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THE CONCEPT OF GRADE IN MINERAL DEPOSITS

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## ABSTRACT

The grade of a mineral deposit is determined by the effectiveness of a geological ore forming process, which is the result of the interaction between an ore forming mechanism and the environment in which it operates. Properties of a mineral deposit controlled by ore forming processes include the distribution, density and nature of ore minerals and gangue, and the metal content and impurities of the ore minerals. More efficient ore forming processes tend to develop in the larger mineralizing systems giving rise to richer deposits. As the geological environment within which a mineral deposit evolves becomes more complex a greater number of variables interact to determine the grade of the deposit. This is reflected in the greater variability of the grade distribution, resulting in greater difficulties in obtaining reliable estimates of the recoverable grade, and increased difficulties in the processing of ores. In response to economic fluctuations the working grade of heterogeneous orebodies, that form in geologically complex environments, can often be altered to ensure the continued viability of a mining venture. In contrast the evenly mineralized orebodies that tend to develop in geologically simple environments do not have this flexibility.

All the important decisions in the mining industry, such as feasibility studies, choice of mining and processing methods, selection and planning, are made on the basis of, or are related to, grade estimates. If the geological controls of grade are fully understood, then it is possible to optimize the selection of the various mining alternatives, leading to the efficient exploitation of ore deposits.

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## INTRODUCTORY DEFINITIONS AND DISCUSSION

### GRADE - MINERAL DEPOSIT - ORE DEPOSIT

Grade is the criterion from which the properties and value of a body of rock may be assessed.

In the mining industry the term 'grade' is used in various senses by different people for different purposes, and without qualification may be ambiguous. A geologist may use the grade of a body of rock to define limits to an orebody, while a financier of a mining venture may use the grade of the body of rock to estimate the potential return on his investment. A mining engineer will use the grade of a body of rock to decide whether to mine it or not, or to decide on the best method of comminution and on the best method to extract metals from the rock.

The term 'grade' has in popular usage become synonymous with 'tenor', and in many publications the definition of grade is similar to that of tenor: 'Content of valuable mineral or elements, expressed as a weight fraction'. This definition is misleading and equates 'grade' with 'assay'. The grade of a body of rock involves more than merely its average assay value and it is as much a qualitative term as it is quantitative, in that assay values are meaningless in themselves if the economic constituent is of such a nature that it cannot be economically extracted (Mason, 1982). Because so much of the process of mining and beneficiation depends on the properties of minerals it is at least essential to think of grade as referring to content and quality of minerals. Mines produce minerals, not chemical elements, and most processing plants deal with minerals. To amplify this point Dixon (1979 b) quotes an example of two different ores, one containing 3% chalcopyrite and the other containing 1% chalcopyrite plus 0,8% chalcocite. Both ores will, however, assay approximately 1% Cu, but a concentrate from the first ore would contain 35% sulphur and the second ore 28% sulphur. Since the oxidation of sulphur is exothermic, more fuel would be consumed in the smelter per ton of copper produced in the second than the first ore, thus affecting the production cost.

The various senses in which the term 'grade' is used are often determined by factors such as political and economic parameters in addition to geological phenomena. For example, 'breakeven grade' is that grade from which the recoverable revenue exactly balances cost of mining, treatment and marketing (Taylor, 1972). Breakeven grade is therefore the grade equivalent of a particular financial specification. On the other hand, 'cutoff grade' is an operational control defined by Taylor (op. cit.) as any grade that, for any specified reason, is used to separate two courses of action, for example, to mine or to leave, to mill or to dump, or to separate mineralized materials into graded fractions. Before continuing the discussion on grade a few more terms and concepts need to be clarified.

The different kinds of rock useful to mankind can broadly be classified into those containing minerals from which metals can be extracted, and those containing minerals used for industrial purposes. In this dissertation only the concept of grade in metalliferous mineral deposits will be considered with emphasis on those geological processes responsible for the formation of viable ore deposits. The first part of this dissertation will deal with factors that directly determine the grade of mineral deposits. In the second part the control of geological ore forming processes on the grade of mineral deposits is to be treated by studying individual ore forming systems. In the final section a comparison will be made between the ore forming systems and their control on the grade of mineral deposits in the broader sense.

A 'mineral deposit' must be thought of as a geological entity and is a body of rock containing one or more minerals or metals in sufficient concentration to make extraction potentially economically feasible. It is a natural geological phenomenon and can be considered as a locality at which one or more metals have been concentrated to many times their average crustal abundance. The 'natural grade' or 'in situ grade' of a mineral deposit is therefore controlled by geological phenomena and it is only during subsequent processing (mining, concentration and extraction) that the processing methods and environmental parameters also affect the average grade of rock produced. Environmental parameters as defined by MacKenzie (1982) refer to the broad spectrum of parameters external to the deposit itself, and existing in the area and during the period in which the

deposit is to be developed and mined such as, market prices, operating and capital costs, and government policy conditions. It is essential however, to stress that the grade of a mineral deposit is totally controlled by geological phenomena.

Where a natural concentration of metals permits economic extraction and beneficiation, it is called an 'ore deposit'. In some mineral deposits all the rock within their observable geological boundaries is ore, but in most cases this is not so. An 'orebody' is a well defined body of rock of sufficient mass and with a sufficient content of one or more minerals or metals so that their extraction is economically feasible under prevailing or predicted conditions (Mendelsohn, 1981). It is important to note that apart from ore an orebody may also include waste (sub-economic ore). The limits of an orebody may be delineated by geological boundaries, but in cases where mineralization gradually decreases to a background value the limits are determined by assay. Being entirely economically determined they may not be marked by any particular geological feature. The term 'orebody' is synonymous with 'ore deposit' but an 'ore deposit' may not constitute a continuous body, while an 'orebody' usually refers to a continuous, well defined mass of material. A number of orebodies in close proximity to each other in the same geological setting can be referred to as an ore deposit, for example, the Mt. Isa ore deposit consisting of a copper orebody and a lead-zinc orebody.

'Ore' is naturally occurring material from which one or more minerals or elements can be extracted profitably. Ore is generally synonymous with orebody, but in common use usually refers to a part of an orebody (in situ ore), or a part of the orebody that has been extracted.

#### VARIOUS SENSES IN WHICH GRADE IS USED

Whenever the word grade is used it must be clear to what it refers, for example grade or ore, concentrate grade or mill head grade, etc. Having defined this, the term must be qualified to distinguish what is meant. Grade can refer to the magnitude of a vector of parameters arrived at by some analysis of a mining situation or it can refer to an

estimate derived from measurements (Dixon, 1979 b). Sample grade, for example, refers to grade measurements such as mineralogical, chemical and other analyses of the sample. The grade of in situ ore arrived at by computation made on sample values will be an expected grade. Expected grades are subject to uncertainty and care must be taken to ensure that the estimates so made are accurate and not biased. Geostatistical methods exist by which unbiased estimates can be made and the uncertainty of the estimates quantified. Accurate estimates are based on reliable sampling and the correct approach to sampling, (taking account of the inherent geological nature of a mineral deposit) is treated in a dissertation by Grant (1981).

The schematic diagram in figure 1 depicts some of the senses in which grade is used in the chain of events leading from the locating of a mineral deposit to the eventual processing and extraction of metal from the ore, and is discussed in the paragraphs to follow.

Some mineral deposits, e.g. orthomagmatic oxide deposits such as chromitite and magnetite layers, can be mined at their 'natural grade', but in most deposits some form of selection is required before economical exploitation can take place. Carbonate hosted lead-zinc deposits tend to have natural grades of 3 to 4 percent combined lead and zinc but because of environmental parameters these deposits can often only be mined at combined metal contents of about 8 percent or higher by applying selective mining (Dixon, 1979 b).

Without detailed regard for mining constraints, an orebody is defined by some or other cutoff boundary, which determines its tonnage and average grade. The cutoff boundary can be demarcated either by a geological feature or by assay. The in situ orebody grade is obviously controlled by geological characteristics as the orebody is part of the mineral deposit. An orebody often cannot be mined without including waste material (planned waste) for example, some waste must be included to give a thin tabular body a mineable width. The total mass of rock that has to be mined during extraction of the orebody is called the recoverable reserve, and the grade of the mass of rock the 'recoverable grade'. Within the total amount of available in situ ore, several possible recoverable reserves can be defined depending on the mining

