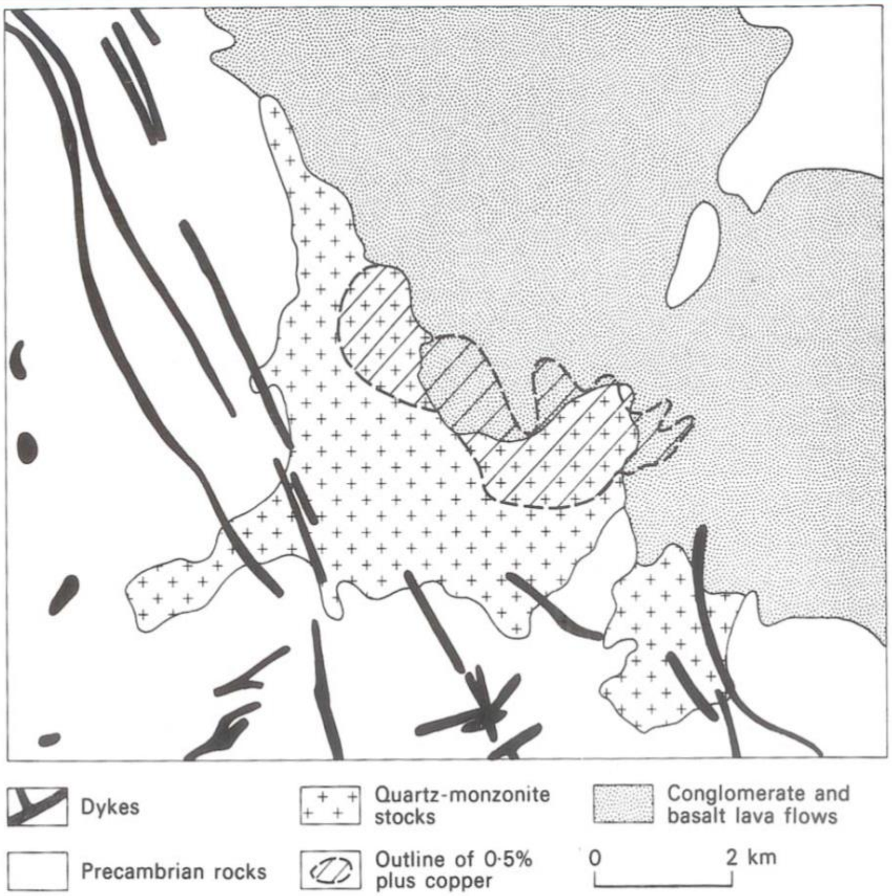


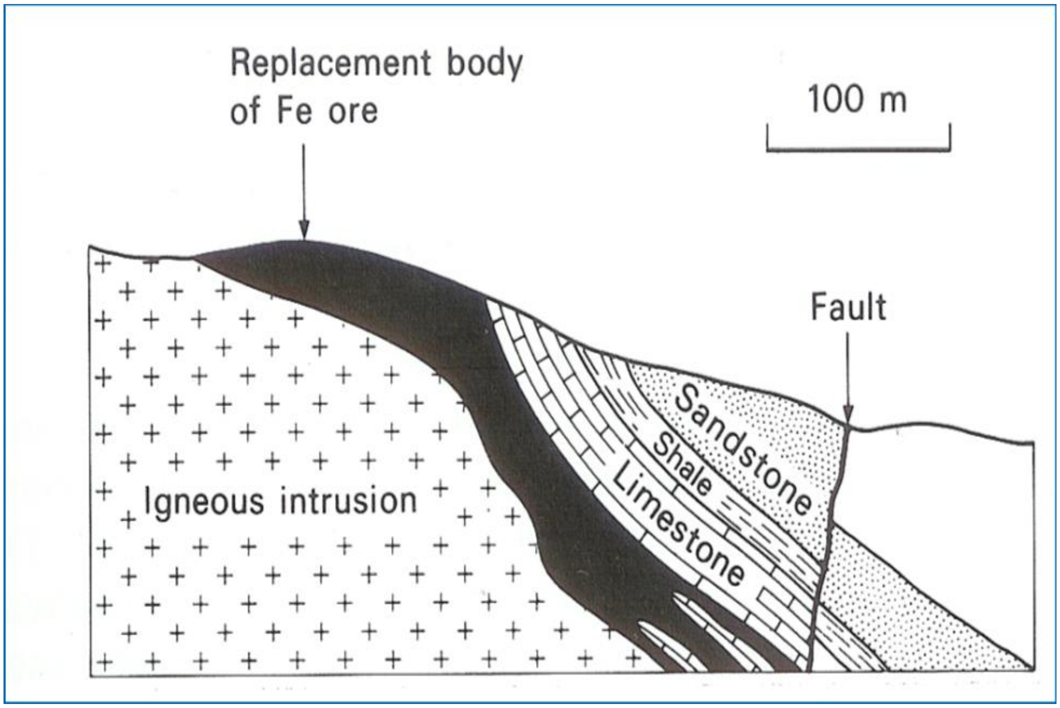
Fig. 2.7. Generalized geological map of the Bagdad mine area, Arizona. (Modified from Anderson 1948.)

* Stockworks are synonymous with disseminated ore deposits.

* These types are often inside felsic and intermediate intrusions but also cut across the contact into the country rock.

Replacement deposits (Skarn) :

* Skarns :



Are contact metamorphic aureoles that develop when silicate magmas intrude carbonate country rock. These types are also termed Pyrometa-somatic deposits . Skarns yield ores of Fe, Cu, W, Zn, Pb, Mo, Sn and U

Concordant Ore Bodies :

*** Sedimentary Host Rocks**

Limestone Hosts ., Argillaceous (shale) Hosts . Arenaceous (sandstone) Hosts

Rudaceous (conglomerate) Hosts, Chemical Sedimentary Hosts.

* Igneous Host Rocks : Plutonic hosts and Volcanic Hosts

* Metamorphic Host Rocks

Residual Deposits , and Supergene Enrichment

Sedimentary Host Rocks

* Mainly important for base metals and iron.

- Ore bodies are concordant to bedding in host rock.
- The term stratiform is used to describe ore bodies that are developed in 2 dimensions parallel to bedding with limited development perpendicular to bedding.
- Strata-bound deposits are ore bodies that are either concordant or discordant but are restricted to a specific stratigraphic interval

Sedimentary Limestone Hosts

*Limestones are common host rocks for stratiform sulfide ores.

* Dolomitization may increase inherent permeability and therefore ore development may be greater in those beds.

*Silvermines, Ireland is a good example; ore is 75% pyrite/ marcasite, 20% sphalerite, 4% galena .

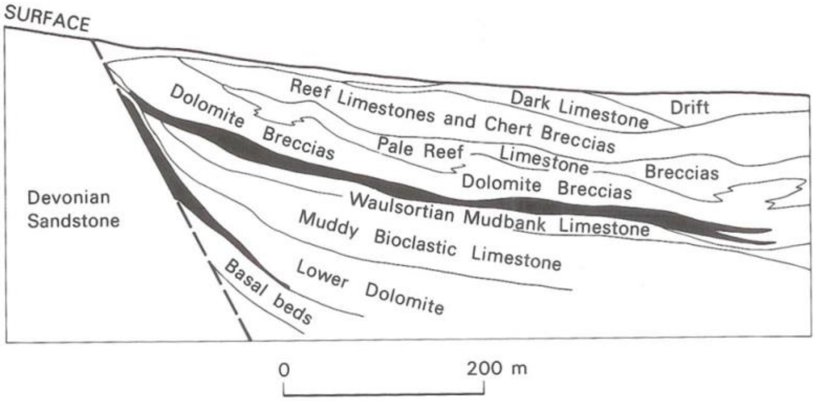


Fig. 2.10. Vertical section through the G zone at Silvermines, Co. Tipperary, Ireland. The orebodies are shown in black. (After Taylor & Andrew 1978.)

Sedimentary Argillaceous Host

* Shales, mudstones, argillites and slates are important hosts for ore bodies that are remarkably continuous and extensive.

* The upper Permian of Kupfers chiefer, Germany, contains an ore body 1 meter thick with an areal extent of 130 km2.

* The world's largest lead-zinc sulfide body is in Sullivan, B.C in Precambrian Argillites.

