Petrology of Ore Deposits

An Introduction to Economic Geology

Introductory Definitions

- Ore: a metalliferous mineral, or aggregate mixed with gangue that can me mined for a profit
- Gangue: associated minerals in ore deposit that have little or no value.
- Protore: initial non-economic concentration of metalliferous minerals that may be economic if altered by weathering (Supergene enrichment) or hydrothermal alteration

Economic Considerations

- Grade: the concentration of a metal in an ore body is usually expressed as a weight % or ppm.
- The process of determining the grade is termed “assaying”
- 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.

Example Economic Trends

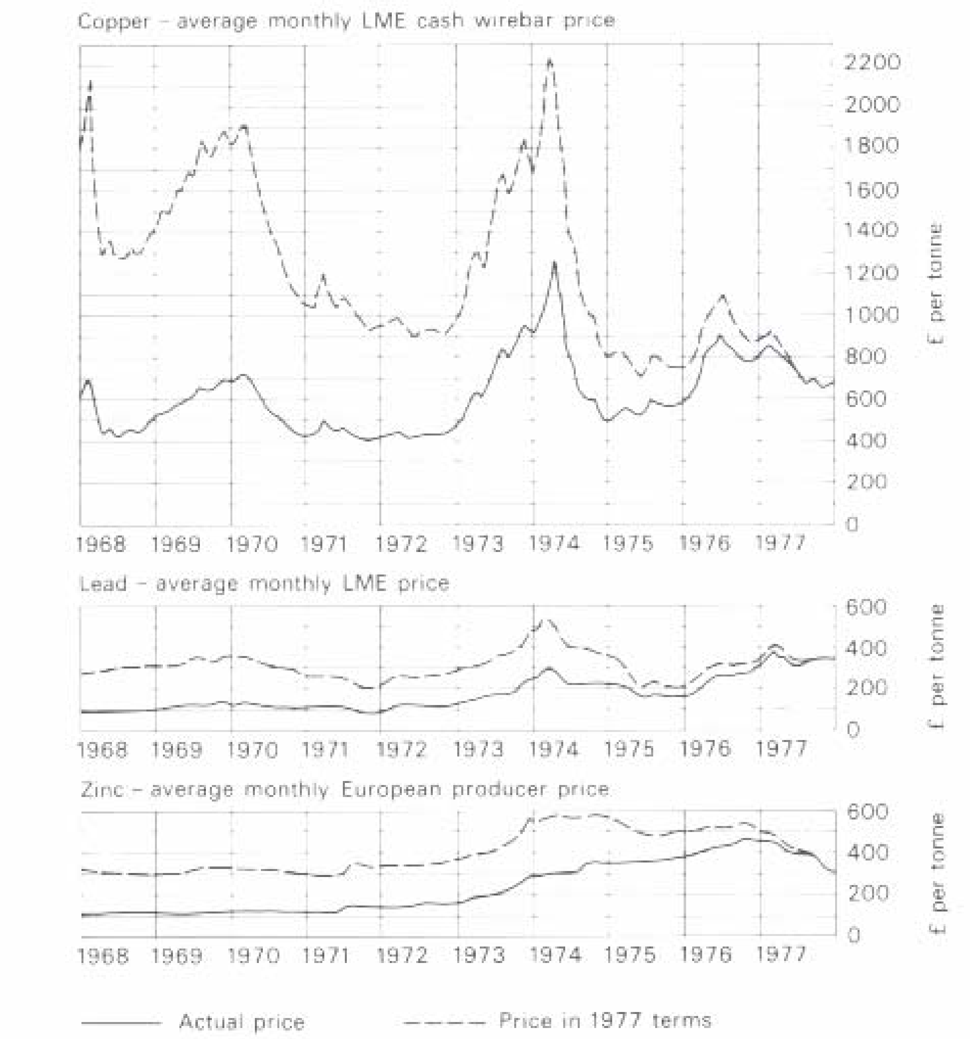


Fig. 1.1. Average prices of copper, lead and zinc during a recent decade showing actual prices, and prices in 1977 terms. (Modified from an RTZ annual report.)

Economy of Scale

- 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 same amount of metal
- Outputs of 40,000 metric tons per day are not uncommon
- 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: ore body is so thoroughly studied and understood that we can be certain of its geometry, average grade, tonnage yield, etc.
- Probable ore: ore body is somewhat delineated by surface mapping and some drilling. The geologists is reasonably sure of geometry and average grade.
- Possible Ore: 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 Metals

- Precious Metals: gold (Au), silver (Ag), platinum 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, zirconium, etc.
- Fissionable metals: uranium (U), thorium (Th), radium (Ra).

Concentration Factors

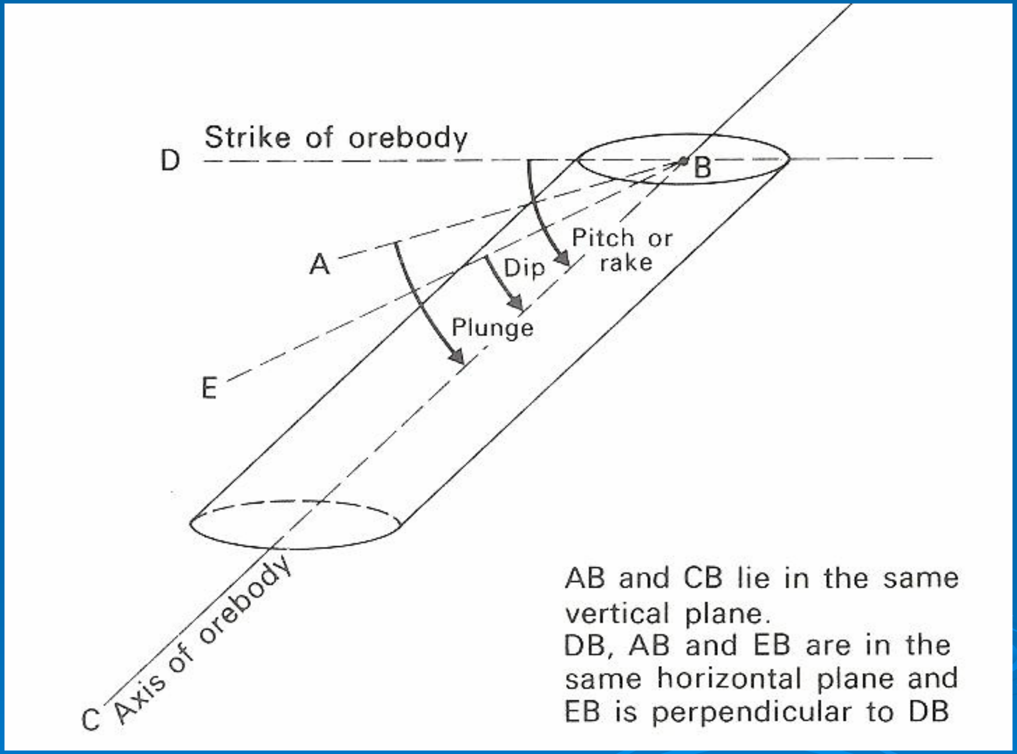
Metal	Crustal Abundance (%)	Ave. Exploitable Grade (%)	Concentration Factor
Aluminum (Al)	8	30	3.75
Iron (Fe)	5	25	5
Copper (Cu)	0.005	0.4	80
Nickel (Ni)	0.007	0.5	71
Zinc (Zn)	0.007	4	571
Manganese (Mn)	0.09	35	389
Tin (Sn)	0.0002	0.5	2500
Chromium (Cr)	0.01	30	3000
Lead (Pb)	0.001	4	4000
Gold (Au)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