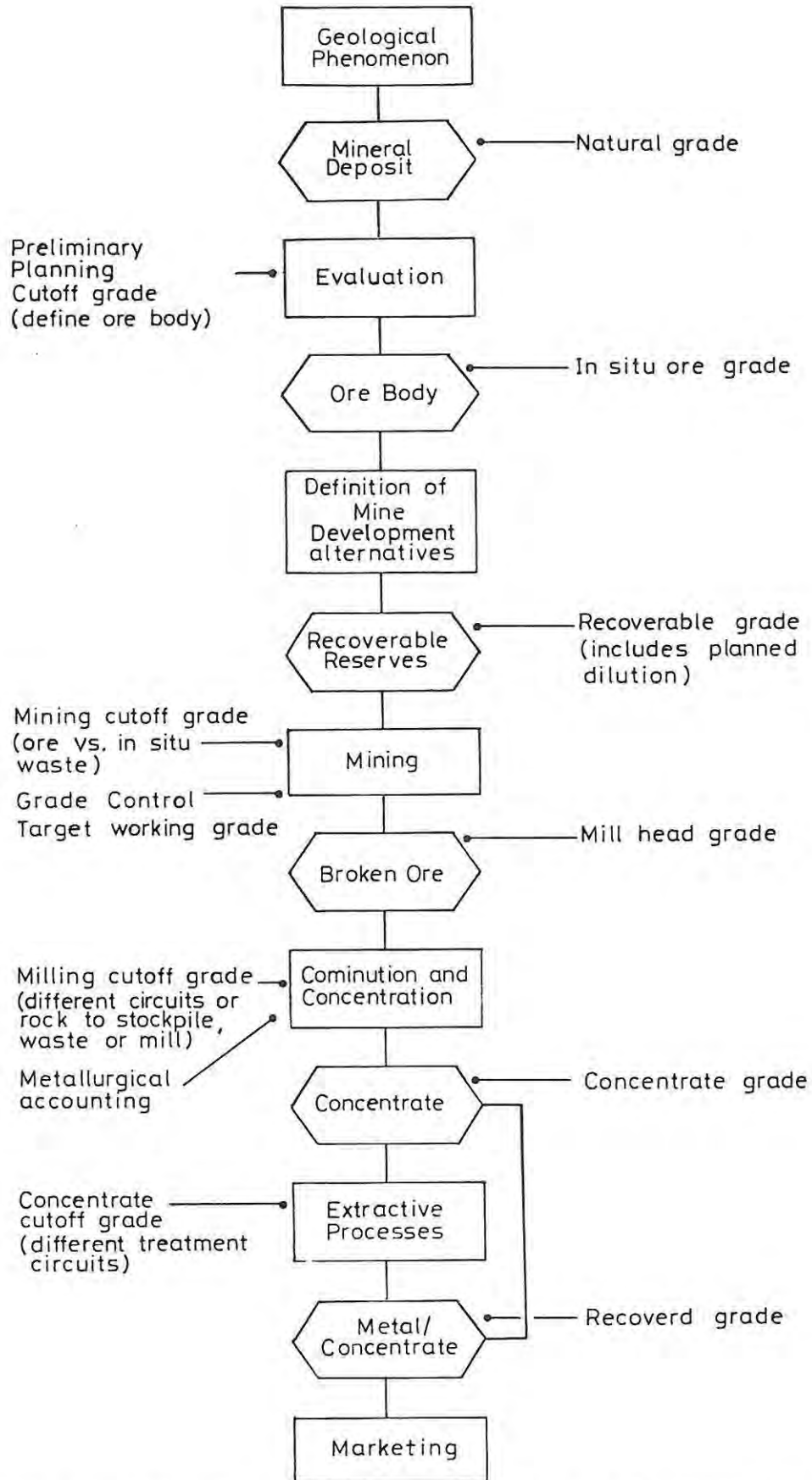


Figure 1: Schematic diagram depicting some of the senses in which grade is used through the various stages from the location of a mineral deposit to the marketing of the final product.

method and the selection parameters chosen. The mining method may influence the size of mining blocks, technical constraints such as slope, stripping and bench height, while selection parameters include the cutoff grade, minimum minable thickness and mining cost. A change in either the environmental parameters or the mining method would result in a different cutoff being applied to define the recoverable reserve (where flexibility of cutoff is possible) to maintain the same profitability. A different cutoff will result in a different recoverable tonnage and average recoverable grade.

In heterogeneous orebodies 'grade control' is applied during mining to ensure a constant feed grade to accommodate various plant restrictions imposed by beneficiation processes. This is particularly important in multi-product mines where variations in the feed grade can have serious repercussions on the performance of a mineral processing plant. Grade control includes cutoff grade decisions relating to closing of old working places and starting of new stope development, production planning, and control of dilution. Grade control is the process whereby a 'target grade' is maintained in order to satisfy the objectives of the mining operation and to respond to changes in the target grade. The operation is so controlled that rock of differing expected grade is mined, and combined to yield a product with an actual grade within the tolerable limits of the target working grade (Dixon, 1979 b).

The 'millhead grade' is the grade of the ore as it comes from the mine and goes into the mill (McKinstry, 1948). The millhead grade differs from the in situ mineable grade because the ore is diluted during the process of mining. Dilution may be physical such as hangingwall overbreak, it may be diluted because of misplacement when ore is trammed to waste and vice versa, or ore may be misclassified at the site of mining (Dixon, 1979 b).

'Concentrate grade,' as the term implies, is the grade of the final product of mineral beneficiation before it is processed to extract metals. A specific cutoff grade is commonly used to produce a final concentrate with the poorest incremental grade allowed (Taylor, 1972). Raising this cutoff improves the average concentrate grade but lowers the metal recovery into the concentrate.

During comminution 'metallurgical accounting,' a form of grade control, is used to control the plant operations by determining the distribution of products of the mill, the values contained in the products, and the overall process efficiency (Wills, 1979).

The 'recovered grade' is a measure of the intrinsic characteristic of every orebody. It relates to that portion of the minerals or metals that eventually reach the market, the remainder being left behind either during mining or lost to tailings during processing. As an example, the Merensky Reef in the Rustenburg area has an average natural grade of 8,10 grams platinoids per ton plus minor recoverable copper and nickel (Buchanan, 1980). Following dilution related to mining the millhead grade drops to 5,30 g/t platinoids. Plant recovery is 78% resulting in an eventual recovered grade of 4,35 g/t. This means that although the in situ grade was 8,10 g/t, only 4,75 g/t is eventually recovered from the mined ore. It is the recovered grade that really matters in a mining operation and is primarily a function of the natural grade of the ore deposit and the effectiveness of the mining and processing operations.

#### FACTORS AFFECTING GRADE

The grade of a body of rock is determined by its geological characteristics, and once processing of the rock has begun, other factors such as environmental parameters and the various mining and processing methods also affect the grade of the extracted rock.

What constitutes an orebody in one part of the world may be quite uneconomical in another part of the world because of environmental parameters. Environmental parameters are mainly those determined by marketing factors and governmental factors. Marketing factors include:- short term fluctuations and long-term trends in supply- demand price conditions; market availability; market accessibility, transportation costs; typical marketing arrangements; and exchange rates. Governmental factors include:- mineral leasing policies; relevant mining taxation and royalty systems; environmental policies; and possibilities for infrastructure support. The effect of environmental parameters on the choice of mine development alternatives, on factors such as the break even grade and on the overall feasibility of mining an ore deposit are dealt with by MacKenzie (1982).

The choice of the correct development, mining and processing alternatives are important, as they determine the amount of dilution during the mining of the ore deposit and together with inherent geological characteristics are largely responsible for the eventual amount of metal recovered. The feasibility of applying different mining methods to different types of ore deposit are treated in a dissertation by Maturana-Bascope (1983).

What ultimately makes an ore deposit a viable proposition is determined by the geological processes that gave rise to the orebody. A sound knowledge of the geological factors controlled by these processes leads to a better understanding of the grade distribution in an orebody, from which reliable tonnages and grades can be estimated for different mine development alternatives at the existing environmental parameters. Geological processes impart certain characteristics to an orebody and in the paragraphs to follow some of these characteristics are briefly reviewed to illustrate their control on the grade of an orebody.

Most of the factors that might affect the grade of potential ore during mining and subsequent processing can be determined during the early stages of the evaluation of a mineral deposit. For example, a competent mineralogical investigation on borehole core can give a good idea of the mineralogical and textural features of the ore which are important for beneficiation. Geological factors within an ore deposit that affect the grade, or whether an ore deposit is viable (high grade) or not, vary from large scale macroscopic factors such as the morphology of the deposit, that affects the recoverable grade, down to microscopic features such as textures that may affect metal recovery from the ore. In the remainder of this chapter factors controlling grade are discussed within the framework of large to small scale.

In orebodies where a flexibility of cutoff grade exists the tonnage and grade are dependent of each other. Generally the lowering of the cutoff grade will result in a greater tonnage and in a lower average grade. Grade estimates are based on assays of adequate sample populations from which the concentration, nature and distribution of the economic constituents can be obtained, while tonnage estimates are based on the volume and density of ore at a given grade.

In general orebodies may have (a) constant density, e.g. orthomagmatic oxide deposits or, (b) a density that shows strong correlation with (valuable) metal concentration, usually the ore minerals being much denser than the gangue or, (c) density will be uncorrelated with metal concentration, which means that the paymetal content per unit volume varies within the orebody even though assay values might be identical. A thorough study of the density variation and its relationship to grade parameters is therefore essential in such an ore deposit. A significant bias could result in the estimation of tonnage from the use of an incorrect specific gravity factor. For instance, the use of a specific gravity factor larger than the true value will lead to overevaluation and vice versa. Likewise, disregard of significant porosity will lead to overevaluation, especially if the value of the sample is expressed as an accumulation of the length of that sample (Dadson, 1968). Specific gravity problems are a characteristic of various ore deposits and in particular of carbonate hosted lead-zinc deposits. At the Tsumeb Pb-Zn-Cu deposit (discussed in a later section) which is hosted in a pipe-like karst structure, density varies according to metal content, metal ratio, degree of oxidation, density of metal bearing mineral, the type of gangue and the presence of vugs, which are all taken into account during ore reserve estimation.