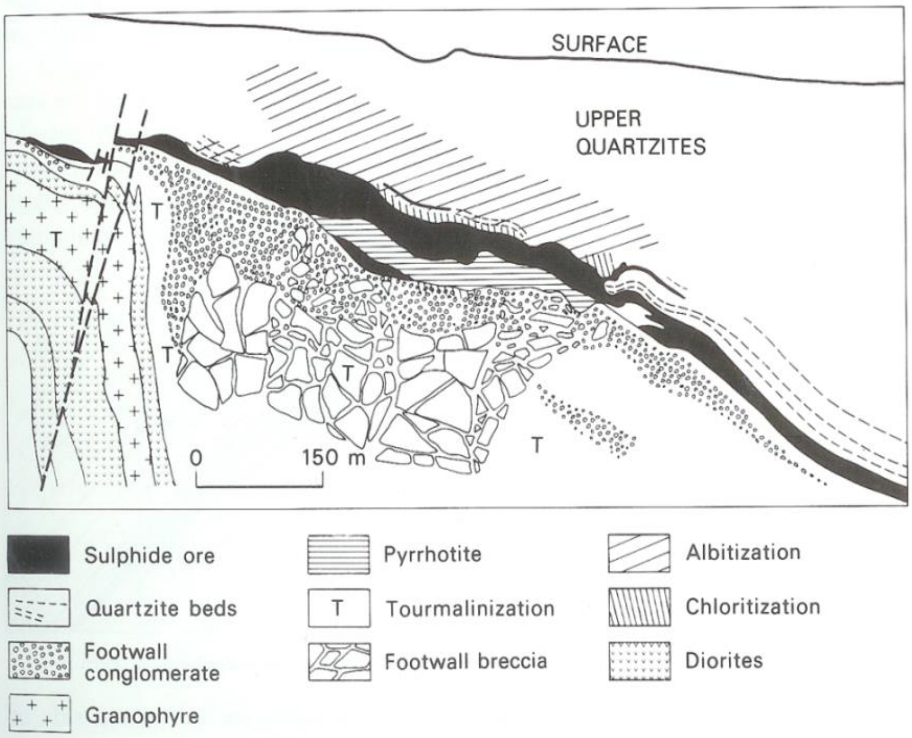


Fig. 2.11. Cross section through the ore zone, Sullivan Mine, British Columbia. (After Sangster & Scott 1976.)

*The ore body is 60-90m thick and yields 6.6% Pb and 5.7% Zn.

Production is 155 million tons of ore as of 1982.

Sedimentary Arenaceous Hosts

*Some of the Zambian copper ore bodies occur in sandstones.

*Ore reserves are 282 million tons assaying at 3.47% Cu with $CuFeS_2$ as the principle ore.

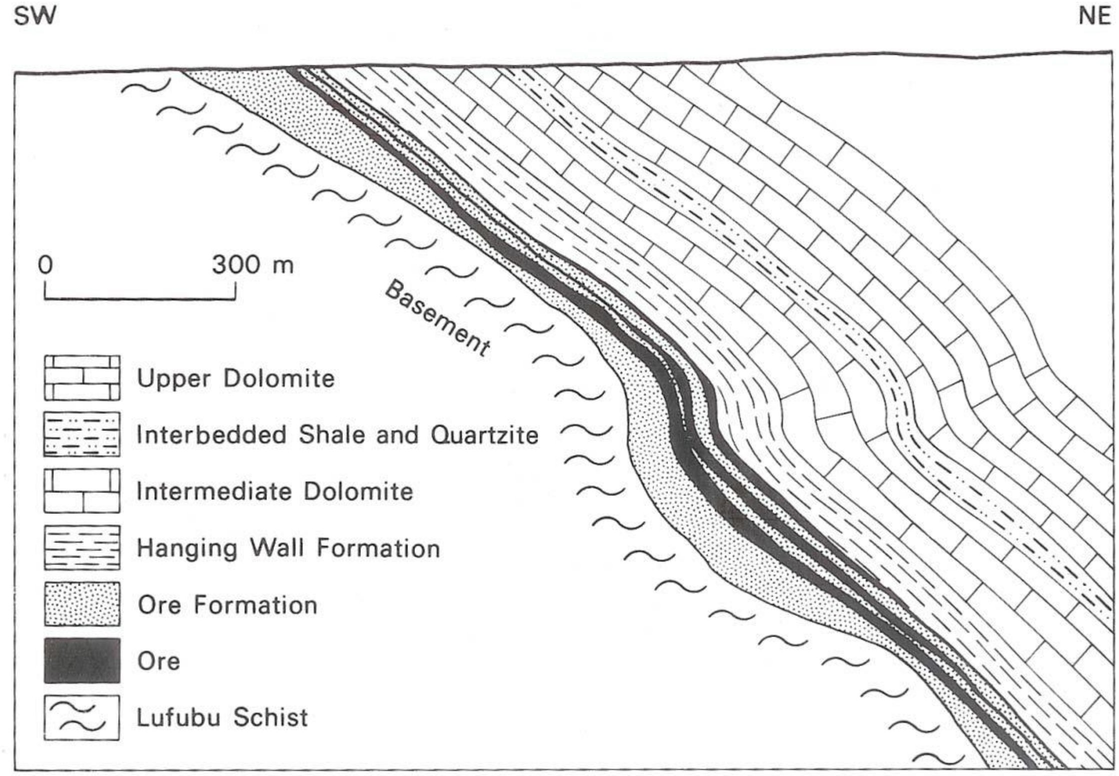


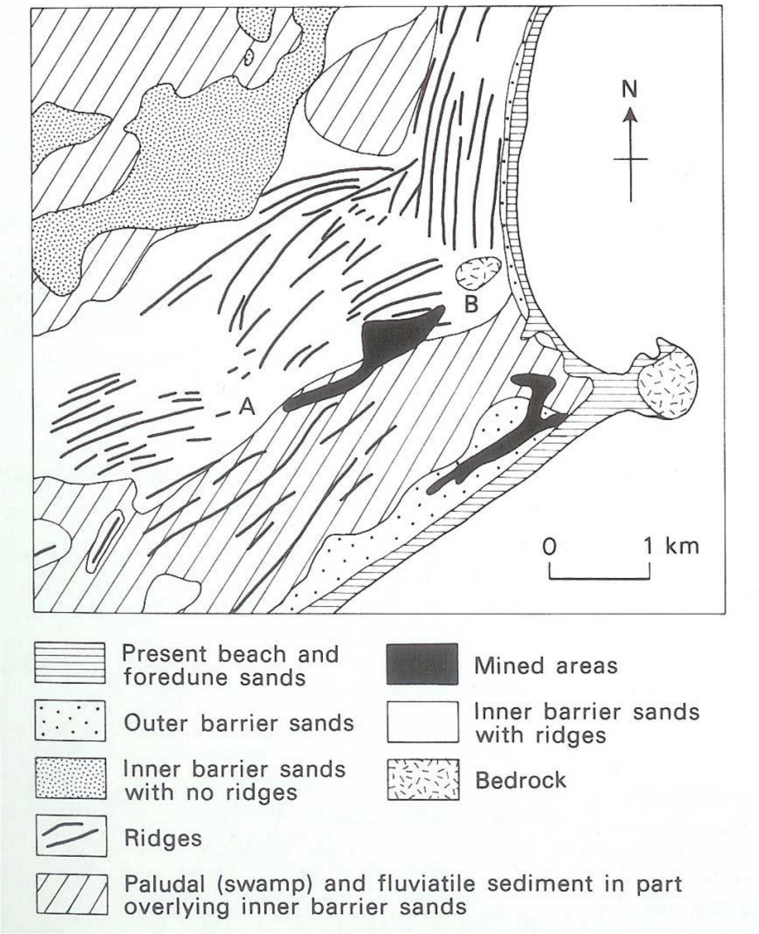
Fig. 2.12. Cross section through the Mufulira orebodies, Zambia. (After Fleischer *et al.* 1976.)

Placer Deposits

* Mechanical concentrations of high density detrital minerals may accumulate in sands as ore deposits.

* Placer deposits may yield magnetite, ilmenite, rutile , Monazite and zircon.

* Because placer deposits are unconsolidated they have low overhead costs.



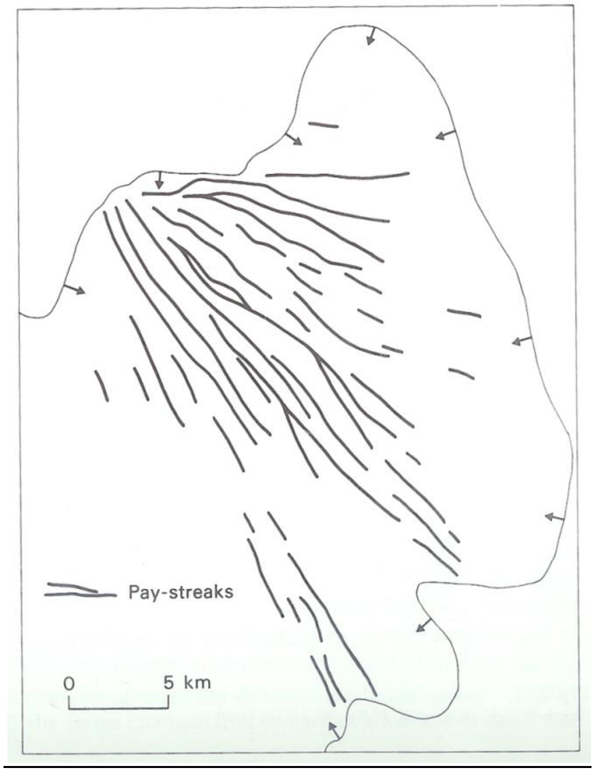
Rudaceous (Conglomeritic) Hosts

* The Witwatersrand of South Africa produced the majority of the world’s gold.

* Ore bodies are distributed in a “fan” pattern that was inherited from an alluvial fan protolith.

* Apparently the placer deposits were first concentrated in point bars in the distributary channels of alluvial fan.

* Similar mineralized conglomerate hosts appearin the Precambian shields of the continents.



Chemical Sediment Hosts

* Sedimentary iron and manganese formations occur throughout the world in stratiform ore deposits.

* These deposits precipitate from seawater or seafloor brines.

Volcanic Host Rocks

* There are 2 principle types of ore deposits in volcanic rocks:

1- Vesicular filling deposits.