Nature & Morphology of Common Ore Deposits

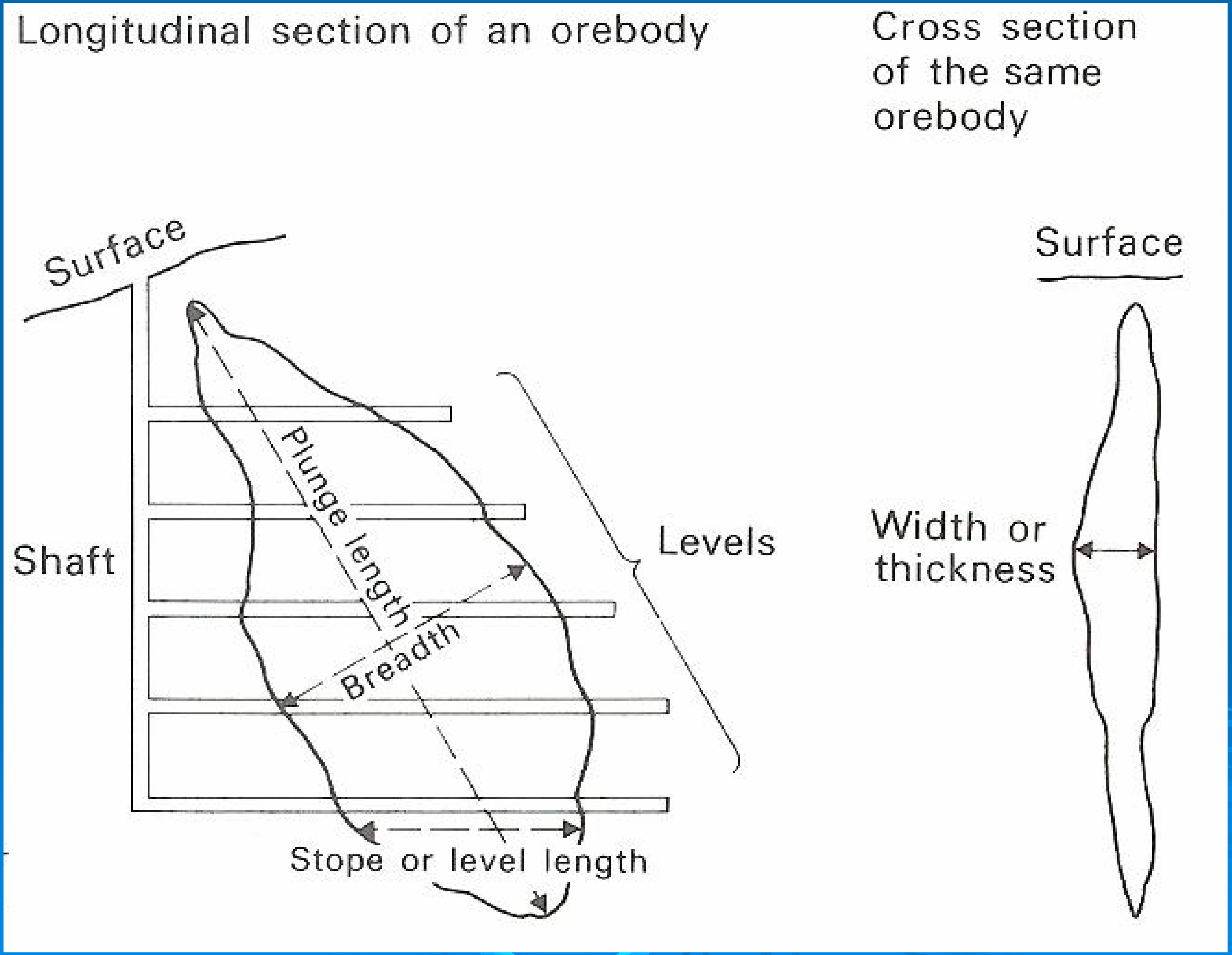
- Syngenetic: ore body forms at the same time as the host rock body
  - Ex. Fe-rich cement in a stratigraphic interval.
- Epigenetic: ore forms at some later time after the host rock body has formed
  - Ex. Gold-bearing vein cutting across a granite pluton.

Geometric Measures of an 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.



Geometric Measures cont.



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; also termed “Skarn”

Tabular Discordant Example

- Vein occupying a normal fault.
- Flat: impermeable shale is a barrier to hydrothermal fluid.

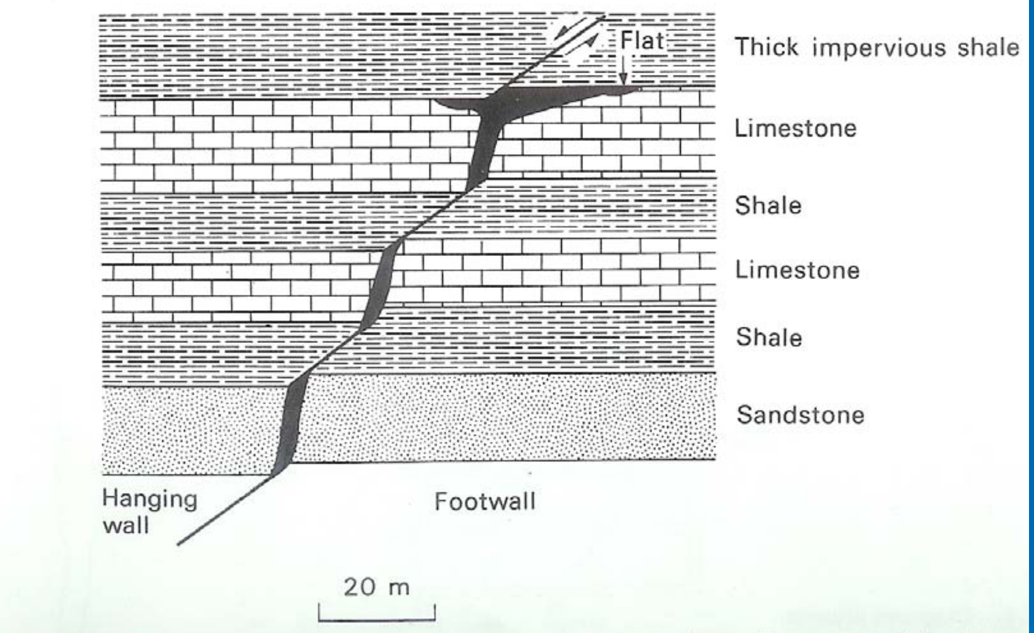


Fig. 2.2. Vein occupying a normal fault and exhibiting pinch-and-swell structure, giving rise to ribbon ore shoots. The development of a flat beneath impervious cover is also shown.