During the early evaluation of a potential orebody, as mentioned previously, a knowledge of the size and structural attitude of the deposit is necessary to define the mine capacity and the mining method to be employed. The structural competence of the ore and host rock and the depth and nature of overburden provide a basis for estimating mine recovery and dilution factors, including the loss of recovery associated with more selective methods of mining. The shape and attitude of an ore deposit therefore also affects the mineable grade. Large, low grade deposits which occur at the surface can be worked by cheap open pit methods, whilst thin tabular deposits will necessitate more expensive underground methods of extraction, although they can generally be worked in much smaller volumes so that a relatively small initial capital outlay is required.

Variability of the ore at the scale of mining also determines the selection of the mining method, mining equipment and the rate of mining. Variability of the ore is influenced by the continuity, regularity and the presence of a fabric in an orebody. Often heterogenous orebodies have to be studied to classify them into homogenous areas, i.e. copper rich versus lead rich where zoning is present; or oxide versus sulphide ore where supergene enrichment has taken place. Homogenous areas are often mined separately as the different types of ore may require different beneficiation processes or they may be mined separately to facilitate grade control. Variations in feed grade can have an adverse effect on the performance of a mineral processing plant. If large variations in the characteristics of the ore are to be expected, adequate provision must be made for this at the design stage which is not always easy to accomplish. Some plants are more sensitive than others to feed grade variations and it is this sensitivity that will determine how much effort can be expended in controlling the grade of ore during mining operations (King, 1979). In the past mining was labour-intensive and at a small scale, resulting in a great flexibility of mining operations so that a large measure of grade control could be exerted during mining. In current times there is a tendency for very large scale mechanised mining using large equipment and resulting in less selective mining operations which are not as flexible and cannot respond to unplanned grade control fluctuations without great cost (Maturana-Bascope, 1983). This underlines the importance of understanding grade distribution within an orebody, so that effective grade control can be built into the planned mining procedures.

The competency of hanging and footwall rocks may also have an effect on the choice of a mining method and the dilution of grade. Incompetent wall rocks will not only cause dilution and variation of the ore grade, but may introduce deleterious minerals either affecting processing procedures or contaminating the final product. The competency of wall rocks is particularly important in tabular orebodies where mineralization may be top and bottom loaded.

The properties of a mineral govern the ease with which existing technology can extract and refine certain metals. The ease with which a metal can be extracted affects the natural concentration required in a

mineral deposit before economic exploitation can take place. Nickel is far more readily recovered from the sulphide than from the silicate ores. Sulphide ores can be worked down to 0,5% Ni while lateritic silicate ores may have to assay above 1,5% Ni to be economic (Evans, 1980).

During mineral beneficiation ore is processed to prepare it for metallurgical extractive purposes. The processes of beneficiation usually involve comminution and concentration. During comminution rock is crushed and ground to liberate the desired minerals in the ore from gangue minerals, or to increase the specific surface area of the crushed ore for further processing. It is obvious therefore that to optimize comminution processes, a thorough knowledge of the mineralogy of the ore is necessary. It is also desirable to know the physical characteristics of the ore to be crushed, e.g. the homogeneity, hardness etc. Other factors controlling size reduction include moisture content, hygroscopicity, tendency to agglomerate, temperature limitations and combustibility of ores (Cummins and Given (eds.), 1973).

Concentration processes depend on the various physical and physico-chemical properties of minerals to separate ore minerals from waste or to separate two sets of ore minerals from each other. The properties include density, magnetic susceptibility, electrical conductivity, surface chemical properties, colour, reflectance, and several others. The choice of processes is dictated chiefly by the type of minerals present and the complexity of their associations in the ore, e.g. froth flotation for beneficiating complex and low grade ores; gravity concentration for separating solids of different specific gravity etc. (Cummins and Given, (eds.), 1973).

The ore textures, the nature of gangue materials, the grain size, the presence and nature of deleterious impurities in the ore, and the hardness and abrasiveness of the ore minerals therefore all influence the way ore will respond to treatment, and have a direct bearing on the recovered grade when the final saleable commodity is produced.

Substantial differences in hardness or resistance to grinding between various ore minerals and between gangue and ore minerals can lead to problems in the grinding circuit e.g., one phase may slime quite readily whereas others may be relatively resistant requiring very complicated grinding procedures (Reynolds, 1982).

The optimum liberation size to which an ore has to be ground in order to achieve adequate separation of the constituent phases is important, as most concentrating processes cannot treat material below a certain grain size. In general terms, the finer the required grind, the greater the milling costs and the necessity for more complex grinding circuits. Fine grinding is also undesirable as it produces excessive amounts of slimes resulting in large losses of valuable minerals (Reynolds, op. cit.). Ore may naturally be very fine grained so that the separation is not feasible, rendering the ore worthless, e.g. at McArthur River, Australia, or complex textural features may be present, e.g. exsolution bodies and complex intergrowths in the minerals such as fine sphalerite intergrowths in chalcopyrite. In some cases separation is achieved but a certain amount of contamination is present in the concentrate. If the contaminant is an ore mineral, e.g. sphalerite intergrowths in chalcopyrite, this may represent a significant loss of one of the economic elements in the deposit, for which no compensation is paid. The presence of more than certain prescribed amounts of impurities in the concentrate may incur penalties from the smelter or buyer of concentrate, but on the other hand bonuses may be paid for small amounts of intergrown silver-bearing phases or the presence of minor amounts of gold in the ore (Reynolds, 1982). The value of by-products may result in a lower grade ore (relative to the major element) being mined. The distribution of the by-product metals in the ore and their relationship to the major element(s) have to be known, as they may not vary sympathetically.

The problem of the metal of interest being present in more than one mineral in an ore will often be mentioned in the sections to follow. Even if a disseminated nickel sulphide ore assays 0,5% Ni, a large proportion of the nickel will be tied up in the silicate form and cannot be treated economically. Copper in sulphides such as chalcopyrite, bornite and chalcocite is readily amenable to flotation but it may also be present in minerals such as valleriite that does not respond well to flotation. What must also be borne in mind is that minerals only contain a certain fixed percentage of a metal and obviously a concentrate cannot have a higher metal content than the metal content of the mineral. For example, a buyer of antimony concentrate might specify 65% Sb in the concentrate. This concentrate could for instance be produced

from ore having an average assay of 3% Sb. What may not be noticed and will not be detected by an assay alone, would be the fact that a batch of ore treated also has a large proportion of berthierite (56% Sb) and not only stibnite (71,7% Sb). In this example the beneficiation of an ore containing more than 45% berthierite would never achieve a concentrate containing 65% Sb. This type of problem is aggravated if both minerals contain the same properties used in the concentrating process.

Other problems affecting beneficiation may be the slight oxidation of minerals which alters their surface properties and hampers recovery during flotation. The presence of clay and other platy minerals in the gangue may also hamper recovery. In some leaching processes the presence of reactive gangue minerals could increase reagent consumption.

Metals are produced from the mineral concentrates by various methods which include pyro-, hydro- and electro-chemical processes. Apart from extracting the desired metal from the mineral, unwanted impurities also have to be removed that would otherwise alter the properties and value of the final product. Minor components of ores are therefore important and their distribution must be well understood as a potential ore could be rendered valueless because an economic treatment or refining process cannot be designed to remove the unwanted impurities (Dixon 1979 a). At the Spargoville deposit near Kambalda, a small nickel massive sulphide deposit adjacent to the main mine orebody was developed by decline at a substantial cost. Only when bulk samples of ore were treated and trial shipments of concentrate were dispatched was it realized that the concentrate was unsaleable because of its excessive arsenic content. Niccolite (NiAs) was identified during mineragraphic work but core samples were never assayed for arsenic (Milne, 1981).

During early evaluation it is essential to obtain reliable and accurate estimations of the in situ grades of a deposit, which is usually difficult due to the limited exposure of the deposit. If the geological controls of grade are understood, then it is possible to interpret statistical and geostatistical studies of assay data in a meaningful manner and optimize the selection of various mining alternatives. Ore grade usually has a greater influence on viability than does tonnage because grade directly affects mine revenue without affecting capital or operating costs. (Mason 1982).

ORE FORMING PROCESSES AND THEIR CONTROL ON  
GRADE OF MINERAL DEPOSITS

ORE FORMING PROCESSES

The primary control on the grade of a mineral deposit is the interaction between an ore forming process and the geological environment in which the process operates. Secondary processes such as metamorphism and supergene enrichment may affect the mineral deposit at a later stage. For example, an exhalative process operating in a volcanic environment may give rise to a fine grained Cu-Pb-Zn sulphide deposit and later metamorphism may recrystallize and coarsen the primary sulphides which will facilitate processing of the ore. While ordinary rock forming processes can give rise to mineral deposits of the abundant metals (Fe, Al, Mg, Mn and Ti), special rock forming circumstances are required before most of the scarce metals will be concentrated into a mineral deposit. The ability of a metal to become concentrated into a mineral deposit depends largely on its distribution and behaviour under the numerous natural environmental conditions.