2- Volcanic massive sulfide deposits.

* Massive sulfide deposits are important producers of base metals with Ag and Au often produced as by-products.

Vesicular Filling Deposits

- Vesicular permeable tops of basalt flows form the host rock.
- The most important example are the <u>native copper deposits</u> in the Keweenwa Peninsula of northern Michigan.

* Similar deposits in Canada have yielded 3,000,000 tons of ore averaging 3.48% copper.

* The ore bodies average only 4m in thickness.

Massive Sulfide Deposits

*Often consist of > 90% Fe sulfide.

*Generally are stratiform

* May grade into massive magnetite oxide deposits

* 3 classes of deposits: 1. Zn-Pb-Cu, 2- Zn-Cu, 3- Cu

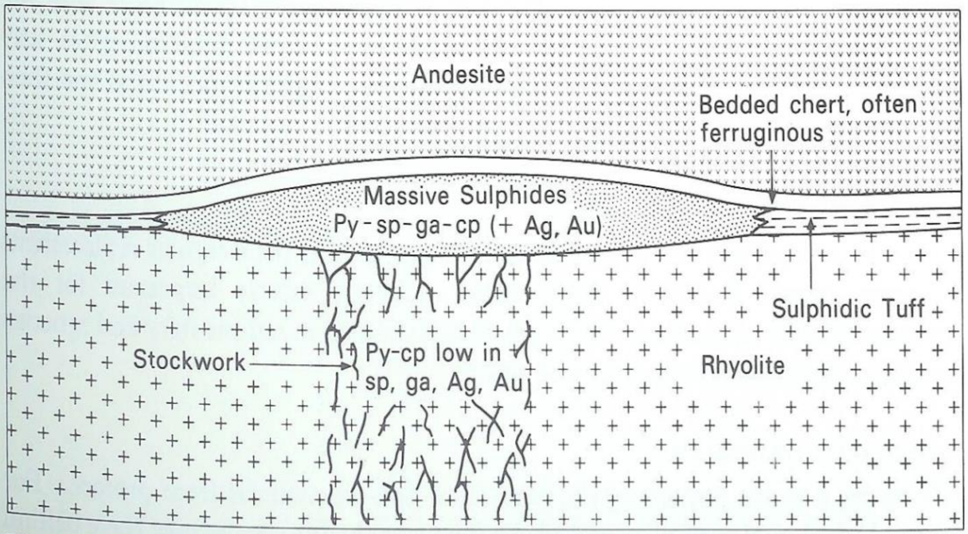


Fig. 2.15. Schematic cross section through an idealized volcanic massive sulphide deposit showing the underlying feeder stockwork and typical mineralogy. Py = pyrite, sp = sphalerite, ga = galena, cp = chalcopyrite.

* The most host rock is rhyolite; Pb ores are only associated with this type.

* The Cu class is only associated with mafic volcanic host rocks.

* Many massive sulfide deposits overlay pyroclastic deposits with stockwork ores being disseminated in the brecciated pyroclastic zone.

Plutonic Host Rocks

* Many plutons are layered from fractional crystallization.

* Chromite, magnetite, ilmenite are often found in economic concentrations in the groundmass of the layers.

* The mineralized seams are stratiform and may extend over many kilometers.

*During fractional crystallization a separate sulfide or oxide magma may separate from the silicate magma and then sink to the bottom of the magma chamber to form the seam.

* Sulfide magmas that form strata form deposits are known as liquation deposits,

Metamorphic Host Rocks

*Metamorphic ore bodies generally are the re-crystallized end-products of a sedimentary or igneous host rock.

Residual Deposits

* Ore deposits formed by the removal of non-ore material from protore.

* Leaching of silica and alkalis from nepheline syenite to leave behind bauxite (Al ore) is one example

Supergene Enrichment

* Groundwater interacting chemically with a mineral deposit may drive reactions that increase the concentration factor of metals so that it is an economic ore deposit.

* Often the re-deposition of enriched ore is below the water table.

ORE MINERAL ASSEMBLAGES

Ore minerals are not uniformly distributed in the earth's crust but generally occur in associations that are characteristic in their mineralogy, textures, and relationships to specific rock types. The existence of these characteristic associations, each containing its own typical suite of ore minerals, considerably simplifies the task of the ore microscopist, because it permits him or her to anticipate the minerals that are likely to be encountered once the general association has been recognized.

Indeed, these associations largely result from the formation of the ores under characteristically limited physico-chemical conditions, the nature of which may often be inferred from detailed study of the ores.

1- ORE MINERAL ASSEMBLAGES OCCURRING IN IGNEOUS ROCKS

1.1. Chromium ores associated with mafic and ultramafic igneous rocks

Major: Chromite (ideally $FeCr_2O_4$, although always containing significant MgO, Al_2O_3, Fe_2O_3***Mineralogy***)

Minor : Sulfides of nickel, copper, and iron . (pentlandite , pyrrhotite, chalcopyrite, bornite)

Mode of Occurrence :

There are two distinct modes of occurrence:

1. In layered basic intrusions as magmatic layers

2. In peridotite or serpentinized peridotite masses associated with orogenic belts

("podiform" or "Alpine-type" chromites).

Examples :

A classic example of a chromite deposit associated with a layered basic intrusion is the Bushveld Complex, South Africa; other examples include the Stillwater Complex, Montana (United States), and the Great Dyke (Rhodesia). occur in tectonically stable environments. The layers of the intrusive complexes can be regarded as magmatic "strata," which may be of considerable lateral extent. Within these, the chromite bands may range from a few millimeters to over 20 m in thickness.

"Podiform" chromites occur in many orogenic belts and are generally much smaller deposits; occur in highly unstable tectonic environments, important examples include deposits in Turkey, the Ural Mountains (Russia), the Philippines, and Cuba.

Origin of chromite Ores :

It is universally accepted that the chromite ores of layered intrusives are magmatic in origin and are related to processes of fractional crystallization and gravitative settling of layers of crystal s on the floor of the intrusive sheets.

The origin of the podiform chromites is clearly very different, form part of so-called ophiolite complexes. Current theories relate the creation of ophiolites to processes along spreading boundaries between lithospheric plates.

1.2. IRON-NICKEL-COPPER SULFIDE ORES

ASSOCIATED WITH MAFIC AND ULTRAMAFIC IGNEOUS ROCKS

Mineralogy :

Major: Pyrrhotite , pentlandite, pyrite, magnetite, chalcopyrite.(Cu,Fe,S2)

Mode of Occurrence:

Massive to disseminated in, or immediately associated with, mafic to ultramafic intrusive or extrusive rocks (gabbro, basalt, peridotite, norite) or metamorphosed mafic to ultramafic rocks.

Origin of ore :

These iron-nickel-copper sulfide ores are generally considered to have formed as a result of the separation of an immiscible sulfide-oxide melt from a sulfur saturated silicate melt shortly before, during, or after emplacement at temperatures Of 900°C or above. The sulfide-oxide melt may have settled through the partly crystalline silicate magma or, if segregated early, may have been intruded separately; the resulting ores range from massive to disseminated, or even brecciated. When emplacement involves subaerial or submarine basaltic extrusions, the separated sulfides are commonly present as millimeter or smaller-sized rounded droplets dispersed within, or interstitial to, the silicates.

1.3. COPPER / MOLYBDENUM SULFIDES

ASSOCIATED WITH PORPHYRITIC INTRUSIVE IGNEOUS ROCKS

Mineralogy: Major: Pyrite, chalcopyrite,$CuFeS_2$, molybdenite, MoS_2,
bornite. Cu_5FeS_4

Minor: Magnetite, hematite, ilmenite, rutile , enargite, gold.

Sulfides are present in veinlets and as disseminated grains in, or adjacent to, porphyritic intrusions ranging in composition from quartz diorite to quartz monzonite.The host porphyry and adjacent rocks are commonly altered in concentric siliceous, potassic, phyllic, argillic, and propylitic zones.

Mineral Zoning in Porphyry Copper Deposits

Porphyry deposits now constitute the world's primary sources of copper and molybdenum and also serve as significant producers of several other base metals, gold, and silver.

According to Lowell and Guilbert (1970): A copper and/or molybdenum sulfide deposit consisting of disseminated and stockwork veinlet sulfide mineralization emplaced in various host rocks that have been altered by hydrothermal solutions into roughly concentric zonal pattern (Ore microscopy and ore petrography, Graig and vaughan 1994).

The low grades of these deposits 0.5-0.8%Cu and 0.02% Mo for a typical porphyry copper, and 0.3% Mo and 0.05% Cu for a typical porphyry molybdenum evidence the dispersed nature of the sulfides. Pyrite is generally the most abundant sulfide and may occur in association with the other sulfides or alone in barren quartz veinlets.

Potassic Zone : The inner zone of potassic alteration commonly coincides with two zones of mineralization:

1.An inner low-grade (<0.3% Cu) core characterized by . pyrite and chalcopyrite in a ratio of roughly 1:2, minor magnetite and minor molybdenite.

2. An ore shell (> 0.5% Cu), in which the pyrite to chalcopyrite ratio is roughly I: I and each mineral constitutes about I% of the rock.