Tabular Veins Controlled by Fracture Systems

Conjugate Fractures

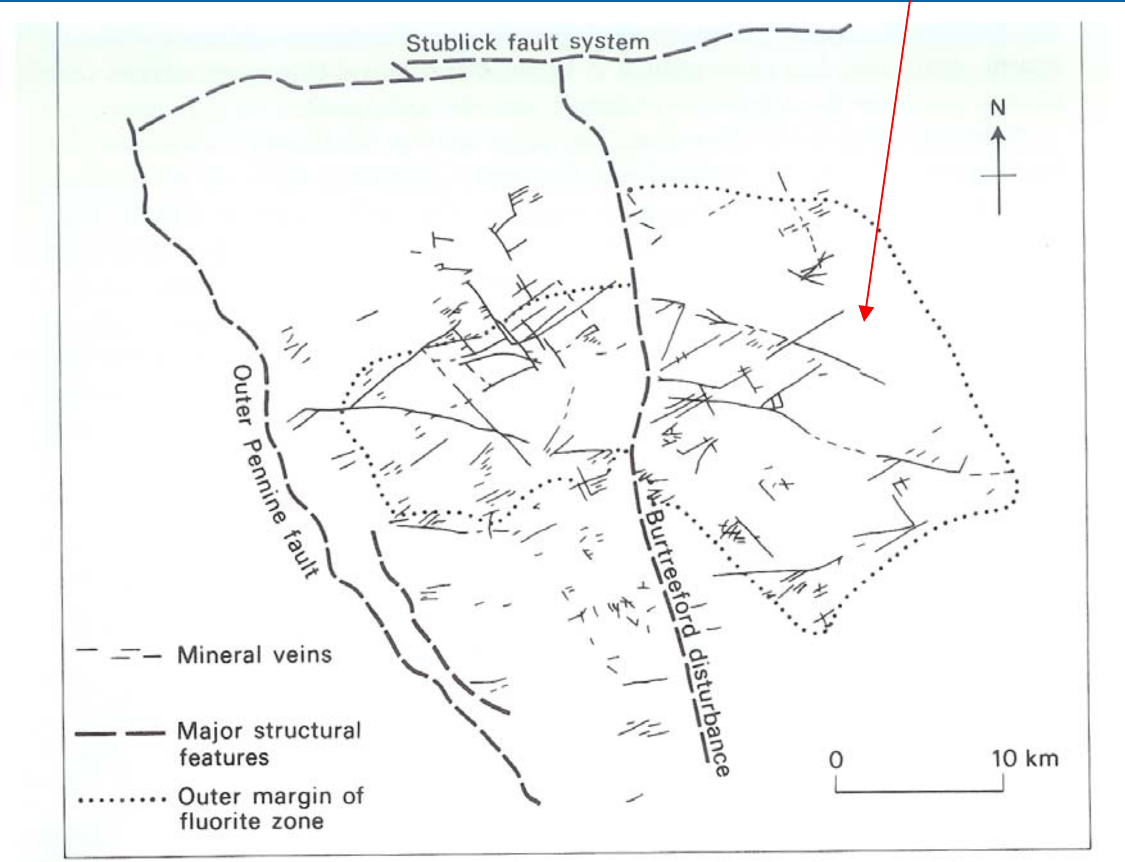
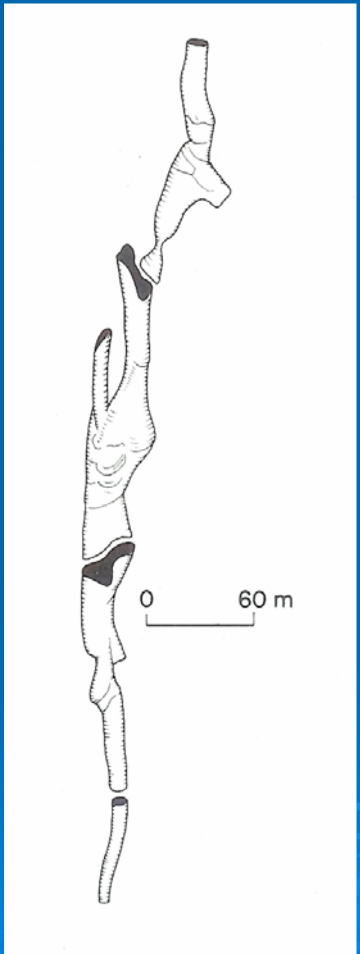


Fig. 2.4. Vein system of the Alston block of the Northern Pennine Orefield, England. Note the three dominant vein directions. (Modified from Dunham 1959.)

Tubular Ore Body Example

- Tubular ore body: this example from the Vulcan tin pipe, Herberton, Queensland, Australia
- Grade averages 4.5% tin
- The Spanish word "manto" has mistakenly been used to describe tubular ore bodies (manto actually means "blanket")



Disseminated Stockworks

- 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

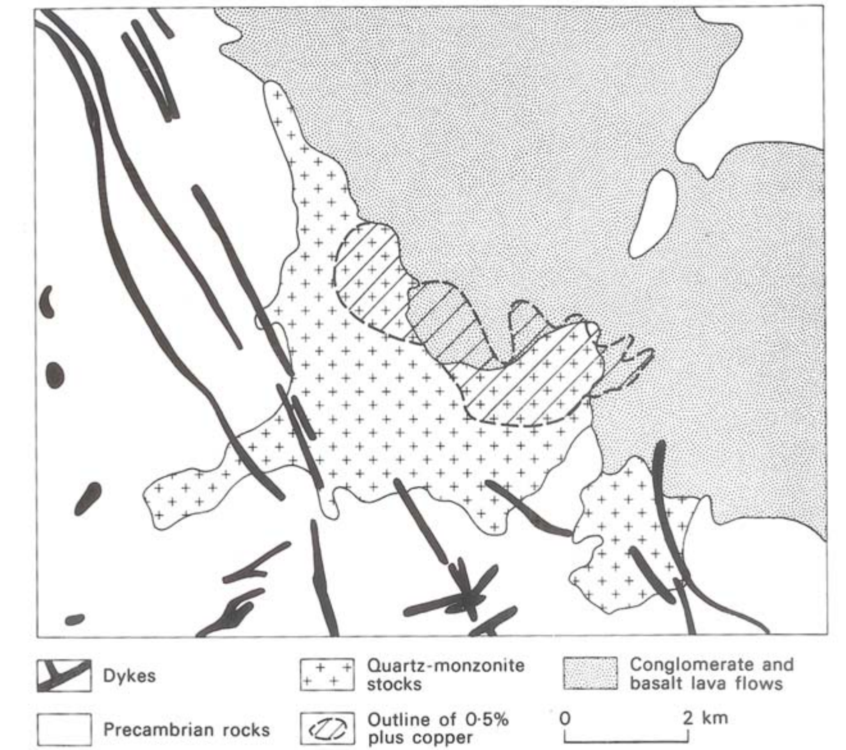
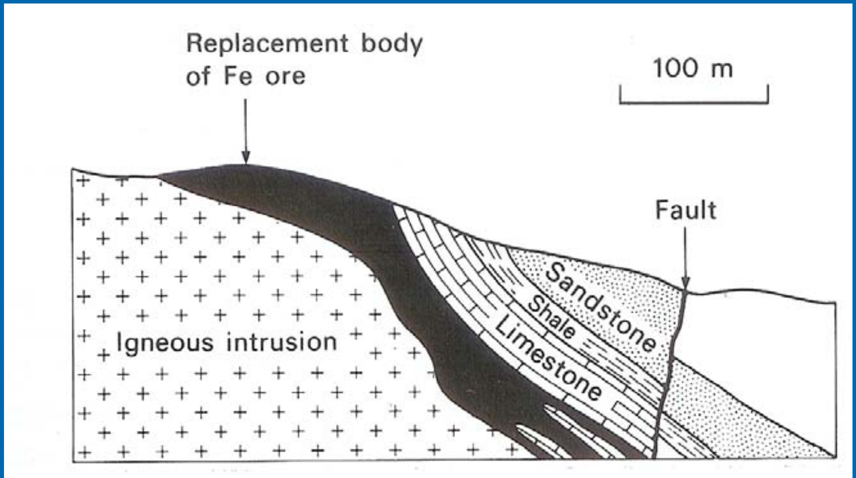


Fig. 2.7. Generalized geological map of the Bagdad mine area, Arizona. (Modified from Anderson 1948.)