Crustal Abundance and Behaviour of Metals in Natural Environments

An example of the range of concentrations required to transform the average crustal abundance of metals to an average ore grade is shown in figure 2 illustrating that the concentration factor varies from element to element. Figure 3 shows the important relationship between the

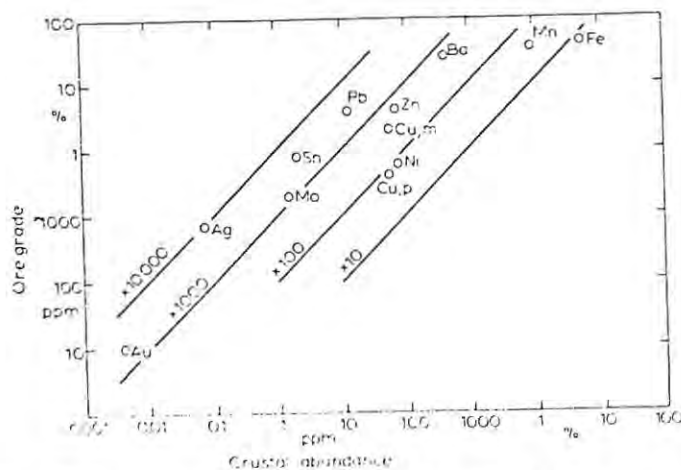


Figure 2: Ore grades versus crustal abundance of selected elements (Wolf, 1981).

composition of an igneous parent-rock and metal content of associated orebodies and also illustrating for example, that nickel only has to be concentrated ten times the average content of a peridotite to reach an ore grade, while from a gabbro a concentration of 100 times is required. Elements such as As, Sb, and Hg require concentrations of higher than 10 000, illustrating that the order of concentrateability of metals by igneous thermal processes result in higher concentrations among the metals that are mobile at the lowest temperatures (Wolf, 1981). In a general way the grade of mineable ore decreases with decreasing crustal abundance.

The connection between crustal abundances and the latter's influence on both the magnitude of reserves and the geochemical mode of occurrence has been stressed by McKelvey (discussed in Wolf, 1981) and Skinner (1979).

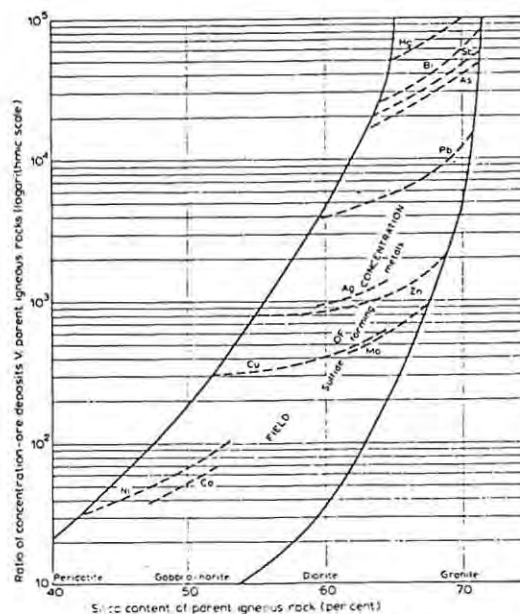


Figure 3: Concentratability of metallic elements by thermal geological processes (Wolf, 1981).

Of the 18 or so elements with crustal abundances greater than 200 parts per million all but fluorine and strontium are rock forming in the sense that some extensive rocks are composed chiefly of minerals of which these elements are a major constituent. Of the less abundant elements, only chromium, nitrogen and boron have this distinction. The rules governing random substitution of one element for another in a mineral structure relate to ionic structure, ionic size, temperature, pressure and the

composition and structure of the mineral in which substitution is occurring. For most elements and most minerals there are specific limits beyond which atomic substitutions cannot occur. The only way in which the scarce elements (which include 'valuable' metals) can form minerals is for special geological processes to cause a local enrichment so that substitution limits are exceeded. Concentrations of the scarce metals are therefore found in localized mineral deposits in which, by a special and rare set of circumstances, saturation is exceeded and a mineral appears, usually a sulphide, oxide or native metal. The major rock forming processes rarely cause sufficiently large local enrichments, so separate minerals of many of the scarce elements rarely form in common rocks. For example, rock forming processes can produce lead enrichments of about twenty times, from 0,001% to 0,02%, but minerals such as mica and feldspar into which it substitutes are still not saturated and no separate lead phases form (Skinner, 1979). Elements such as W, Sn, Mo, Au and U have ionic charges which are incompatible and form minerals at much lower concentrations than most scarce elements.

The chemical behaviour or properties of elements, particularly when in an ionic state, determine under what conditions they would form stable solutions to become part of a specific geochemical cycle or cycles, either to be concentrated or dispersed within or along the earth's surface. Certain elements show a tendency to be associated with specific naturally occurring compounds and minerals, e.g. biophile, lithophile, sulfophile, siderophile, etc., which to a large extent would determine the conditions under which they would become enriched. Figure 4 is an interesting presentation of the distribution of elements as mineral constituents versus geological environments and host rocks, showing the preferential association of certain elements to certain environments of ore deposition. Note that the abundant metals are present in virtually all the environments. The principle ore minerals of iron, for example, are oxides and hydroxides and because these minerals are formed by processes of weathering and sedimentation, by igneous processes and by metamorphism they are present in essentially all rocks.

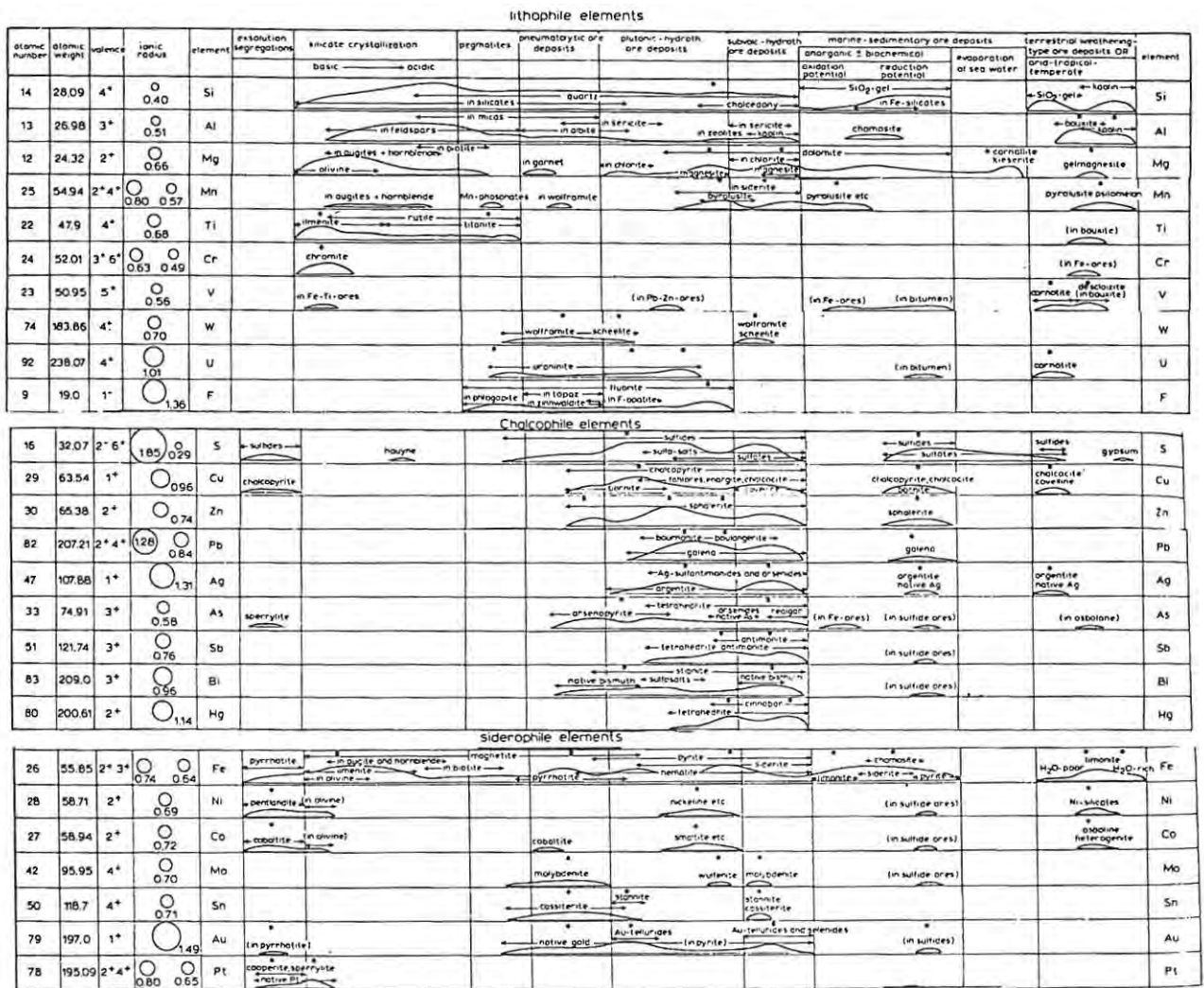


Figure 4: Schematic summary by Cissarz, 1951, of the geochemical distribution of some lithophile, chalcophile and siderophile elements and most important minerals among the major groups of ore deposits. (abbreviated from Wolf, 1981)

Ore Forming Processes and the Environments in which they Operate

Mineral deposits can form from a number of different processes operating in a variety of geological environments. Numerous classifications of their origins, each based on a different set of parameters, are found in literature, some of which are summarised by Wolf (1981) and Stanton, (1972). All the processes important in the genesis of mineral deposits affect the grade of a mineral deposit in some or other way. Certain factors such as a deformational event affecting the structural

attitude of a deposit may not influence the in situ grade of an orebody but will most probably affect the mineable grade and the overall viability of the deposit.