Phyllic and Argillic Zones: The phyllic zone coincides with the outer portion of the "ore shell " and the surrounding low-grade portion of the "pyrite shell“ in which copper grade decreases to 0.1-0.5%. The pyrite-to-chalcopyrite ratio is roughly 10:I, and pyrite may constitute as much as 10% of the rock volume. The outer part of the "pyrite shell" contains up to 25% pyrite in the form of coarse anhedral pyritic-quartz veins up to 2Cm thick.

Propylitic Zone *:*

In this zone, the outer zone of the ore body, mineralization consists of pervasive pyrite in veinlets (2-6% of the rock) and local small veins containing typical hydrothermal base-metal assemblages, such as the pyrite-chalcopyrite-galena-sphalerite- tetrahedrite associations.

Origin of the Ores :

Porphyry copper deposits are emplaced in igneous belts located either on continental margins or in island arcs. These belts are related to partial melting of wet oceanic crust descending along Benioff zones at depths of 150-250 km. Deposition of the copper occurs where metal-carrying solutions rising from the descending crust meet meteoric brines.

1.4.COPPER-LEAD-ZINC-SILVERASSEMBLAGES IN VEIN DEPOSITS

Mineralogy

Major : Pyrite, sphalerite, galena, chalcopyrite, tetrahedrite. $(Cu,Fe)_{12} Sb_4 S_8$

Minor : Bornite, chalcocite, enargite, argentite, gold, hematite, Pb-Bi-Sb-sulfosalts

Associated Gangue Minerals : Quartz, calcite, dolomite, barite,fluorite, rhodochrosite, siderite, chlorite,sericite.

Mode of Occurrence :

Copper-lead-zinc-silver sulfide ores occur as hydrothermal vein fillings and replacement (usually of limestone) bodies often associated with intermediate to acid intrusions.

Supergene Alteration: Near-surface portions of these ores often reveal moderate to extensive alteration by meteoric waters. The oxidation of pyrite causes the formation of sulfuric acid and ferrous sulfate, which results in the breakdown of other sulfides. The end result is that the uppermost parts of the veins consist of a boxwork gossan of iron oxides and hydroxides.

Origin of Ores :

Copper-lead-zinc-silver vein deposits form as a result of circulating hydrothermal fluids that extract, transport, and then precipitate sulfide minerals as open-space fillings and replacements. Studies of fluid inclusions, wall-rock alteration, and the sulfide ore minerals indicate that the ore-forming fluids were chloriderich brines precipitated the sulfides in response to a decrease in temperature, a decrease in pressure (which may sometimes allow boiling),reaction with wall rocks, or mixing with other fluids .

ORE MINERAL ASSEMBLAGES OCCURRING IN SEDIMENTARY,VOLCANIC, AND METAMORPHIC, ENVIRONMENTS

INTRODUCTION

In this chapter, the discussion of characteristic associations is continued and extended to ores occupying a variety of sedimentary, volcanic, and metamorphic environments. The first associations described represent part of the continuum of sedimentary processes and include placer-type titanium, tin, and gold deposits, chemical precipitates, coal, and base-metal accumulations that are spatially related to submarine hydrothermal vents and volcanism. Lead-zinc deposits in carbonates (and arenites), although normally regarded as epigenetic, are included here because of their stratabound nature and the increasingly prevalent belief that they are related to diagenetic processes and to the migration of connate brines.

1 - IRON AND MANGANESE ORES IN SEDIMENTARY ENVIRONMENTS

1.1 Iron :

Most sedimentary rocks contain significant quantities of iron, and there is a complete range up to those of ore grade. Sedimentary iron ores can broadly be considered as occurring in three major classes : bog iron ores, ironstones, and (banded) iron formations. This also is the increasing order of their economic importance.

Bog Iron Ores

Mineralogy:
Goethite, limonite, siderite; minor carbonates, vivianite Fe3(P04h·8H20).

Mode of Occurrence :

As lake or swamp sediments, often in temperate or recently glaciated reas or in volcanic streams and lakes; also in association with coal measures in older sedimentary sequences ("black band ironstones ").

Examples

In tundra areas of Canada and Scandinavia; temperate coastal areas of the eastern United States and Canada; in volcanic provinces such as Japan and the Kurile Islands; in carboniferous and Permian sedimentary sequences in the eastern United States and North England.

Mineral Associations :

Goethite, the major phase of many bog iron deposits, occurs as oolitic or pisolitic grains (1-10 mm) cemented to form disks (-3- 30 ern iameter), which, in tum, form bands or lenses of ore. The ores also commonly ccur as colloform bands and irregular module-like masses that are composed of mrn-to-cm-length radiating fibrous crystals of goethite.

Banded iron Formations

Mineralogy:

Major hematite and magnetite, and in some cases iron carbonates and silicates may be important; pyrite usually minor.

Mode of Occurrence :

As well-bedded, elongate bodies, often with alternating chert-iron mineral stratification. The ores occur as laterally and vertically extensive sequences in Precambrian strata throughout the world. In some cases, the sedimentary setting appears to have been marine; in others, estuarine or fresh water; and sometimes an association with volcanic rocks is evident.

Examples :

Widespread in Precambrian sequences, but major examples include the Lake Superior district and the Quebec belts of North America.

Mineral Associations :

Characterized by banding resulting from the interlayering of xides and silica, both on a coarse and a fine scale the units may be lenses rather than layers, giving a "wavy" appearance to the stratification. Hematite and magnetite constitute the major ore minerals, but iron in carbonate, silicates (e.g. greenalite), and sulfides (pyrite and very minor pyrrhotite) is also found.

Origins of Iron-Rich Sediments

The bog iron ores can be observed in the process of formation, so their origin is clearly understood. In the closed drainage systems in tundra areas, these ores are derived by subsurface weathering and leaching, with transport of the iron as bicarbonates and humates in ground water and asubsequent concentration and deposition in lakes and marshes by loss of CO2 and, commonly, oxidation.

1.2. Manganese

Most sedimentary rocks also contain detectable concentrations of manganese. although, generally lower in concentration than iron; as with iron-rich sediments, there is a complete range from minor amounts to ore grades. The major classes of sedimentary manganese ores are marsh and lake deposits, deposits of the ortho- quartzite-glauconite-clay association, deposits of volcanic affiliation, and modern marine deposits (inchiding *manganese nodules)*. The marsh and lake deposits are commercially insignificant and are undoubtedly the analogues of bog iron ores, being derived by the same processes. The manganese occurs as poorly crystalline hydrous oxides. The other classes of sedimentary manganese deposits will be briefly discussed in turn.

1.2.1 Manganese Deposits of Orthoquartzite-Glauconite-Clay Association

Mineralogy :

Pyrolusite, psilomelane, manganite, manganocalcite, and rhodochrosite (MnCO3).

Mode of Occurrence :

Thin lens-shaped beds conformable with enclosing sedimentary strata, the sediments having generally been deposited on a stable platform area and being estuarine through to shallow marine deposits (sandstones, silts, clays, glauconitic beds, limestones, and even coaly beds).

1.3. Gossans

Gossans, or 'iron caps," develop on many types of iron-sulfide-bearing deposits as a result of surface or near-surface weathering and oxidation.

Mineralogy:

Goethite, limonite, lepiclocrocite, hematite in varying proportions, sometimes with minor amounts of manganese oxides and residual basemetal sulfides and, locally, trace quantities of gold.

Examples: Developed worldwide at surficial exposures of sulfide-containing deposits.

Mineral Associations:

Gossans generally consist of porous irregular laminae and colloform bands of mixed iron oxides with minor, but variable, amounts of residual sulfide minerals. Remnant textures or primary grain shapes, cleavages, and fractures are commonly preserved in the iron oxides. The grain size is usually very fine (< 10 um), but radiating bundles of fibrous crystals (like those in Figure 7.13) up to 1 millimeter or more in length maybe locally developed. In recent years, several gossans have been mined for gold that was dissolved from the primary ores and reprecipitated during the gossan-forming process.

1.4 OPAQUE MINERALS IN COAL

Mineralogy :

Major : Pyrite, marcasite

Associated Minerals :

Quartz, calcite, dolomite, siderite, kaolinite, illite, gypsum, and a variety of secondary iron sulfates and iron oxides.

Mode 0f Occurrence:

The sulfides are generally present in coal as:

(1) veins that are thin or film-like on the vertical joints (cleats),

(2) lenses that range from millimeters to tens of centimeters across,

(3) nodules or balls in which sulfides are intergrown with variable amounts of carbonates and clays, and

(4) disseminated crystals and globules replacing organic matter.

Examples:

Virtually all known coal deposits contain sulfides, although the amount present is highly variable. Work in several coalfields has demonstrated a correlation of sulfide occurrence with the proximity of overlying marine strata, suggesting that sulfur may have been derived by bacterial reduction of seawater sulfate.

Origin of the Opaque Minerals in Coals :

The sulfides in coal constitute approximately one-half of the total sulfur content of the coal and are believed to have formed, for the most part, through the activity of sulfate-reducing bacteria during diagenesis. Studies of sulfur isotopes support this mode of origin of sulfur (Price and Shieh, 1979). The original sulfur content of the plant matter remains trapped in the organic substances now constituting the coal and was clearly insufficient to account for the bulk of the sulfide present in many coals.