Skarn Replacement Ore Body

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



Iron Springs, Utah

Concordant Ore Bodies

- Sedimentary Host Rocks
  - Limestone Hosts
  - Argillaceous (shale) Hosts
  - Arenaceous (sandstone) Hosts
  - Rudaceous (conglomerate) Hosts
  - Chemical Sedimentary Hosts
- Igneous Host Rocks
  - Volcanic Hosts
  - Plutonic Hosts
- Metamorphic Host Rocks
- Residual Deposits
- 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

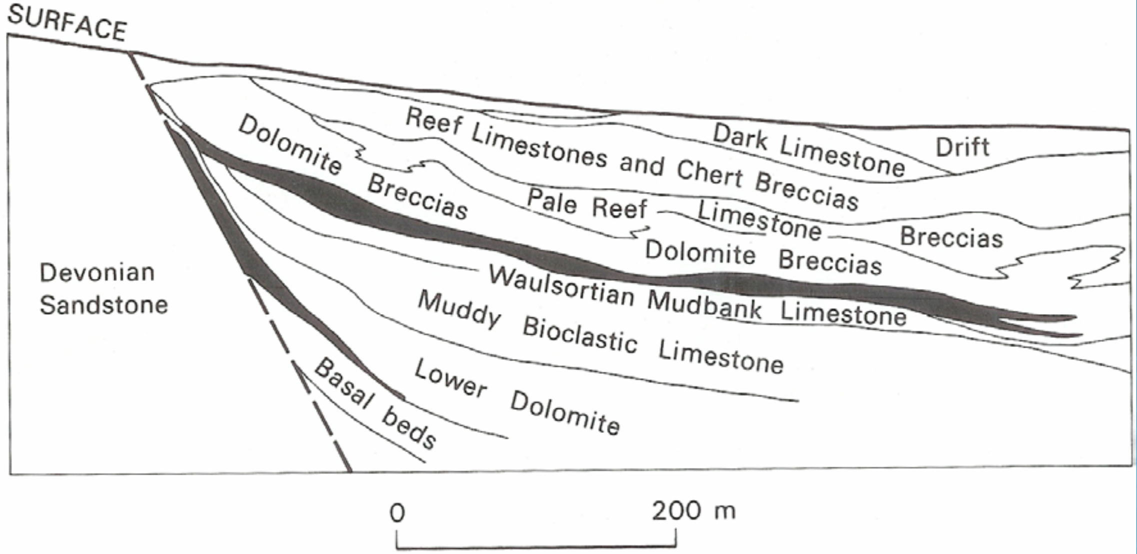


Fig. 2.10. Vertical section through the G zone at Silvermines, Co. Tipperary, Ireland. The orebodies are shown in black. (After Taylor & Andrew 1978.)

Sedimentary Argillaceous Host

- Shales, mudstones, argillites and slates are important hosts for ore bodies that are remarkably continuous and extensive
- The upper Permian of Kupferschiefer, Germany, contains an ore body 1 meter thick with an areal extent of 130 km^2
- The world's largest lead-zinc sulfide body is in Sullivan, BC in Precambrian Argillites
- 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.

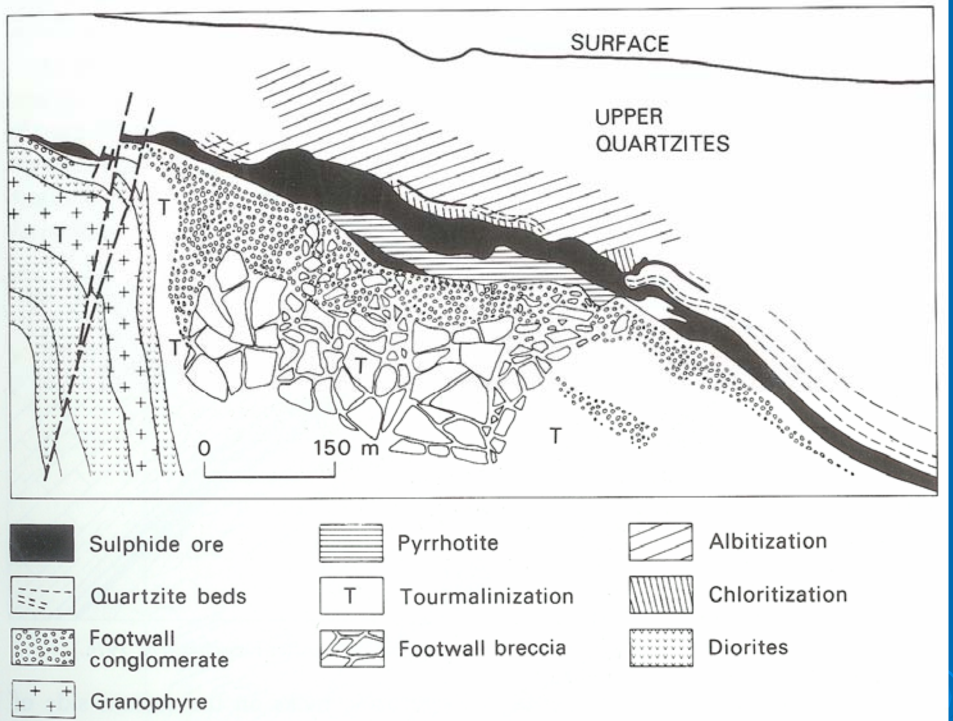


Fig. 2.11. Cross section through the ore zone, Sullivan Mine, British Columbia. (After Sangster & Scott 1976.)

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.