Factors controlling tonnage and grade in mineral deposits can be subdivided into two major sets of geological factors, a set of primary features of igneous, sedimentary and structural parentage (structures of igneous, sedimentary or tectonic origin), and a set of secondary features related to metamorphism, deformation, supergene and geomorphological factors (Mason, 1982). The primary features are the geological controls of ore deposition and preservation, inherent in various mineralized environments, and may contribute positively or negatively to the formation of an ore deposit. Primary factors are those related to processes giving rise to ortho- and para-magmatic deposits, and also those due to surface or near- surface processes giving rise to the various sedimentary deposits.

Primary factors are controlled by ore forming processes such as the separation of minerals by gravitational fractionation in cooling magmas, deposition from hydrothermal solutions, the formation of placers by concentration of heavy durable minerals in flowing water and the precipitation of salts from lakes and seawater. The secondary factors are post-depositional and may be constructive, contributing towards making a better orebody such as the coarsening of sulphide minerals during metamorphism to facilitate processing, or they could be destructive due to events such as post-ore shearing or intense faulting rendering the deposit unmineable.

Numerous environmental and other variables interact with the ore forming processes to determine the grade of ore deposits (figure 5). Often geological time and the evolution of the earth's physical and chemical make-up also play an important role in determining whether an ore forming process operates or whether an ore forming process operates efficiently. When considering the influence of mineralizing processes on grade of a mineral deposit it is also necessary to consider the scale at which the processes operate and the transition between different processes. Some processes are responsible for variations in grade at such a small scale that it would not influence mining of an ore deposit,

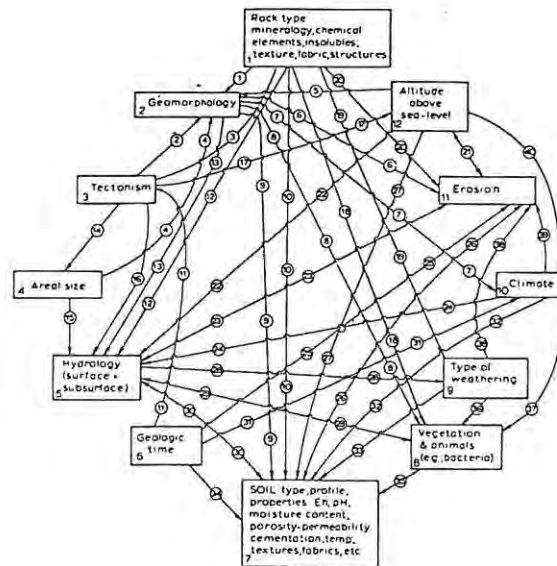


Figure 5: Model relating all parameters important in the genesis of supergene ore concentrations such as bauxite and laterite. (Wolf, 1981)

others will influence grade at a regional scale and are more important for prospecting ventures. Figure 6 shows the range in scale of factors responsible for ore genesis. The factors range from large to small scale and from general to particular, also illustrated is the transition or continuum of scale (and size) between the processes. The gradational or transitional characteristics of natural phenomena and also of their products, the ore deposits, are emphasized in figures 7 and 8. Figure 7 depicts seven ore forming processes illustrating that different mechanisms or a combination of mechanisms can have an influence on the

CONTINENT		REGIONAL		LOCAL ENVIRONMENT	
paleo-lineament	→ sedimentary-volcanic belt	→ sedimentary-volcanic basin	→ macro-scale	→ meso-scale	→ micro-scale
(e.g., Hudson-Bay)	(e.g., Abitibi belt)	(e.g., Helen basin in the Michipicoten area)	(a) e.g., particular volcanic vent (b) e.g., oxide-carbonate-sulfide facies	e.g., individual lenses	e.g., individual patches of framboidal pyrite

Figure 6: Table showing range in scale in studies of ore genesis : a Canadian example. (Wolf, 1981)

genesis and viability of an ore deposit. Numerous possibilities of mixing the various solutions shown in Figure 7 exist to give rise to hybrid fluids. Likewise there is a transition between different types of ore deposits and in figure 8 this is illustrated for varieties of ores in sedimentary and sedimentary- volcanic piles (Wolf, 1981).

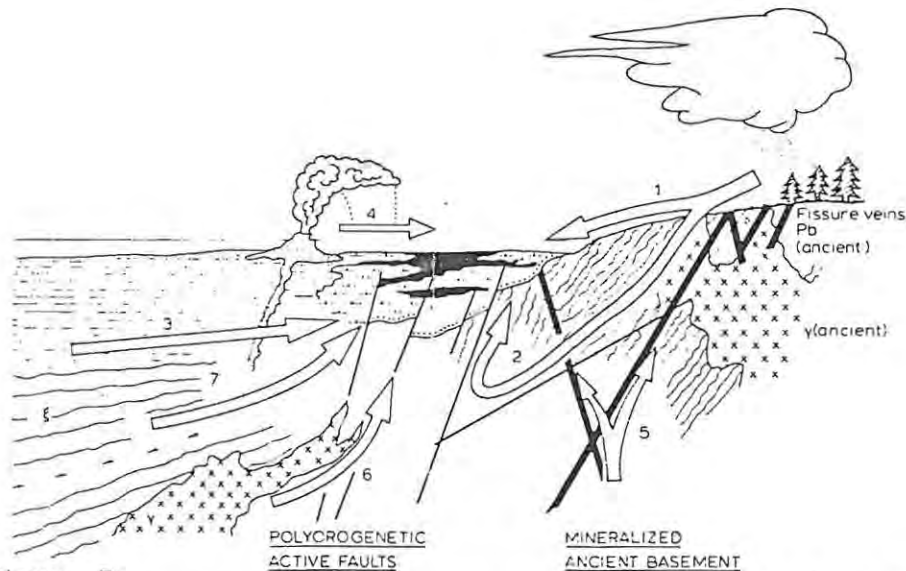


Figure 7:

Diverse processes contributing contemporaneously and/or successively to the origin of stratiform ore deposits in a transgressive marine milieu after an orogenic episode. (After Laffite, 1967; courtesy of *Econ. Geol.*) 1 = sedimentary (chemical or biochemical); origin of the metal: leaching; 2 = circulating hydrologic-hydratogenic; origin of the metal: leaching; 3 = connate waters; 4 = volcanic-sedimentary; 5 = rejuvenation of ancient veins and hydrothermal migration; 6 = postmagmatic-tepithermal; 7 = postmetamorphic migrations.  $\xi$  = compacting, permeable sediments,  $\gamma$  = intrusions, in some cases supply heat driving/hydrologic cell (hydrothermal);  $f$  = fluid. (Wolf, 1981)

As mineral deposits can generally be considered to have formed from ordinary rock forming processes (some specialized) the comparison between the rock or geochemical cycle and ore forming mechanisms is one approach within which factors affecting grade, and factors responsible for high grade deposits, can be discussed. In figure 9 this approach has been incorporated resulting in a pictorial scheme and emphasizing that all processes resulting in the origin of ordinary lithologies can also form economical mineral concentrations, but as Wolf (1981) points out most classifications trying to incorporate a wide variety of features are oversimplified and convey a bias and simplistic situation. Consequently the subsequent parts of this chapter will concentrate on specific ore varieties within selected ore forming systems so that the influence of the numerous variables on grade can be discussed in detail.



	ORE FORMING MECHANISM / PROCESS						SECONDARY
	PRIMARY					SECONDARY	
	Syn-sedimentary		Diagenetic	Post-sedimentary-unconformity			
	Chemical	Mechanical	Low temperature epigenetic	Diverse	Residual		
Some requirements for high grade deposits.	Large system. Paucity of co-precip. gangue & deleterious phases	Rich provenance. Favourable tectono-sedimentary environment.	Pre-conditioning of host rock. Timing of entry of large volume of ground water / brine.	Diverse - primary and secondary.	Suitable bedrock & climate.		
Examples	Fe, Mn	Au - Wits	Cu; U - V	Pb - Zn - (Cu)	U	Al, Mn, Ni	
ENVIRONMENT ↑ GENERAL INCREASE IN COMPLEXITY OF FACTORS CONTROLLING GRADE ↓	Continental	Within fan processes (Elseburgs) On irregular unconformity (VCR) On smooth unconformity (Carbon Leader)	Sedimentary U. Complex hydrology of host Trend, stack type U-(Mo) (Colorado-Karoo) Roll front-type (U-V-(Mo-Cu) Wyoming)  Sedimentary Copper simple hydrology of host (Oamites; Chibuluma; Rokana; Klein-Aub; White Pine)	Highly variable and complex deposits  Carbonate hosted - complex origin of openspace (Mississippi Valley-type - Pine Point)	Unconformity related U deposits (Athabasca; Northern Territories)	Unconformity (Ni-Laterite) Bauxite Dolomite (Mn-Post-masburg)	
	Lacustrine / Evaporitic / Shallow Marine	Sedimentary Fe, Mn (Khalahari Manganese)					
	Volcanic	Sedimentary exhalative (epigenetic) (Broken Hill) Volcanic - exhalative (distal - Rosh Pinah) (near main vent - Flin Flon and Kuroko)	Volcanic facies. (El Indio)		Komatiite flows ± structural trap (Kambalda, Shangani - Ni)		IN ADDITION, ANY MINERAL DEPOSIT MAY BE SUBJECTED TO SECONDARY PROCESSES WHICH MAY BE CONSTRUCTIVE, DESTRUCTIVE OR NOT ALTER THE GRADE OF THE DEPOSIT  Deformational processes: (Structural altitude, folding, attenuation, faulting etc.)  Metamorphic processes: (Upgrade disseminated Ni recrystallize fine sulphides, remobilize sulphides etc.)  Post ore magmatic or sedimentary phenomena: (Igneous intrusions, e.g. dykes or disruptive stocks - Urad Porphyry; erosion channels - Carbon Leader, Carletonville; etc.)  Geomorphological processes: (Supergene alteration - Cu; weathering - Sn greissen; level of exposure; topography - accessibility.)
	Sub-volcanic		Sub-volcanic facies (El Abra, Haib)  Sub-volcanic to batholithic facies. (Los Pelambres.)	Structural control (vein-type-Aberfoyle) and lithological control - replacement (Rooiberg) (Renison Bell) - low temperature.  Reactive host high temperature (Skarn - King Island)	Komatiite - Ni sulphurization (Thomson)  Tholeiite & contamination. (Plat Reef, Noril'sk, Sudbury, Ni-Cu-PGE)		
	Plutonic		Batholithic facies (Los Loros)	Endogranitic (greissen-altered granite) (Anchor - Zaaiploats)	Reactive host. (Rössing)	Endomagmatic (PGE-Ni-Cu Merensky Reef) Oxide Cr, Ti-V-Fe (Bushveld; Great Dyke)	
Examples	Cu-Pb-Zn	Cu-Porphyry	Sn - W	U	Ni-Cu, PGE   Cr, Ti-V-Fe		
Some requirements for high grade deposits.	Large volume of exhaled solution, tectonic quiescence, secondary up-grading.	Favourable structural environment, reactive country rock, multiple phases or pulses of mineralisation.			Large volume of magma and/or external contamination causing sulph. immisc. Structural trap.		
	Hydrothermal Exhalation	Hydrothermal	Pyrometamorphic Pneumatolytic - Hydrothermal	Pegmatic Deposition. Aqueo-igneous	Sulphide Immiscibility Magmatic - Segregation	Fractional Crystallization	
	PRIMARY					SECONDARY	
	ORE FORMING MECHANISM / PROCESS						