10.11 SKARN DEPOSITS

Mineralogy

The mineralogy of skarn deposits varies widely; hence, generalizations should be regarded with caution. This discussion is confined to skarns that are important as sources of iron, molybdenum, tungsten, copper, lead, zinc, and tin.. Skarns have been classified in several ways. The economic viability of many skarns is based as much upon the gold content as on other metals; hence, many deposits originally classed as one of the types previously listed are now called goldskarns if they contain more than 1 g/ton Au (Meinert, 1989: Theodore, et al., 1991).

Major minerals:

(But highly variable from one deposit to another) magnetite,molybdenite, sphalerite, galena,chalcopyrite, pyrrhotite, pyrite, a resenopyrite, wolframite,scheelite-powellite(fluorescent under UV light.

Associated minerals:

Quartz, various garnets, amphiboles, pyroxenes, calc-silicatcs, olivines, talc, anhydrite (some phases fluorescent under UV light)

Mode of Occurrence:

Skarns (tactites) are composed dominantly of coarsegrained, commonly zoned calc-silicates, silicates and aluminosilicates, and associated sulfides and iron oxides. They form in high-temperature contact metamorphic halos at the junction of intrusions and carbonate-rich rocks or, more rarely, Al- and Si-rich rocks. The occurrence of ore minerals in skarns ranges from massive iron oxides or sulfides in some deposits to disseminated grains and veinlets of sulfides, molybdates, and tungstates in others. Reaction skarns are narrow rims, often rich in Mn-silicates and carbonates, formed between an intrusion and carbonate-rich host rocks. Replacement skarns (ore skarns) are large areas of silicate replacement of carbonate rocks resulting from the passage of mineralizing solutions. These often contain appreciable amounts of Fe, Cu, Zn, W, and Mo

Mineral Associations :

Skarn deposits are typified by compositional banding, an abundance of garnets and calc-silicate minerals, and a wide variation in grain size. The garnets and calc-silicates are often poikiloblastic, with enclosed pyroxenes and ore minerals. The thickness of compositional bands and the size of mineralized areas vary from a few millimeters to hundreds of meters, depending on the nature of the intrusion and its fluid content and the type of host rock. In tungsten-bearing skarns, such as that in Bishop, California, the ore minerals occur as tiny inclusions, grain coatings, narrow veinlets, and occasionally as irregular polycrystalline aggregates up to 10 cm across.

Mineral equilibrium of ore deposirs

(Geothermometry and geobarometry)

Ores are deposited at temperatures and pressures ranging from very high, at deep crustal levels, to atmospheric, at the surface. Some pegmatites and

magmatic segregation deposits have formed at temperatures around lOOOOC and under many kilometres of overlying rock, whilst placer deposits and sedimentary ores have

formed under surface conditions. Most orebodies were deposited between these two extremes. Clearly, knowledge of the temperatures and pressures obtaining during the precipitation of the various minerals will be invaluable in assessing their probable mode of genesis and such knowledge also will be of great value in formulating exploration programmes. In this small volume it is only possible to touch on a few of the methods that can be used.

Fluid inclusions

The nature of fluid inclusions and the principle of this method have been outlined in Chapter 3. Clearly, it is the primary inclusions that must be

examined. Secondary inclusions produced after the mineral was deposited and commonly formed by the healing of fractures will not give us data on the mineral depositional conditions, but their study can be very important in the investigation of certain deposits, e.g. porphyry copper(Chapter14). The filling (homogenization) temperatures of aqueous inclusions (i.e. the temperature at which the inclusion becomes a single phase fluid) indicate the depositional temperature of the enclosing mineral if a correction can be made for the confining pressure and salinity of the fluid. The salinity, in terms of equivalent weight per cent NaCI, can be determined by studying the depression of the freezing point using a freezing stage. Frequently, confining pressures have to be estimated by reconstructing the stratigraphical and structural succession above the point of mineral deposition. This clearly leads to a degree of uncertainty. Pressure corrections increase the homogenization temperatures obtained in the laboratory, so these are still of great value even when uncorrected as they record minimum temperatures of deposition and can be used to map temperature gradients along mineral deposits. Where CO2-rich and H20-rich inclusions coexist, the pressure can be estimated from the filling temperature of the aqueous inclusions and the density of the CO2 inclusions (Groves & Solomon 1969). If the fluid inclusion assemblage indicates boiling at the time of trapping then the depth of formation can be estimated (Haas 1971). However, if boiling did not occur, then the confining pressure must have exceeded the vapour pressure of the fluid, which can be calculated from the salinity and temperature data, giving us a minimum pressure value. Studies on the use of fluid inclusions in geobarometry were reviewed byRoedder & Bodnar (1980).

Processes of Ore Formation

Table (   ) : **Principal theories of ore genesis**

THEORIES OF ORE GENESIS		
Origin Due to Internal Processes		
Magmatic Segregation	Separation of ore minerals by fractional crystallization during magmatic differentiation.	Pt—Cr deposits Bushveld, S.A.Titanium deposit
	Liquid immiscibility. Settling out from magmas of sulfide, sulfide-oxide or oxide melts which accumulate beneath the silicates or are injected into country rocks or extruded on the surface.	Cu-Ni ores of Sudbury, Canada and the nickel extrusives of Kambalda, West Australia.
Pegmatitic Deposition	Crystallization as disseminated grains or segregations in pegmatites.	Li-bearing pegmatites of Kings Mtn. N.C.
Hydrothermal	Deposition from hot aqueous solutions of various sources.	Porphyry Cu-Mo deposits of the W. Cordillera.
Lateral Secretion	Diffusion of ore and gangue forming materials from the country rocks into faults and other structures.	Gold deposits of Yellowknife, B.C. and the Mother Lode, CA.
Metamorphic Processes	Pyrometasomatic (skarn) deposits formed by replacement of wall rocks adjacent to an intrusive.	W deposits at Bishop, CA. Fe deposits Iron MtnUT.
	Initial or further concentration of ore elements by metamorphic processes.	Homestake Au Mine, Lead, South Dakota.

Origin Due to Surface Processes		
Mechanical Accumulation	Concentration of heavy minerals into placer	Placer Au deposits of Alaska and California.
Sedimentary Precipitation	Precipitation of certain elements in sedimentary environments.	Banded Iron Fm.of the Canadian Shield.
Residual Processes	Leaching of soluble elements leaving concentrations of insoluble elements.	Nickel laterites of New Caledonia and Arkansas bauxite.
Secondary or Supergene Enrichment	Leaching of certain elements from the upper part of a mineral deposit and their reprecipitation at depth to produce higher concentrations.	The upper portion of many porphyry copper deposits.
Volcanic Exhalative Process	Exhalations of sulfide-rich magmas at the surface, usually under marine conditions.	Mt. Isa, Aust., Sullivan and Kidd Creek,Canada, Kuroko,Japan.

Current theories of the genesis of ore deposit can be divided into internal (endogene) and external(exogene) or surface processes. It must be understood that more than one mechanism may beresponsible for the formation of an ore body. Example - stockwork porphyry copper deposit at depth (epigenetic) with a syngenetic massive sulfide deposit at the surface.

Depending upon whether an ore deposit formed at the time of and together with the enclosing rock, or was introduced into it by subsequent processes, they are classed as:

Syngenetic - A deposit formed at the same time as the rocks in which it occurs. Ex.

Banded Iron Formation.

Epigenetic - A deposit introduced into the host rocks at some time after they were deposited. Ex. Mississippi Valley-type Deposits

Magmatic Deposits: Those deposits, not including pegmatites that have formed by direct crystallization from a magma. Two types:

- ***Fractional crystallization***–(magmatic segregation) . Any process whereby early formed crystals can not re-equilibrate with the melt. , then, gravitative settling occurswhich is the most important and results from the settling of early formed crystals to the bottom of the magma chamber. Rocks formed in this manner are termed cumulates and are often characterized by rhythmic layering. In ore deposits the alternating layers are often magnetite and/or chromite between layers of silicate . Ex.Bushveld igneous complex.Usually olivine , pyroxene, or plagioclase – rich layers are formed. However, when oxides such as chromite are precipitated , layers of this mineral may develop as in Bushveld igneous complex of south Africa. This enormous layered intrusion is characterized by cumulus magnetite In the upper zone. The chromite layers have been mined for decades, the magnetite now being exploited for its high vanadium content. Another mineral which may be concentrated in this way is ilmenite . Whilest chromite accumulations are nearly all in ultrabasis rocks and to lesser extentin gabbroic or noritic rocks , ilmenite accumulations show an association with anorthosites or gabbros.These striking rock associations are strong evidence for the magmatic origin of the minerals.
- ***Immiscible liquid*** - A different form of magmatic segregation results from liquid immiscibility. Typical example is oil and water. In ore deposits we deal with

silicate and sulfide magmas. As a magma cools, sulfides coalesce as droplets and due to higher density settle out. Most common sulfides are iron sulfides, but nickel, copper and platinum also occur. Ex. Sudbury, Canada. The settling out of the heavier sulfides results in the peculiar net-textured ores often found in many of these deposits.Iron sulphides is the principle constituent of these droplets which are associated with basic and ultrabasic rocks , because sulphur and irn are both more abundant in these rocks than in acid or intermediate rocks. The accumulation of Fe- Ni- Cu sulphide droplets beneath the silicate fraction can produce massive suphide ore bodies. These are overlain by a zone with subordinate silicates enclosed in a network of sulphides – net- textured ore, sometimes called disseminated ore. This zone is , in turn overlain by one of week mineralization which grade up into Overlying peridotite ,gabbro or komatite deponding on the nature of the associated silicatefraction.