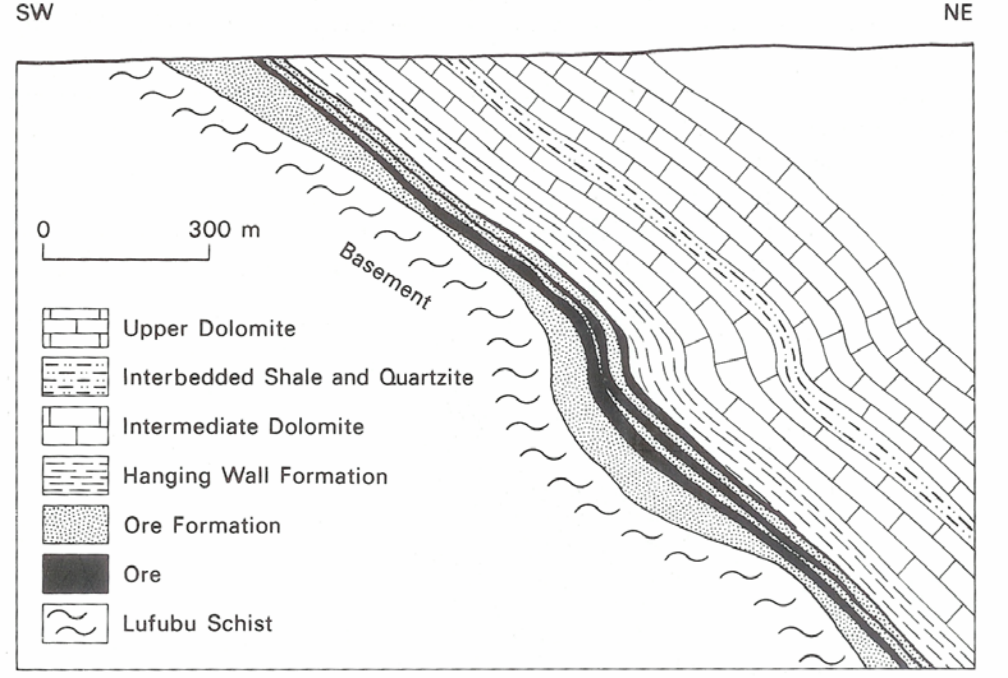
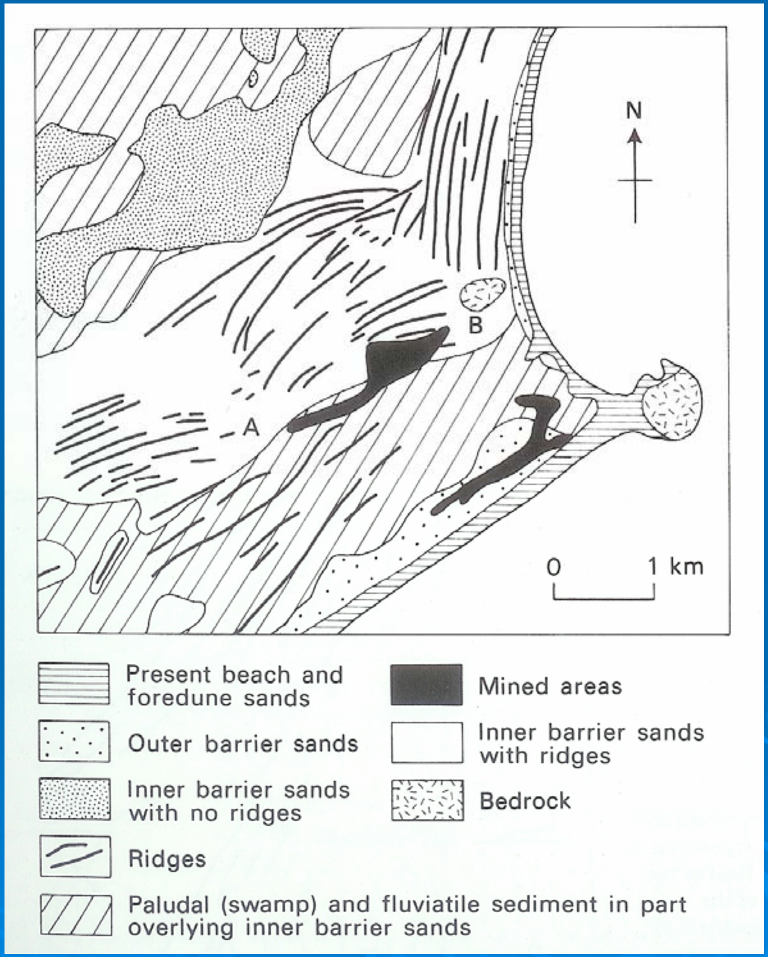


Fig. 2.12. Cross section through the Mufulira orebodies, Zambia. (After Fleischer *et al.* 1976.)

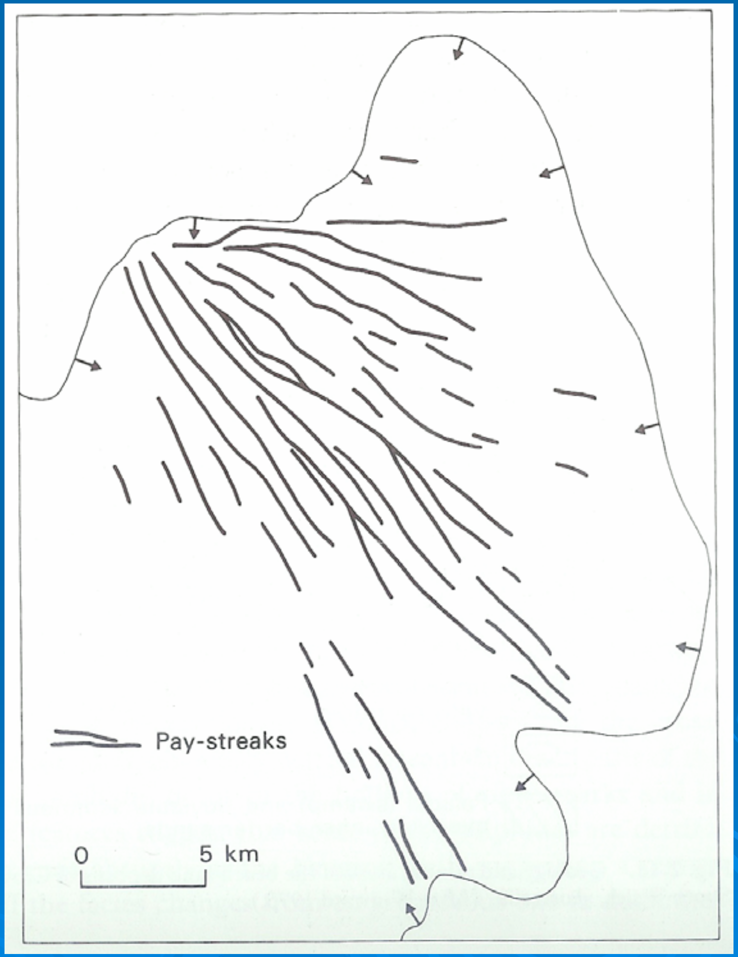
Placer Deposits

- Mechanical concentrations of high-density detrital minerals may accumulate in sands as ore deposits
- Placer deposits may yield magnetite, ilmenite, rutile 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 appear throughout 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:
  - Vesicular filling deposits
  - 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 native copper deposits 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:
  - Zn-Pb-Cu
  - Zn-Cu
  - Cu