Figure 10: Factors determining the grade of selected metalliferous mineral deposits.

environments in which they operate to give rise to viable ore deposits. Although more than one type of ore deposit may form from a similar ore forming process there may not be a genetic link between the deposits. Factors controlling grade have been subdivided into primary- and secondary factors as discussed above. Also indicated in figure 10, and discussed below, is the fact that the complexity of the environment in which an ore forming process operates determines to a large extent the complexity and grade characteristics of the resultant mineral deposit.

Some of the major ore forming systems related to magmatic processes which are treated below include:

- (1) Orthomagmatic systems in which open versus closed systems are contrasted. Deposits forming in the closed system are characterized by simple configurations dominated by the magmatic processes. In the open system the influence of reactive host rocks and structural traps play an important part in ensuring the formation of a viable deposit, but also result in complex grade relationships.
- (2) Paramagmatic systems in which repeated pegmatitic-pneumatolytic-hydrothermal mineralizing events are required to make viable deposits but at the same time each pulse of mineralization adds to the complexity of the deposit. Paramagmatic deposits are characterized by their complexity and often random distribution of mineralization, which is determined by reactive lithologies and the structural environment of deposition.
- (3) Volcanic and sedimentary exhalative deposits that form from hydrothermal fluids depositing their metals at the surface, usually under marine conditions to produce stratiform deposits. Grade characteristics are mainly determined by factors such as the distance of the deposit from the main exhalative or volcanic vent and subsequent deformation and metamorphism.

Deposits related to sedimentary processes form from various mechanisms that often grade into each other and it is difficult to draw distinct boundaries between definite ore forming processes and between primary and secondary processes. As shown in figure 10 and previously

in figure 8, gradational relationships exist between exhalative volcano- sedimentary deposits and chemical (syn- and epi-genetic) sedimentary deposits. The sedimentary ore forming systems discussed below include:

- (1) Symsedimentary deposits formed by mechanical accumulation (placers). Selected Witwatersrand placers are described to illustrate the tectono-sedimentary control on their grade characteristics.
- (2) Low temperature epigenetic deposits that form from a brine entering into a sedimentary host during or after diagenesis. The timing of entry of sufficient mineralizing fluid into the host rock and conditions such as porosity- permeability trends and presence of reductants in the rock largely determine the metal content and grade distribution.
- (3) Unconformity related uranium deposits which are of diverse origin, structurally controlled, and metamorphically redistributed to give rise to deposits with extremely complex grade and morphological characteristics.

#### ORTHOMAGMATIC SYSTEMS

Orthomagmatic deposits are those that have crystallized directly from the magma either by fractional crystallization and gravity settling or through liquid immiscibility. Orthomagmatic deposits can be divided into two distinct types, (a) the oxide ores of Cr, Ti, Fe and V and (b) the sulphide ores of Ni, Co, Cu, and Pge. These elements are present in very low concentrations in igneous rocks, e.g. 180 to 2500 ppm Cr and 148-330 ppm V, and considerable concentration would be required before a viable deposit would form. Illustrated by these deposits is the concept of open versus closed magmatic systems on the factors controlling grade. In the closed ore forming systems the total amount of metal, or constituents forming the ore deposit, is fixed and ore forming processes control the grade. The ore forming processes tend to be predictable and lead to extensive blanket-like ores with a simple configuration and even grade. Their wide extent and richness is directly related to the size of the magma body and include the

oxide ores and endomagmatic sulphide deposits such as the Merensky Reef of the Bushveld Complex. In the open systems in which the bulk of the magmatic sulphide deposits are formed, an interaction between the magma and the pre-existing rocks into or onto which it is emplaced causes the massive sulphide to separate in economic quantities, e.g. the Noril'sk deposits, Sudbury deposits and the Plat Reef, Bushveld Complex. In contrast to the factors controlling grade in the endomagmatic systems the factors controlling grade in the open systems are more complex giving rise to variable orebodies, often larger than would be expected from the volume of the accompanying magma.

#### Magmatic oxide deposits

The formation of magmatic oxide deposits and factors controlling their grade are discussed by Reynolds (1982 a), and only some of the more important points illustrating the controls on grade are repeated in this section.

The mode of occurrence of chrome and titanium-vanadium-iron minerals and their compositional variations are consistent with their having formed during magmatic fractional crystallization processes. The chrome ores are restricted to the early crystallizing portions of large stratiform basic intrusions, while the iron ores are associated with the later crystallizing and more highly fractionated mafic igneous rock types.

Chrome ores are composed largely of Cr-rich spinels that display marked compositional variations between different deposits and between different layers within an intrusion. Potential chrome ore consisting almost entirely of Cr-spinels can be expected to contain between 30 and 60 percent  $\text{Cr}_2\text{O}_3$ . The use to which a chrome ore is put depends largely on its Cr:Fe ratio, which is determined by the timing of the separation of the chromite crystals by gravity fractionation (or flowage differentiation, etc.) from the solidifying magma. The crystallization processes are determined by factors such as the varying oxygen fugacity in the magma and are an integral part of the crystallization process. They can be repeated at various stages during solidification to account for the development of more than one layer. Because the process of forming chromite layers is an integral part of the crystallization process the deposits are thin and blanket-like with an even grade over a considerable lateral extent.

Likewise extensive vanadium bearing titaniferous iron ore layers with even grade form in the stratiform basic intrusions. The ores consist dominantly of Ti- magnetite and small, but variable amounts of granular ilmenite. The Ti- magnetite is characterized by a wide range of one or more of ilmenite, pleonaste and ulvospinel microintergrowths, the development of which depends largely on composition and oxygen fugacity at the time of crystallization. Vanadium probably occurs in solid solution in the Ti- magnetite where it substitutes for  $\text{Fe}^{3+}$ . The very fine-grained nature of the Ti- intergrowths precludes the use of conventional ore dressing techniques for the production of separate Ti- rich and Ti- poor fractions from these ores and has hindered their exploitation in the past. These ores cannot be utilized for large-scale iron production in conventional blast furnaces since the Ti- necessitates extremely high operating temperatures and also forms infusible products that interfere with furnace operation. The ores are however treated economically by electric arc furnaces if more than one product can be recovered. The Main Magnetite Layer of the Bushveld Complex typically contains about 57% Fe, 13%  $\text{TiO}_2$  and 1,5%  $\text{V}_2\text{O}_5$  and is treated economically for iron and vanadium. Upwards in the succession from the Main Magnetite layer the magnetite layers display a gradual increase in their  $\text{TiO}_2$  content and a decrease in  $\text{V}_2\text{O}_5$  content making them unattractive for exploitation.

Vanadium is present only as a trace element in the residual melt and during fractional crystallization is strongly partitioned into the spinel phase as a substitute for  $\text{Fe}^{3+}$ . Vanadium is therefore rapidly depleted from the residual melt once magnetite crystallization commences. The low concentration of vanadium in the residual melt at the initiation of Fe- rich spinel crystallization does not favour the incorporation of large amounts of vanadium into the early-formed magnetite. As a result the  $\text{V}_2\text{O}_5$  content of igneous Ti- magnetite is fairly low. This explains the phenomenon that higher concentrations of vanadium ( $> 1,5\% \text{V}_2\text{O}_5$ ) are only found in large stratiform basic intrusions. Likewise, economical chromite-rich layers are also only found in the larger magmatic intrusions. Chromite is always an early crystallizing phase and will precipitate readily from melts containing as little as 70 ppm Cr. Chrome is extremely insoluble in mafic and ultramafic magmas (a maximum of 500 and 1500 ppm respectively) indicating that economically interesting chromite

deposits will only be developed in the very largest of igneous intrusions, as observed in the Bushveld Complex and Great Dyke.