Pegmatitic Deposits:

Pegmatites are very coarse grained igneous rocks. They form dike-likemasses a few meters to occasionally 1-2 km in length. Economic ore deposits are associated with granitic pegmatites since felsic magmas carry more water. Residual elements such as Li, Be, Nb, Ta, Sn and U that are not readily accommodated in crystallizing silicate phases end up in the volatile fraction. When this fraction is injected into the country rock a pegmatite is formed. Temperatures of deposition vary from 250-750°C. Pegmatites are divided into simple and complex. Simple pegmatites consist of plagioclase, quartz and mica and are not zoned. Complex have a more varied mineralogy and are strongly zoned. Crystals in pegmatites can be large, exceeding several meters.

Three hypotheses to explain their formation:

A - fractional crystallization

B - deposition along open channels from fluids of changing composition.

C -crystallization of a simple pegmatite and partial to complete hydrothermal Replacement.

Hydrothermal Deposits:

Hot aqueous solutions are responsible for the formation of many ore deposits. Fluid inclusion research indicates most ore forming fluids range in temperature from50°C to 650°C. Analysis of the fluid in inclusions has shown that water is the most important phase and salinities are often much greater than those of seawater.

The chemistry of ore fluids andthe mechanism of deposition of ore minerals remains a subject of hot debate. Arguments boil down to a) source and nature of the solutions , b) means of transport of the metals and c) mechanism of deposition.

There are many different types of fluids circulating through the Earth's crust and these have given rise to a wide variety of hydrothermal ore deposit types that exist in virtually every tectonic setting and have formed over most of Earth history. Juvenile fluids exsolve from magmas, in particular those with felsic compositions, and give rise to granite(*sensulato*) related ore deposits that include porphyry Cu–Mo, skarn and greisen related Sn–W,intrusion linked Fe oxide–Cu–Au, and high sulphidation

Au–Ag ores (discussed in Chapter 2). Metamorphic fluids, derived from volatiles liberated during prograde mineral reactions, are typically aqueo-carbonic in composition and are associated worldwide with orogenic gold deposits that are particularly well developed in Archean and Phanerozoic rocks. Connate fluids formed during diagenesis interact with either reduced (forming Pb–Zn dominant ores) or oxidized (forming Cu dominant ores) sedimentary environments.These fluids are implicated in the formation of Mississi.Valley type (Pb–Zn) and stratiform sediment-hosted copper ores. Circulation of near surface meteoric waters can dissolve labile constituents such as the uranyl ion, giving rise to a variety of different sediment-hosted uranium deposits. Finally, sea water circulating through the oceanic crust in the vicinity of (ridge-related) fracturing and volcanic activity is vented onto the sea floor as black smokers, providing a modern analogue for the formation of Cu–Zn-dominated VMS deposits. Similar exhalative processes also occur in different tectonic settings and with different metal assemblages, giving rise to sediment hosted، Zn–Pb-dominated SEDEX type deposits Formation of hydrothermal ore deposits is linked not only to the generation of significant volumes of fluid in the Earth's crust, but also to its ability to circulate through rock and be focused into structural conduits (shear zones, faults, breccias،etc.) created during deformation. The ability of hydrothermal fluids to dissolve metals provides the means whereby ore-forming constituents are concentrated in this medium. Precipitation of metals is governed by a reduction in solubility which can be caused by either compositional changes (interaction between fluid and rock, or mixing with another fluid), or changes in the physical parameters P and T) of the fluid itself. Economically viable hydrothermal ore deposits occur when a large volume of fluid with a high metal-carrying capacity is focused into a geological location that is both localized and accessible, and where efficient precipitation mechanisms can be sustained for a substantial period of time.

Metamorphic/Metasomatic Deposits:

Pyrometasomatic deposits (skarns) developed at the contact of plutons and host rock. Generally, host rock is a carbonate and new minerals formed are the calc- silicates diopside, andradite and wollastonite. Temperatures involved are thought to be 300-500°C, but pressure is probably quite low. Three stage process:

1. Recrystallization
2. Introduction of Si, Al, Fe, Mg
3. Hydration and introduction of elements associated with volatile fraction .

Other metamorphic processes are relatively unimportant, but hydration/dehydration during regional metamorphism may concentrate metals at the metamorphic front. Sodic metasomatism of K-spar is thought to have been important in the concentration of gold at Kalgoorlie. Conversion of feldspar from K-spar (1.33A) to Na plag (.97A) resulted in the expulsion of gold (1.37A) which could no longer be accommodated in the feldspar lattice.

Mechanical accumulation: Placer deposits

In geology, a **placer deposit** or **placer** is an accumulation of valuable minerals formed by gravity separation during sedimentary processes. The name is from the Spanish word *placer*, meaning "alluvial sand". Placer mining is an important source of gold, and was the main technique used in the early years of many gold rushes, including the California Gold Rush. Types of placer deposits include alluvium, eluvium, beach placers, and paleoplacers. Placer materials must be both dense and resistant to weathering processes. To accumulate in placers, mineral particles must be significantly denser than quartz (whose specific gravity is 2.65), as quartz is usually the largest component of sand or gravel. Placer environments typically contain black sand, a conspicuous shiny black mixture of iron oxides, mostly magnetite with variable amounts of ilmenite and hematite. Valuable mineral components often occurring with black sands are monazite, rutile, zircon, chromite, wolframite, and cassiterite. Since sulphides break up readily and decomposc they are rarely concentrated into placers.

Placer deposits have formed throughout geological time, but most are of Tertiary and Recent age. The majority of placer deposits are small and often ephemeral as they form on the earth's surface usually at or above the local base level, so that many are removed by erosion before they can be buried. Most placer deposits are low grade, but can be exploited because they are loose, easily worked materials which rcquire no crushing.

Residual placers

These accumulate immediately above a bedrock source (e.g. gold or cassiterite vein) by the chemical decay and removal of the lighter rock materials and they may grade downwards into weathered veins as in some tin areas of Shaba. In residual placers chemically resistant light minerals (e.g. beryl) may also occur.

Residual placers only form where the ground surface is fairly flat; when a slope is present, creep will occur and eluvial placers will be generated (Fig. 18.1). Residual placers formed over carbonatites are important as producers of apatite, e.g. at Jacupiranga, Brazil; SokIi, Finland (Notholt 1979) and Sukulu, Uganda (Reedman 1984). They are sources and potential sources of niobium, zircon, baddeleyite, magnetite and other minerals. These residual placers have often formed on carbonatites which are themselves subeconomic.

Eluvial placers

These are formed upon hill slopes from minerals released from a nearby source rock. The heavy minerals collect above and just downslope of the source and the lighter non-resistant minerals are dissolved or swept downhill by rain wash or are blown away by the wind. This produces a partial concentration by reduction in volume, a process which continues with further downslope creep. Obviously, to yield a workable deposit this incomplete process of concentration requires a rich source. In some areas with eluvial placers, the economic material has accumulated in pockets in the bedrock surface, e.g. cassiterite in potholes and sinkholes in marble in Malaysia.

Alluvial placers :

Alluvial placers are those formed in river or stream sediments. Typical locations for alluvial gold placer deposits are on the inside bends of rivers and creeks; in natural hollows; at the break of slope on a stream; the base of an escarpment, waterfall or other barrier. Alluvial placers are formed by the deposition of dense particles at a site where water velocity remains below that required to transport them further. To form a placer deposit, the particles desired must show a marked density contrast with the gangue material, which is able to be transported away from the trap site.

It is well known that the heavy mineral fraction of a sediment is much finer grained than the light fraction (Selley 1976). There are several reasons for this. Firstly, many heavy minerals occur in much smaller grains than do quartz and feldspar in the igneous and metamorphic rocks from which they are derived. Secondly, the sorting and composition of a sediment is controlled by both the density and size of the particles, known as their hydraulic ratio. Thus a large quartz grain requires the same current velocity to move it as a small heavy mineral. Clearly, if we have a very rapid flow all grains of sand grade will be in motion, but with a slackening of velocity, the first materials to be deposited will be large heavy minerals, then smaller heavy minerals, plus large grains of lighter minerals. If the velocity of the transporting current does not drop any further then a heavy mineral concentration will be built up. For this reason such concentrations are developed when we have irregular flow and this may occur in a number of situations- always provided a source rock is present in the catchment area.

Sedimentary precipitation

Banded iron formation

Banded iron formations (also known as **banded ironstone formations** or **BIF**s) are distinctive units of sedimentary rock that are almost always of Precambrian age. A typical BIF consists of repeated, thin layers (a few millimeters to a few centimeters in thickness) of silver to black iron oxides, either magnetite (Fe_3O_4) or hematite (Fe_2O_3), alternating with bands of iron-poor shales and cherts, often red in color, of similar thickness, and containing microbands (sub-millimeter) of iron oxides.[1] Some of the oldest known rock formations, formed over 3,700 million years ago, include banded iron layers. Phanerozoic ironstones generally have a different genesis. Banded iron

beds are an important commercial source of iron ore . The conventional concept is that the *banded iron* layers were formed in sea water as the result of oxygen being released by photo synthetic cyanobacteria, combining with dissolved iron in Earth's oceans to form insoluble iron oxides, which precipitated out, forming a thin layer on the substrate, which may have been anoxic mud (forming shale and chert). It is assumed that initially the Earth started out with vast amounts of iron dissolved in the world's acidic seas.Eventually, as photosynthetic organisms generated oxygen, the available iron in the Earth's oceans was precipitated out as iron oxid.