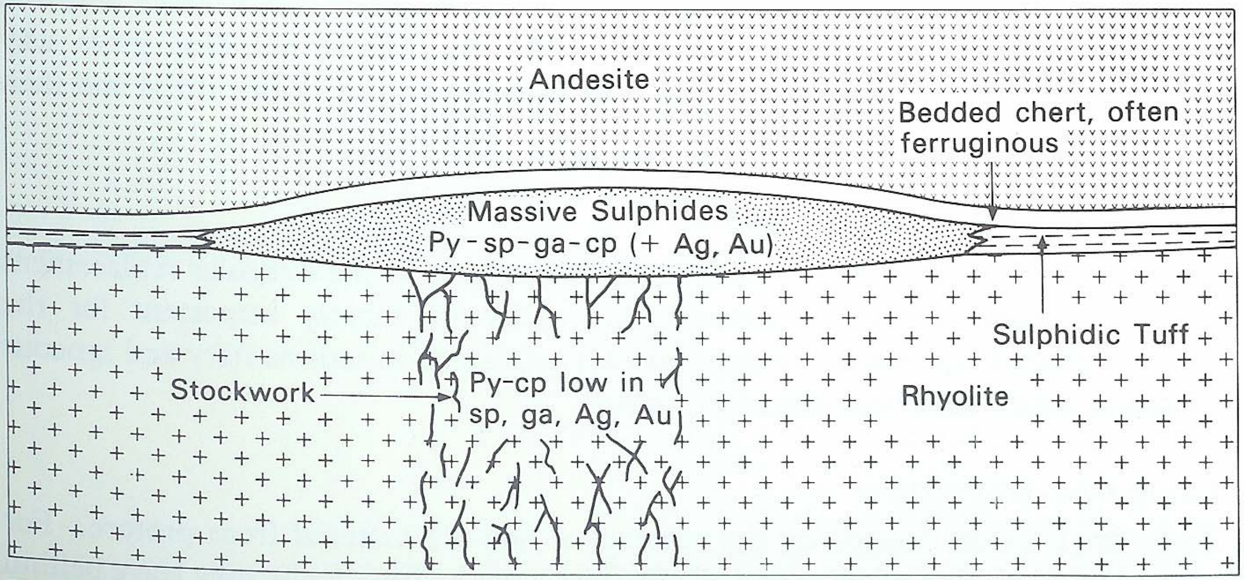


Fig. 2.15. Schematic cross section through an idealized volcanic massive sulphide deposit showing the underlying feeder stockwork and typical mineralogy. Py = pyrite, sp = sphalerite, ga = galena, cp = chalcopyrite.

Massive Sulfide Deposits …

- The most important 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 strataform 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.

Textures and Structures of Ore and Gangue Minerals

- Open Space Filling
  - Precipitation from Silicate Melts
  - Precipitation from Aqueous Solutions
- Replacement
- Fluid Inclusions
- Wall Rock Alteration
  - Advanced Argillic Alteration
  - Sericitization
  - Intermediate Argillic Alteration
  - Propylitic Alteration
  - Chloritization
  - Carbonatization
  - Potassium Silicate Alteration
  - Silicification
  - Feldspathization
  - Tourmalinization
  - Other alteration types

Precipitation form Silicate Melts

- Oxide ore minerals such as chromite or magnetite may be near-liquidus phases forming phenocrysts that precipitate with other cumulus phases during fractional crystallization
- Hypidiomorphic textures similar to granite develop during fractional crystallization
- Sulfides may separate as a sulfide magma and form an intercumulus liquid

Chromite Textures

- Chromite may be resorbed in favor of later silicate phases
- Chromite bands in the Bushveld complex of South Africa are the world's richest source of Cr

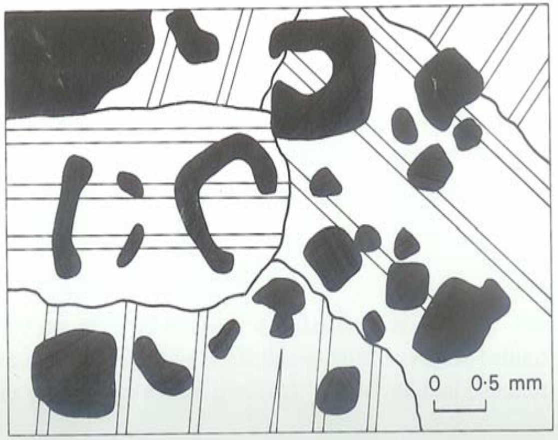


Fig. 3.1. Chromite grains in anorthosite, Bushveld Complex, South Africa. The chromites are euhedral crystals which have undergone partial resorption producing rounded grains of various shapes, including atoll texture.

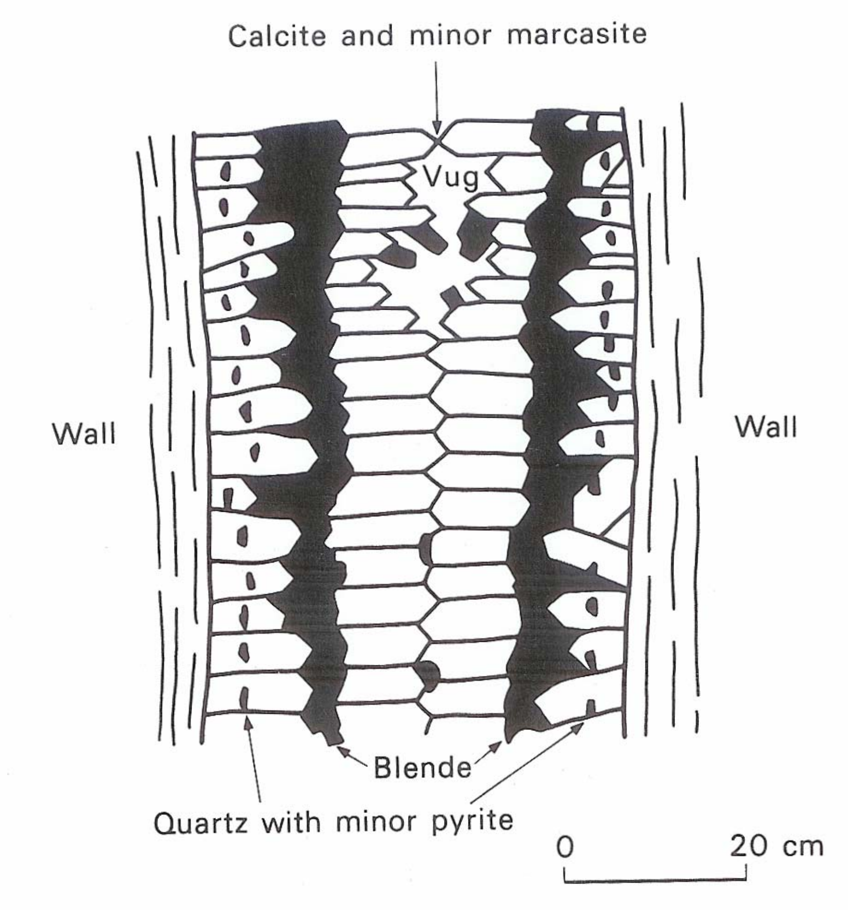
Fig. 3.2. Chromite bands in anorthosite, Dwars River Bridge, Bushveld Complex, South Africa. The central band is 1.3 mm thick at the right-hand end.

Precipitation from Aqueous Solutions

- Open spaces along faults, joints, karst cavities, etc. may serve as sites for ore formation via precipitation from aqueous solutions.
- Ore minerals will generally nucleate on the walls of the fracture surface growing from the contact to the center of the vein.