Secondary processes such as deformation and regional metamorphism may also have the effect of upgrading these deposits. An increase in temperature will cause continued growth of ilmenite exsolution bodies in Ti-magnetite and the expulsion of this material in the form of external granular exsolution bodies, resulting in an overall coarsely crystalline aggregate of ilmenite and V-bearing Ti-poor magnetite. This process is reported by Reynolds (op. cit.) to have operated in the Rooiwater (Murchison Range) and Mambula (Tugela River) complexes. Recrystallization of small amounts of intercumulus serpentinite in chromite layers during slight deformation results in the formation of hard, lumpy chromite ore. This product is preferred to friable chromite ore as it does not break up on handling and is suitable material for direct furnace feed.

#### Magmatic sulphide deposits

Although different in many aspects, overall the various types of magmatic sulphide deposits are strikingly similar. This results from basically similar mechanisms of formation that involve the gravity settling of an immiscible sulphide liquid melt that develops during the cooling of a tholeiitic or komatiitic magma. For a rich concentration of magmatic sulphur it is necessary that the host magma is saturated in sulphur and that a reasonably high proportion of sulphide droplets can settle rapidly to form an orebody. Slow settling may give rise to a disseminated, uneconomic ore. The sulphide ores associated with mafic and ultramafic igneous rocks usually consist of nickeliferous pyrrhotite as the dominant phase, together with lesser but variable amounts of magnetite, pentlandite, chalcopyrite and cubanite. Pyrite is present in very minor amounts and the platinoid metals, particularly platinum and palladium may occur as important traces. Gold and silver occur native in chalcopyrite and as tellurides and selenides (Stanton, 1972).

Certain combinations of rock-type and tectonic setting have proved to be particularly productive as hosts to magmatic sulphide deposits in the past. Economic concentrations of nickel-copper-platinoid ores occur in

(a) noritoid rocks intruding an astrobleme (Sudbury); (b) intrusions feeding flood basalt activity associated with intracontinental rift zones (Noril'sk); (c) komatiitic and tholeiitic flows and intrusions in Precambrian greenstone belts (Kambalda, Shangani) (Naldrett, 1981) and; (d) the endomagmatic Merensky Reef of the Bushveld Complex, principally an ore of platinoids. Unless mined primarily for their PGE content, only those deposits in which a massive sulphide ore has developed in the base of the lava flow, or intrusion, tend to be economical.

The greatly different absolute amounts of Ni, Cu and PGE in otherwise similar deposits can be explained in some cases by postulating that the amount of sulphide reacting with a given magma varies, or in other cases by postulating that some magmas had differentiated to some extent under sulphur saturated conditions before precipitation and economic concentration of sulphides had taken place. The variations in Ni : Cu ratios of deposits from mafic and ultramafic rock associations can therefore be explained by normal fractional crystallization processes. Ores associated with more ultramafic magmas tend to be Ni-rich as opposed to Cu-rich ores associated with mafic rocks (Reynolds, 1982). Komatiite deposits are characterised by fairly low ratios of Pt + Pd + Rh to Ru + Ir + Os, while gabbro-related deposits are characterised by higher ratios. (Naldrett et al., 1980)

Based on their texture three distinct ore types are recognised in magmatic sulphide deposits, all three present in some of the komatiite hosted ore deposits. The ores occur as (a) fine dusty disseminated grains and small blebs interstitial to silicate minerals, (b) net textured types consisting of a continuous network of sulphides enclosing 30 to 60% of olivine grains (commonly serpentinized) and (c) massive sulphide types. Inclusions such as wall rock breccias are often present in some of the massive sulphide ores.

The production of a high proportion of immiscible sulphides at a given stage in the history of a magmatic body can be brought about in a number of ways. The way in which this is brought about largely determines the grade characteristics of a deposit. The solubility of sulphur in a magma may be reduced by endomagmatic processes (Merensky

Reef) or an immiscible sulphide liquid could separate due to contamination with, or assimilation of, country rocks into which the magma is intrusive (the Noril'sk deposit and the Plat Reef of the Bushveld Complex).

The latter process is shown in figure 11 B.

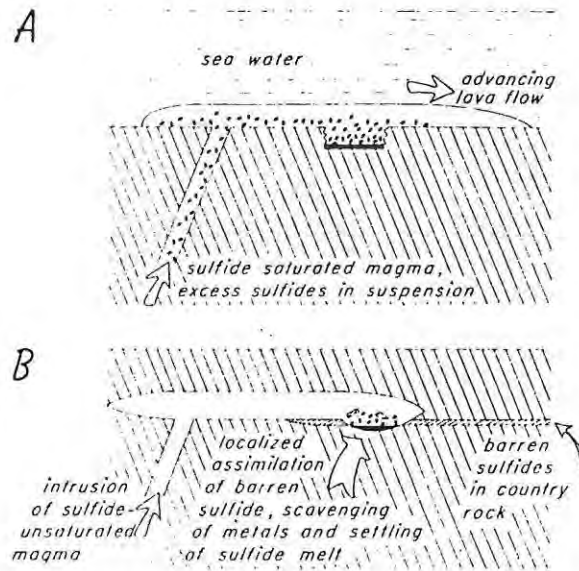


Figure 11: Schematic diagram illustrating (A) the settling of sulphides from a sulphide-saturated Archaean komatiitic flow carrying excess sulphide and (B) the formation of nickeliferous sulphides as a result of assimilation of barren country rock sulphide by an ultramafic intrusion. (Naldrett et. al., 1980).

A third mechanism probably involved magmas that carried excess mantle derived sulphides in suspension when they were emplaced (Naldrett et al., 1980). Many Archaean komatiite deposits probably formed in this way, e.g. Langmuir 2, Kambalda and Shangani. (figure 11 A). Obviously, some deposits formed as a result of more than one mechanism which lead to the separation of a sulphide phase.

The platinum-bearing Merensky Reef of the Bushveld Complex is an example of an orebody formed by endomagmatic processes. Although the exact mechanism resulting in the formation of the Merensky Reef is still debated, precipitation of the sulphides could have been brought about by factors such as changes in temperature,  $Fe^{2+}$  content,  $f(O_2)$  or  $f(S_2)$  within the magma chamber. The Merensky Reef consists of thin hangingwall and footwall chromite rich seams generally about 5 mm thick, which are separated by pegmatoid that has a thickness of between 50 and about 500 cm. Mineralization is not confined between sharp boundaries but is

also disseminated into the foot and hangingwall of the reef. Platinoids occur with copper and nickel iron-bearing sulphides as irregular patches, together with magnetite and silicate phases in the interstitial spaces between the large cumulate orthopyroxene crystals. Despite an irregular footwall contact the distribution of platinum in the Reef at the scale of mining is very consistent (figure 12). Sample values are normally distributed and show no trends or pay-shoots (Barry, 1979). This is a reflection of the fine grained nature and even distribution of the platinum minerals, due to the undisturbed precipitation of immiscible sulphide droplets from the magma resulting in the homogenous stratiform orebody.

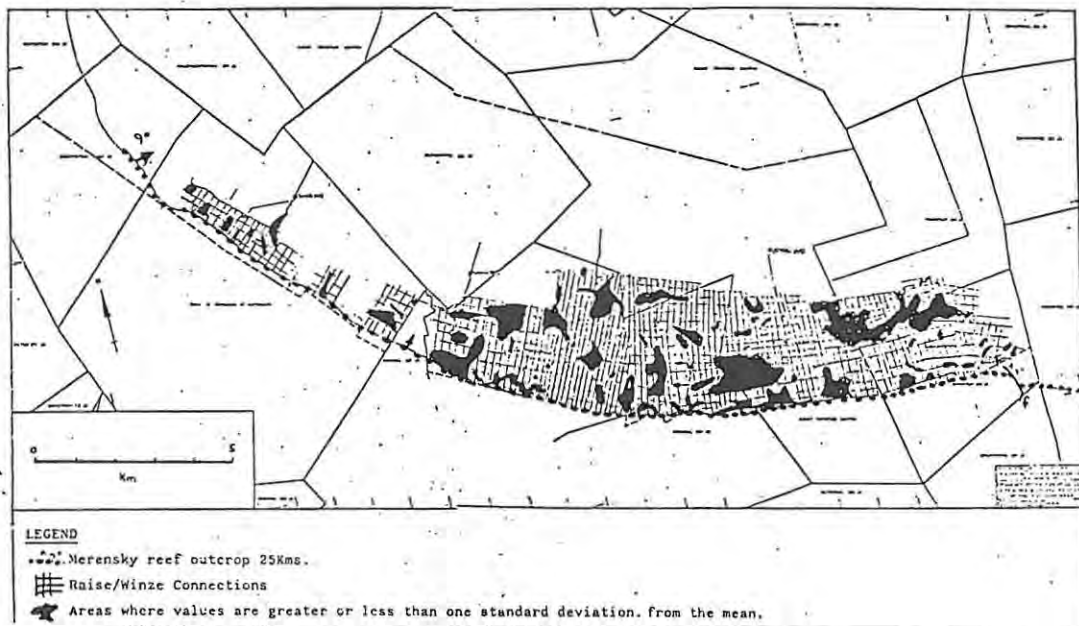


Figure 12: Grade distribution of the Merensky Reef, Rustenburg Area (Barry, 1979).