Volcanic Exhalative Deposits:

Some ore depositsoften show spatial relationships to volcanic rocks.They are conformable with the host and frequently banded suggesting sedimentary processes. Principal constituent is pyrite with lesser chalcopyrite, aphalerite, galena, barite and Ag-Au. These were thought until the late 60’s to be epigenetic, but it is now realized they are syngenetic. They show three distinct end members:

1. Cyprus type - Associated with mafic volcanics and ophiolite sequences. Found in Spreading centers and back arc basins. Consist predominantly of pyrite with lesser chalcopyrite. Typifie by the Cyprus pyrite-cu ores.
2. Besshi type - Associated with basaltic to dacitic volcanism. Thought to form during the initial stages of island arc formation. Many Besshi type deposits occur in Precambrian rocks and these may have been generated in entirely different tectonic settings. Pyrite dominant, but chalcopyrite and sphalerite very common.

Typified by many of the volcanogenic deposits of Canada.

2. Kuroko type - Associated with dacitic to rhyolitic volcanics. Form during the waning stages of island arc volcanism. Pyrite occurs, but is not dominant Usually galena or sphalerite are predominate with lesser chalcopyrite and tetrahedrite. Also significant silver in this type. Typified by the Kuroko deposits. Although it is agreed ores are associated with volcanism the source of the ore bearing solutions continues to be debated. Many feel ore fluids are of magmatic origin, but others feel they are merely convecting seawater.

Relation between mineralization and plate tectonics

Mining geologists have for many decades attempted to relate various types of mineralization to large scale crustal structures. When relating the genesis of ore bodies to major tectonic features, such as island arcs and continental_mountain chains, it is essential to know the age relations between the mineral deposits and their host rocks; that is, whether the ores are syngenetic and thus part of the stratigraphical sequence, or whether they are epigenetic and therefore younger, perhaps much younger, than their host rocks. We now know a great deal concerning plate tectonic development during the Phanerozoic; Evidence for similar activity during the Proterozoic is also abundant and, for many, Convincing. Plate convergence and spreading centres are among the important features that control the global location of mineral deposits.

There are six tectonic settings discussed by Mitchell & Reading, which are:

1 - interior basins, intracontinental rifts and aulacogens.

2 - Oceanic basins and rises.

3 - Passive continental margins.

4 - Subduction-related settings.

5 - Strike-slip settings.

6 - collision-related settings.

1. Interior basins, intracontinental rifts and aulacogens

There are two types of sedimentary basin within continental interiors: large basins often over1000 km across, and relatively narrow, fault bounded rift valleys.

Continental interior basins:

These may contain entirely continental sediments, much of which may have been deposited in large lakes, e.g. the Chad Basin in Africa (600000Km2), and the Eyre Basin, Australia . The Chad Basin contains up to 2 km of Mesozoic and Tertiary sediments.

In some of these the marine transgression is accomp anied by mineralization, e.g. the Permian Kupferschiefer of northern Europe and the late Proterozoic Central African Copper belt. Witwatersrand continental basin (proterozoic) in southern Africa with their important gold Mineralization were developed ,besides the Huronian Supergroup with the uraniferous conglomerates of Blind River (ElliotLake),, and those of the Athabasca (Canada) and Alligator River (Australia) successions with their unconformity-associated uranium deposits.Phanerozoic intracontinental basins are often important for thcir evaporite deposits,which are important for potash and soda production, such as:

- Permian Zechstein evaporites of Europe.
- The Devonian evaporites of Elk Point Basin, Canada.
- Evaporites of the Elk Point Basin of western Canada.
- The Silurian evaporites of the Michigan Basin.
- Platform carbonates are present around some basins which host lead-zinc
- mineralization, e.g. At margin of the Elk Point
- Sandstone uranium-type deposits developed in the Wyoming and Colorado
- Basins .

* These basins are gas, oil and coal producers.

Hot spot-associated mineralization

The triple junction by the shoulder of Brazil is thought to have been generated by the Niger Mantle Plume (Fig. 22.4). Plumes may cause melting of the continental crust forming granite intrusions. e.g. the Cabo Granite of Brazil. **Now the large** tin-tungsten provinces are associated with subduction zones throughout the world.

The huge granite intrusion of the Bushveld Complex, and that of the Stillwater Complex, USA have been attributed to hot spot activity in an anorogenic setting.

Mineralization associated with continental rifting

The initial stage of graben development is marked by deeply penetrating faults forming pathways to the mantle and giving rise to volcanism. This is usually of alkaline type, sometimes with the development of carbonate lavas and intrusives and occasionally kimberlites (Fig. 23.3). Erosion of these may lead to the formation of soda deposits (e.g.

Lakes Natron and Magadi in East Africa) and the intrusive carbonatites may carry a number of metals of economic interest (Chapter 9) as well as being a source of phosphorus and lime.

2 . Ocean basins

The later stages of rifting lead on to the development of embryonic oceans, such as the Red Sea. With further extension of the crust and the commencement of continental drift and tensional faulting will combine to thin the crust along the graben. At some stage during this process an opening to the sea may initiate marine conditions. Evaporite series of great thickness may form in as observed along the Atlantic coastlines (Rhine Graben) and the Miocene of the Red Sea region. These evaporites contain halite as well as gypsum and therefore have a double economic importance. Along its median zone, pelagic sediments are forming without leading to phosphorite development. There is strong evidence that many Cyprus-type sulphide deposits (Cupriferous pyrite ore bodies)are formed during this process of crustal birth. Hydrothermal mineralization with the development of copper, zinc, silver and mercury has been reported from oceanic ridges in the Atlantic and Indian Oceans. Cupriferous pyrite mineralization of stockwork-type, which occurs in metabasalts, has been reported by Bonatti *et al. (1976) from the Mid-Atlantic Ridge, t*hey put forward evidence that it was generated by sea water solutions circulating through the oceanic crust.

3 . Passive continental margins

As ocean spreading gradually forces two continents apart, both sides of the original rift become passive margins (also termed Atlantic type), with the development of a *continental shelf*, bounded oceanwards by a slope and landwards by a shoreline or an epicontinental sea. shelves often covered with substantial platform carbonate successions, and these can be hosts for base metal deposits of both epigenetic and syngenetic nature (so-called Mississippi Valley-type,Irish-type and Alpine-type deposits)

A number of small, stratiform, sandstone-hosted copper and lead-zinc deposits occur in the Cretaceous along the western edge of Africa from Nigeria to Namibia.

manganese deposits occur just above an unconformity and were formed under shallow marine conditions on shelf areas. Passive continental margins that have suffered marine transgressions are also important for phosphorite deposits. Many workers now favour a continental shelf environment for the deposition of the Proterozoic Superior-type BIF. Beach placer deposits are developed along the trailing edges of many continents,eg. the diamond placers Of the Namibian coast, the rutile-zircon-monazite ilmenite deposits of the eastern and western coasts of Australia, etc.

Metallogenic provinces and epochs

It has long been recognized that specific regions of the world possess a notable concentration of deposits of a certain metal or metals and these regions are known as metallogenic provinces. Such provinces can be delineated by reference to a single metal (Figs 1-3) or to several metals or metal associations.

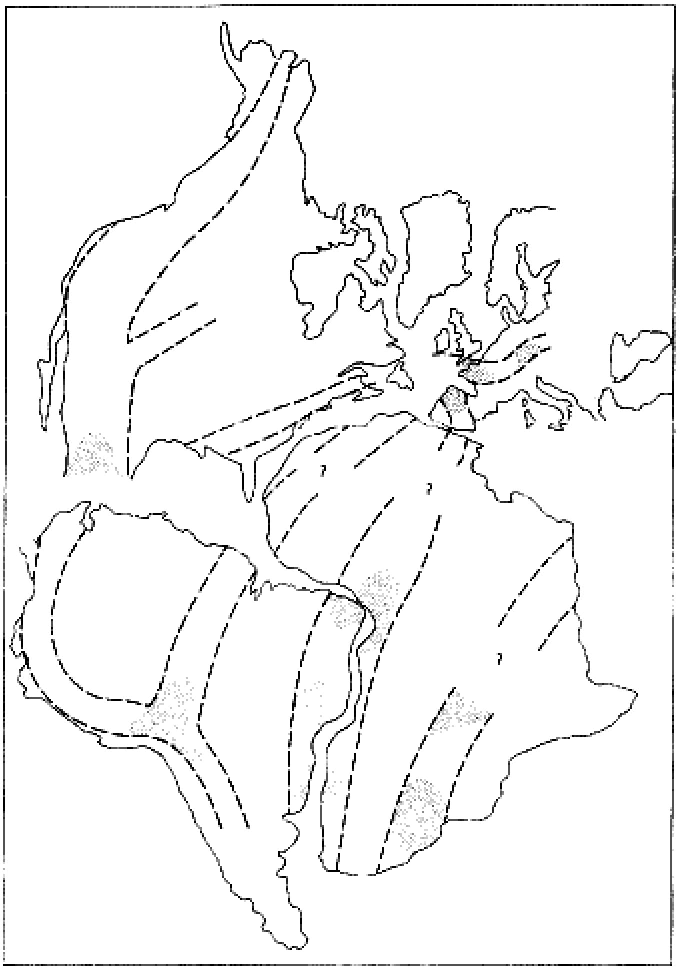


Fig. 1. Tin belts on continents around the Atlantic Ocean. Dotted areas indicate concentrations of workable deposits. (Modified from Schuiling 1967