Precipitation in Open Fractures

- Crustiform banding: the banding of different ore and gangue minerals paralleling the contact of a fracture
- Order of mineralizing fluids is termed the paragenetic sequence



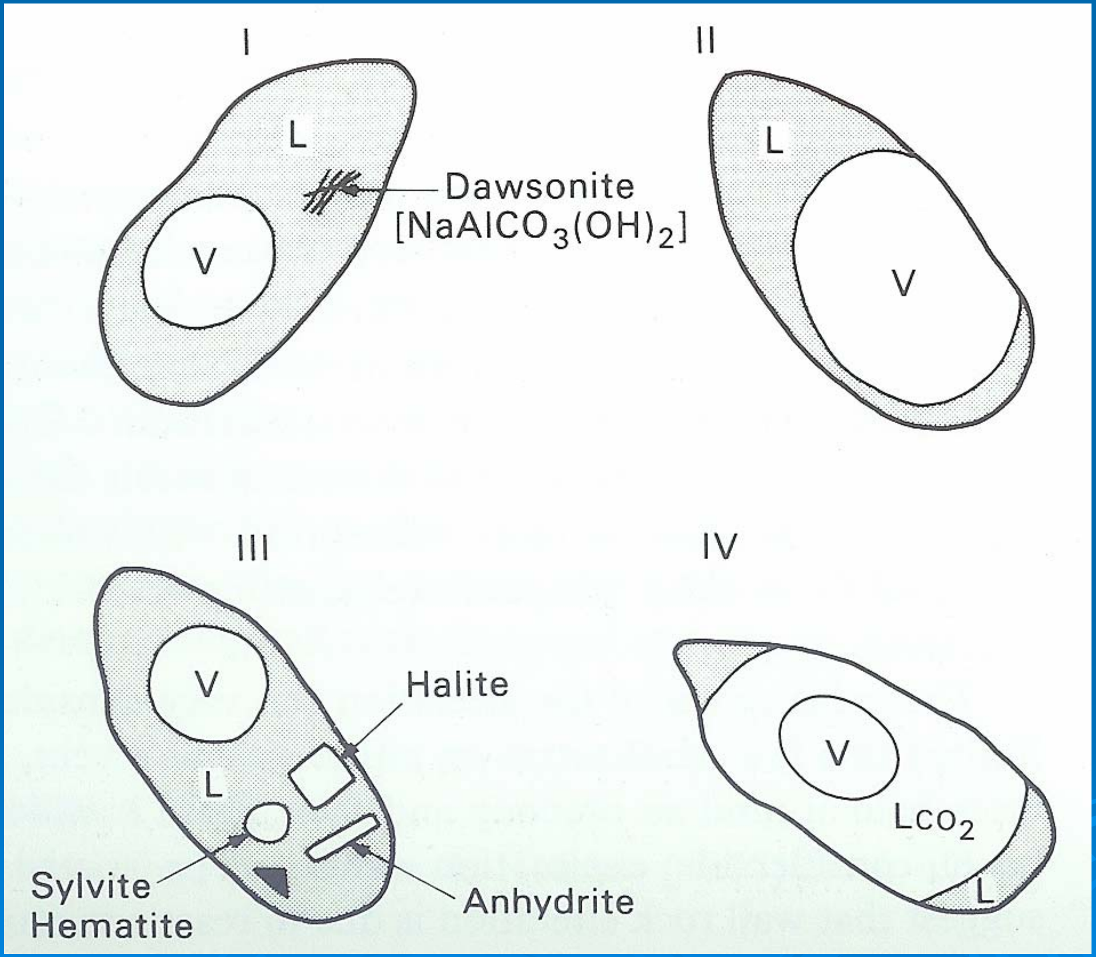
Replacement

- Replacement: the dissolution of one mineral in favor of the simultaneous precipitation of another, often producing pseudomorphs
- Examples include:
  - Pseudomorphs of cassiterite after orthoclase (Cornwall, UK)
  - Preservation of plant cell morphology by Marcasite replacement

Fluid Inclusions

- Fluid inclusions are fluids trapped inside precipitating minerals. They are common in all rocks.
- Four types of fluid inclusions are recognized:
  - Type I: moderate salinity with mainly water and a gas bubble (10-40% of inclusion)
  - Type II: Gas rich (>60%) with fluid as mainly H2O
  - Type III: Halite bearing inclusions with salinities ranging up to > 50%
  - Type IV: CO_2 rich inclusions with CO_2/H_2O from 3-30 mole %
- Type I inclusions may be heated until a single phase to indicate the temperature at capture
- Type II inclusions indicate "boiling" conditions at capture
- Type III inclusions prove the existence of very high salinity brines that are probably important transport fluids for metals because of Cl complexing

Fluid Inclusion Sketches



Wall Rock Alteration

- Frequently associated with ore bodies are altered zones of host rock
- Generally the more intense the alteration the higher the temperature of the alteration fluid
- The different types of alteration types are similar in concept to metamorphic facies because they represent chemically stable mineral assemblages that formed at different temperature ranges
- Hypogene alteration: ascending hydrothermal fluids.
- Supergene alteration: descending meteoric fluids reacting with previously mineralized zones.
- Similar to metamorphic reactions wall rock alteration depends on a “reactive” wall rock composition such as slate.
- Chemical Eh-pH diagrams are often useful in predicting chemical reactions in hypogene or supergene alteration.

Wall Rock Alteration Types

- Detailed descriptions can be found in Meyer & Hemley (1967)
- Types:
  - Advanced argillic alteration
  - Sericitization
  - Intermediate argillic alteration
  - Propylitic alteration
  - Chloritization
  - Carbonatization
  - Potassium silicate alteration
  - Silicification
  - Feldspathization
  - Tourmalinization

Advanced Argillic Alteration

- Characterized by kaolinite, pyrophyllite and quartz as alteration products
- Sericite is usually present. Alunite, pyrite, tormaline, topaz, zunyite and clay minerals are common
- One of the more intense types of alteration, often associated with felsic to intermediate intrusives
- Sulfide ore minerals include covelite, digenite, pyrite and enargite
- This alteration involves leaching of K, Na, and Ca from all aluminous phases such as feldspar and mica leaving Al-rich silicates

Sericitization

- One of the commonest types of alterations occurring throughout the world's ore-fields.
- Affects Al-rich host rocks such as slate, shale, granite, etc.
- Dominant alteration products are sericite (fine-grained muscovite) and quartz.
- In F-rich environments topaz, zunyite and quartz may form with sericite to produce a "greissen".

Intermediate Argillic Alteration

- Principal minerals are kaolinite, montmorillonite from alteration of plagioclase
- This zone will contain dominantly montmorillonite near the border with the Propylitic zone
- This zone will contain dominantly kaolinite near the Sericitization zone

Propylitic Alteration

- Characterized by chlorite, epidote, albite, and carbonate alteration products
- Minor sericite, pyrite and magnetite may be present
- The propylitic alteration zone is usually very wide and therefore is a very useful exploration target
- For example in Telluride, CO, wide propylitic zones flank thin sericitization zones

Chloritization

- A subcategory of propylitic where chlorite dominates but epidote, albite and carbonate may also be present
- Chlorite normally displays an increase in Fe/Mg ratio proximal to ore sulfides
- Sn ore in Cornwall, UK, display hydrothermal chlorite proximal to ore bodies. Chlorite develops as halos around biotite in the host granite

Carbonatization

- A subcategory of propylitic where a carbonate such as calcite or dolomite predominates
- This type of alteration occurs in limestones and dolostones
- Mississippi Valley Type ore deposits are a good example: Pb, Zn, Cu sulfide ore bodies in Missouri
- Dolomitization generally predates sulfide ore formation

Potassium Silicate Alteration

- K-feldspar and biotite are the essential alteration products
- Anhydrite often appears in porphyry Cu type deposits
- Common associated ore minerals are pyrite, molybdenite, chalcopyrite
- Hematite and magnetite may also be alteration products

Silicification

- Involves an increase in the proportion of quartz or chert to the host rock
- Silica may be introduced by hydrothermal solutions, or may be the by-product of chemical reactions
- Associated with Pb-Zn-Ba-F deposits
- At the Climax, CO, porphyry MoS_2 deposit silicification is widespread and intense.

Feldspathization

- Alteration product is K-feldspar or albite
- Secondary K-feldspar is produced by K-rich fluids separating from late-stage fractional crystallization of magma
- An example would be the deeper zones of porphyry Cu deposits adjacent to the top of the intrusion
- Albitization is driven by Na-rich fluids that are produced when fluids permeate through plagioclase-rich rocks
- Albitization is found adjacent to Au deposits and replaces K-feldspar in deposits near Treadwell, Alaska

Tourmalinization

- Associated with medium to high temperature deposits.
- Many Au and Sn deposits have tourmaline in the wall rocks and sometimes in the ore vein itself.
- At Llallagua, Bolivia, the world's largest primary Sn mine the porphyry host is altered to a quartz-sericite-tourmaline rock.

Influence of Host Rock Type on Alteration

- Felsic Rocks: sericitization, argillic, silicification
- Intermediate to Mafic Rocks: chloritization, carbonatization, sericitization, propylitic
- Shale, Slate, Schist: tourmalinization with W, Sn ore deposits

Examples of Major Ore Deposits

- Bushveld, South Africa
- Sudbury, Canada

Bushveld Complex

- Au, Ag, Cr, Pt, Ni, Cu

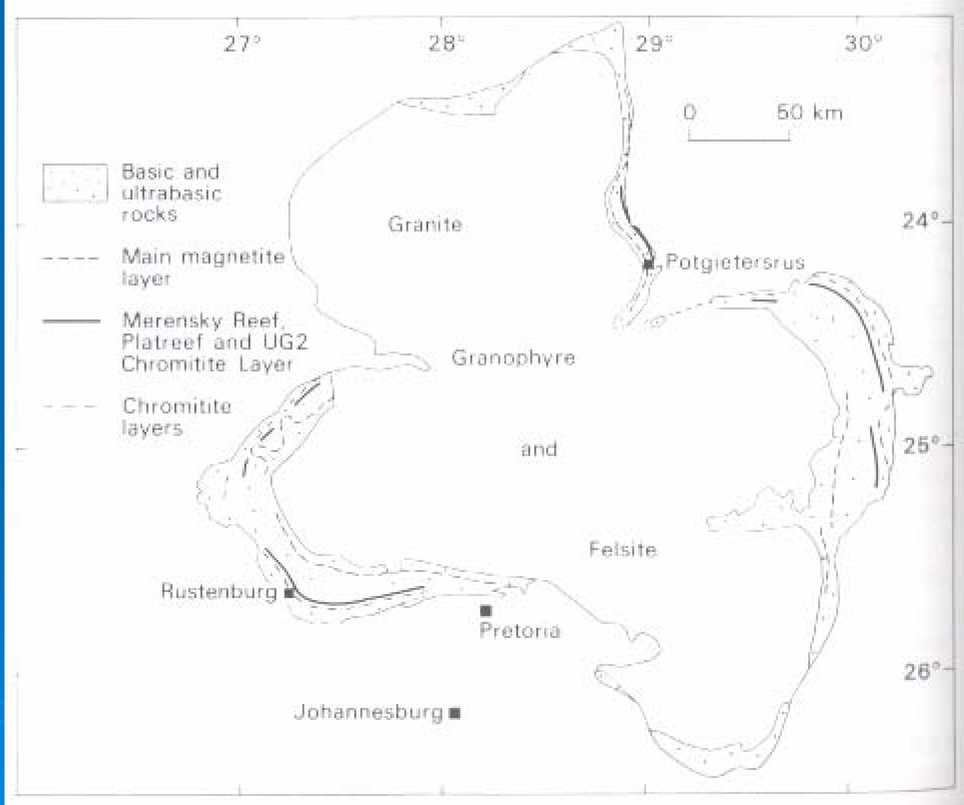


Fig. 8.1. Sketch map of the Bushveld Complex. (After van Gruenewaldt 1977.)

Bushveld Complex

- Stratiform depos

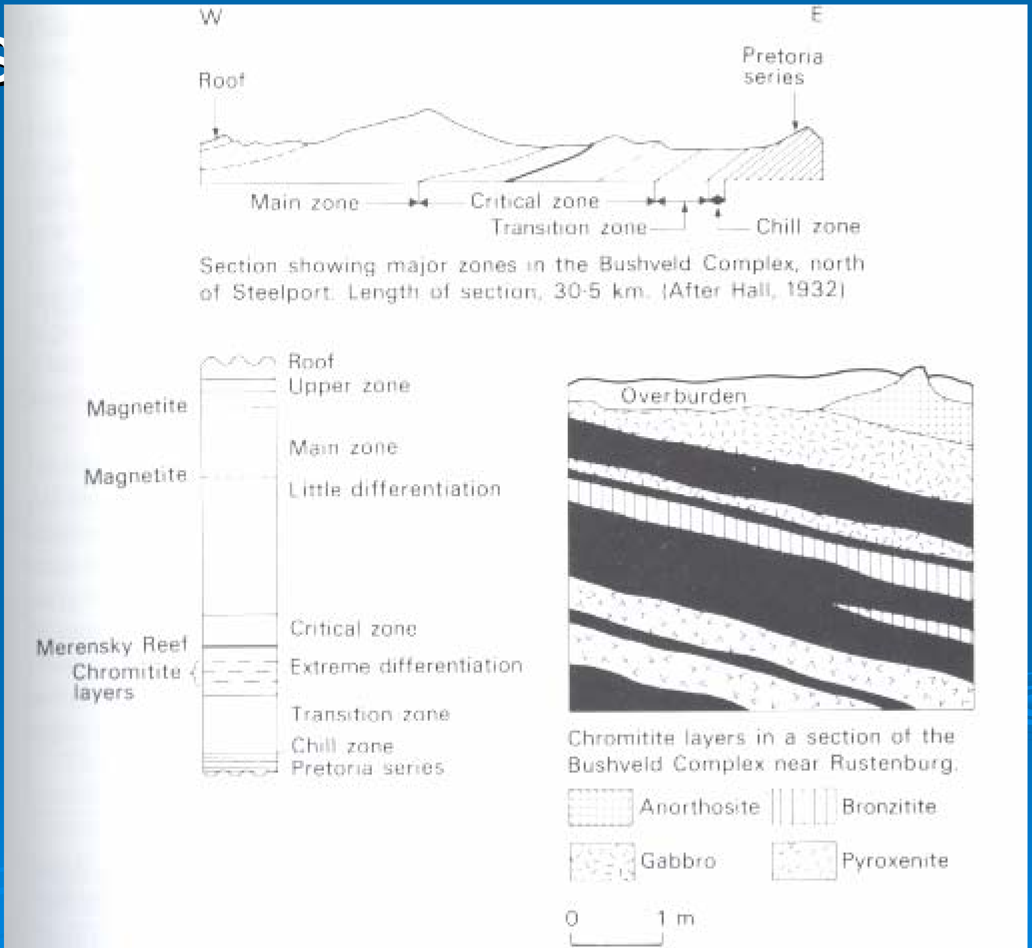


Fig. 8.2. Sections showing the occurrence of economic minerals in the Bushveld Complex.