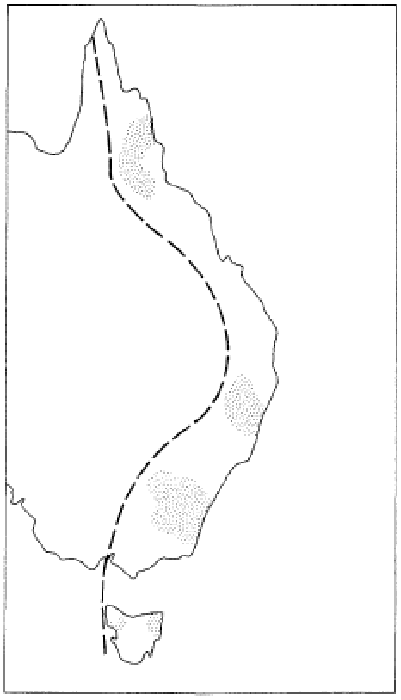


Fig.2. The Palaeozoic tin belt of eastern Australia.The principal fields are shown with dotted ornamentation. (Modified from Hills 1953.)

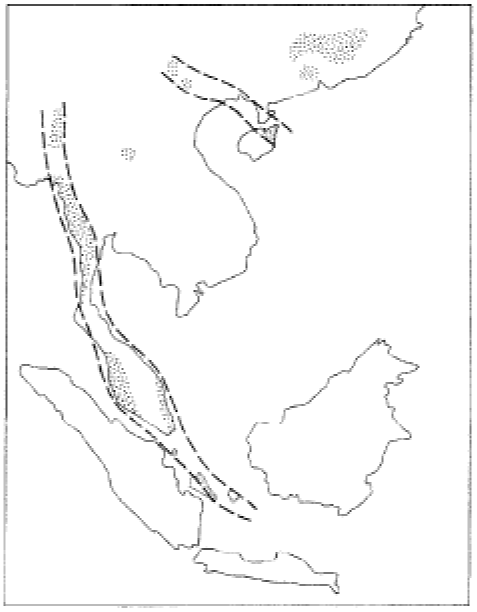


Fig.3. Tin belts and fields of south-eastern Asia. These form the so-called tin girdle of south-eastern Asia.

In the latter case, the metallogenic province may show a zonal distribution of the various metallic deposits (Fig. 4). The recognition of metallogenic provinces has usually been by reference to epigenetic hydrothermal deposits.

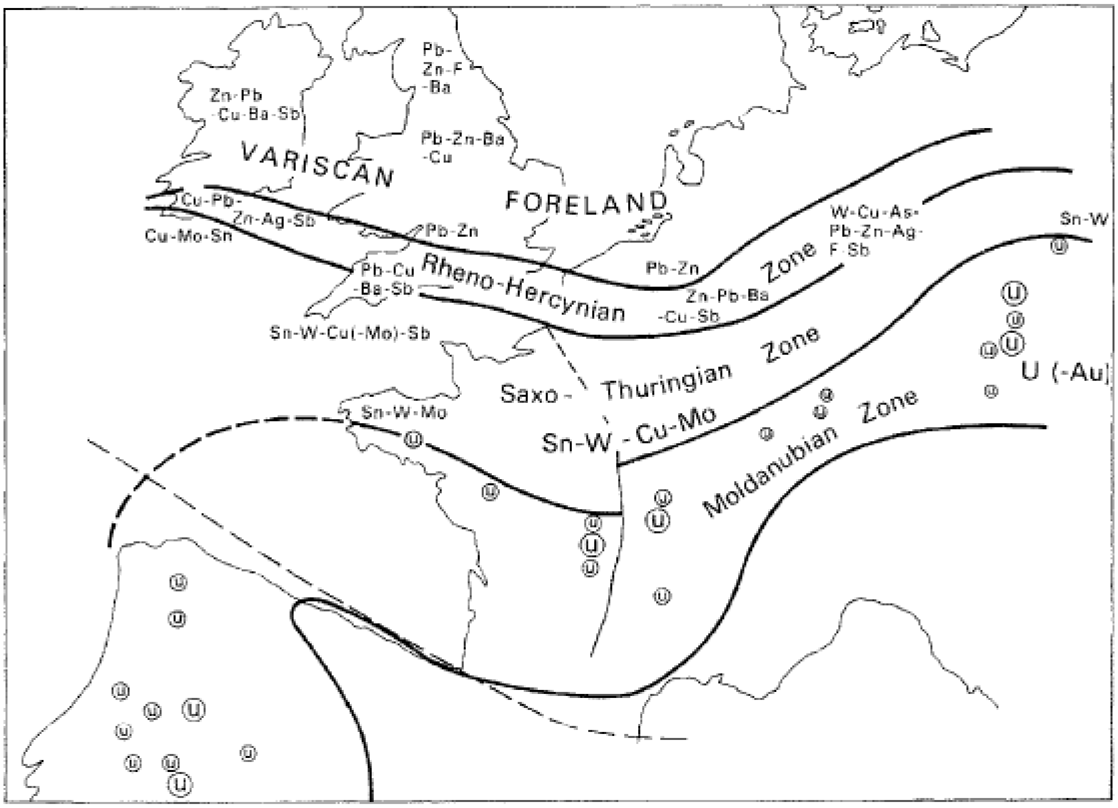


Fig. 4 . Regional metal zonation of epigenetic deposits in the Variscan Metallogenic Province of north-west Europe. (Evans 1976a and Cuney 1978.) Sizes of symbols in Moldanubian Zone and Spain indicate relative sizes of uranium deposits.

Within a metallogenic province there may have been periods of time during which the deposition of a metal or a certain group of metals was most pronounced. These periods arc called metallogenic epochs.

in Fig. 4 the principal epochs of epigenetic mineralization were Hercynian (end Carboniferous to early Permian) and Saxonian (middle Triassic to Jurassic). The orogenic events in this belt culminated about the end of the Carboniferous

and the Saxonian mineralization and associated vulcanicity is post-orogenic.

Metallogenic provinces and epochs of tin mineralization

Tin deposits are an excellent example of an element restricted almost entirely from the economic point of view to a few metallogenic provinces. Those are shown in Figs 1- 3. Even more striking is the fact that most tin mineralization is post-Precambrian and confined to certain well-marked epochs. Equally striking is the

strong association of these deposits with post tectonic granites. Among tin deposits of the whole world, 63.1%are associated with Mesozoic granites, 18.1% with Hercynian (late Palaeozoic) granites, 6.6% with Caledonian (mid-Palaeozoic) granites and 3.3% with Precambrian granites.

Some other examples of metallogenic epochs and provinces

Banded iron formation

These rocks, ofwhich the commonest facies is a rock consisting of alternating quartz and hematite-rich layers, are virtually restricted to the Precambrian. They occur in the oldest (> 3760 Ma old) western Greenland sediments and in most

1900 Ma ago, in early Proterozoic basins or geosynclines situated near the boundaries of the Archaean cratons.

Nickel sulphide deposits

These deposits are almost entirely Precambrian in age and are mainly restricted to a few Archaean greenstone belts in Ontario, Manitoba and Ungava (Canada); the Western Australian Shield; the northern part ofthe Baltic Shield; and in Zimbabwe. They show, therefore, a good development of metallogenic provinces, but there is considerable evidence that those with mantle-derived sulphur are confined to the Archaean and early Proterozoic

Trace element provinces

Burnham (1959) showed that the major ore deposits of the south-western USA lie in provinces outlined by greater than average trace element content in the crystal lattices of chalcopyrite and sphalerite. The most useful trace elements were found to be cobalt, gallium, germanium, indium, nickel, silver and tin. These exhibit well-defined geographical distributions (Fig. 5). Burnham suggested that the variations in trace element content are probably due to variations in the compo-sitions of the fluids during crystal growth. and they are of deep-seated origin.

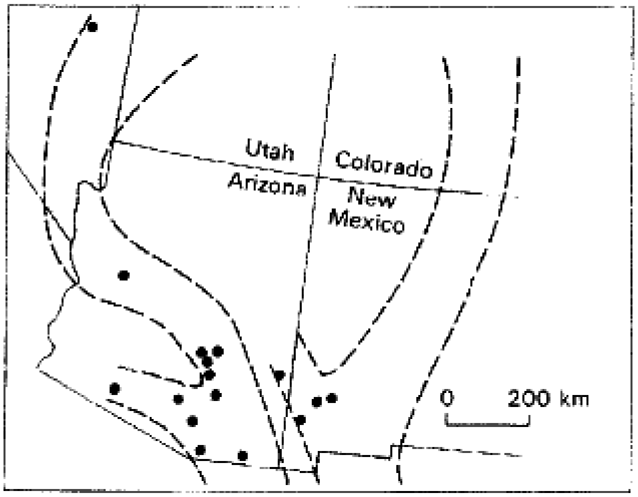


Fig. 5 Trace element metallogenic provinces in the south-western USA.