Due to the low solubility of sulphur in mafic magmas the separation of an immiscible sulphide phase will not readily lead to the formation of an endomagmatic massive sulphide body. Endomagmatic sulphide bodies are therefore only economical if they contain precious metals such as the platinoids. As illustrated by the Merensky Reef, endomagmatic sulphide deposits will tend to occur only in the larger magmatic intrusives. Some komatiite-nickel deposits are an exception to this rule and will be discussed in a later section.

The contamination of a magma with sulphur from an external source or the assimilation of reactive country rocks, are by far the most important processes in inducing the sudden segregation of sulphide liquids from the magma and resulting in rich Ni-Cu-PGE deposits. This process is responsible for the large deposits at Noril'sk (Naldrett et al., 1980); the Plat Reef (Buchanan, 1981) and also operated in numerous Archaean deposits (Hopwood, 1981; Naldrett, 1981).

As stated above, the solubility of sulphur in mafic and ultramafic magmas is extremely low with the result that the large scale separation of an immiscible sulphide liquid required for the effective scavenging of metals can only result from mechanisms such as the introduction of sulphur from an external source. Reaction of the magma with sulphur-rich sediments such as black shale, sulphate bearing evaporates and sulphide bearing iron-formations would be particularly favourable (Reynolds, 1982). Whereas deposits formed by orthomagmatic processes result in large, extensive, evenly mineralized deposits, those formed by contamination and assimilation leading to the separation of an immiscible sulphide phase are characterized by their inherent irregularity and different styles of mineralization due to the strong influence of the reactive country rock. Factors affecting the viability in some of these deposits e.g. Noril'sk and the greenstone belt deposits have been discussed by Harrison (1983).

The 120 m thick Platreef sequence of contaminated pyroxenite gabbros formed during emplacement of the Bushveld Complex, when gabbroic magma intruded into, and reacted with, the floor rocks of dolomite, banded ironstone, argillitic sediments and early micronoritic sills. Disseminated sulphides (0,5% Cu, 1,7% Ni and up to 28 ppm PGE at places) are developed throughout the Platreef zone and are erratically distributed without any type of zoning (Buchanan, 1980; Buchanan, et al., 1981). Sulphide deposits of the Sudbury irruptive probably formed from a tholeiitic magma of mantle origin which had assimilated significant amounts of sialic crustal material inducing a sudden segregation of a sulphide melt. Figure 13 shows a cross section through the Levack mine at Sudbury in which massive, blebby, disseminated and stringer sulphides occur not only in the sublayer norite but also within the brecciated footwall rocks (Naldrett, et al., 1981). The brecciated footwall rocks probably acted as a trap in localizing the sulphide liquid.

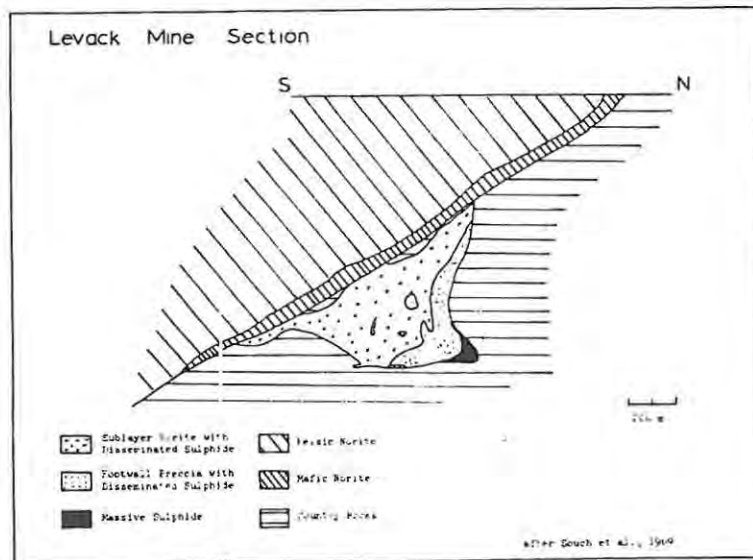


Figure 13: Section through Levack Mine, Sudbury, showing different ore types. (Naldrett et al., 1980)

On the scale of an orebody, the size, shape, continuity and metal content of deposits formed by assimilation of country rocks can be expected to vary rapidly. For example, a xenolith of dolomite may trigger the separation of a sulphide phase in its immediate vicinity while not affecting magma further away.

In contrast to deposits that form by sulphurization or a related process which are not time-bound, the third group of magmatic sulphide deposits are distinctly bound to Archaean komatiitic assemblages and are dominantly Ni-rich and Cu-poor. These deposits are associated with bodies of high magnesium undifferentiated magma, many of which were emplaced as flows only 20 to 100 m thick. Naldrett, et al., (1980) concluded that the Archaean komatiitic magmas that gave rise to the orebodies carried excess mantle derived sulphides in suspension when they were emplaced and the sulphides settled out rapidly to form the ores, becoming riffled out and trapped as the magma passed over irregularities in the underlying topography (figure 14). Commonly, in the case of flows, these irregularities are fault controlled. Movement along such faults appears to have both preceded and succeeded extrusion (figure 15).

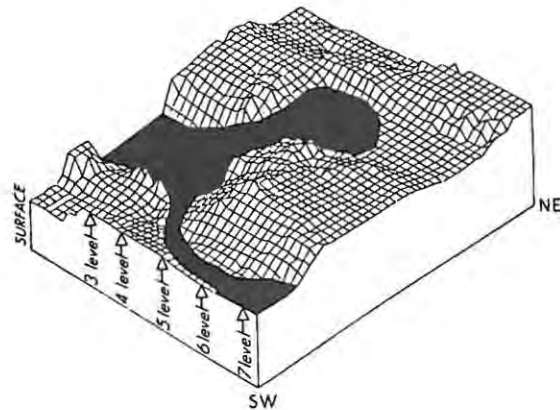


Figure 14: Three-dimensional view of the Langmuir 2 deposit illustrating the distribution of massive ore (black) in relation to irregularities in the upper contact of the footwall andesite or foot-wall peridotite. (Naldrett, 1981)

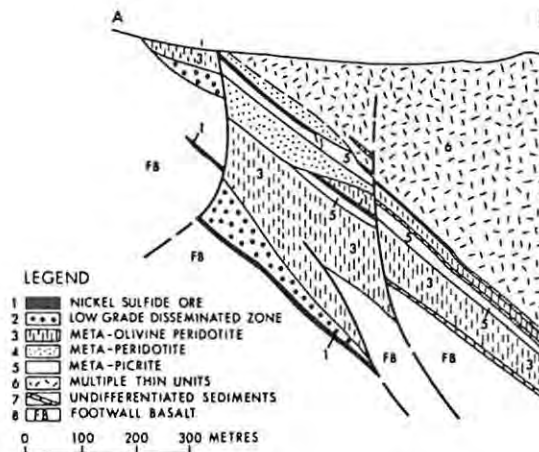


Figure 15: Vertical section through the Lunnon shoot, Kambalda, Western Australia. (Naldrett, 1981)

Separation and concentration of immiscible sulphide liquids from the komatiitic magmas is therefore a gravitational process which produces the observed basal pool of accumulated sulphide melt, an overlying zone of net-textured ore due to displacement of residual ultramafic liquid, and an uppermost zone of disseminated sulphides that were trapped by the crystallizing silicates (Naldrett et al., 1980). The very large tonnage, disseminated, low grade dunitic pods containing disseminated Ni-(Cu) sulphides and no massive sulphide zones probably also formed by a similar

process but the early crystallization of olivine cumulates hampered the settling of the sulphides into economic quantities.

Distribution of primary mineralization in deposits related to the high magnesium komatiites can therefore be expected to be more even, particularly in the net and disseminated sulphide zones. Secondary deformational events may complicate relationships. Irregularities in the floor and the presence of barren country rock inclusions may have an adverse effect on the grade of the massive sulphide zones.

#### Secondary factors affecting grade

The roles of metamorphism and deformation in modifying magmatic sulphide ores are described in detail by Harrison (1983). These processes are largely responsible for the present orientation of the deposits, in many cases making them amenable to easier mining, and responsible for the occurrence of offset mineralization, thickened ore sections, stringer mineralization, breccia ores, and sulphides in metasomatic reaction zones.

In sulphide-rich deposits the mineral assemblages are buffered against oxygen and sulphur and therefore are largely unaffected by alteration reactions. Mineralogical and chemical modification of low-grade disseminated sulphide ores may, however, occur during serpentinization and metamorphism. During serpentinization  $H_2$  is released, altering pentlandite to reduced assemblages characterized by low sulphur assemblages such as awaruite and haezewoodite. Serpentinization can also convert some of the silicate nickel into sulphide form, a process which is important in upgrading low grade dunite deposits.

During metamorphism and ductile deformation massive ores are commonly remobilized and the boundaries between it and other types of ore are tectonized. Due to the ductility of chalcopyrite during deformation it is often remobilized into veins in the immediate vicinity of the orebodies, likewise pyrrhotite is separated from pentlandite and pyrite due to its greater ductility. Some massive ores could be generated from the net-textured ores during metamorphism.

The development of supergene sulphide profiles is common in pyrrhotite-pentlandite orebodies under favourable geomorphological conditions (Blain and Andrew, 1977). The deepest supergene alteration occurs where pentlandite is replaced by violarite accompanied by the release of iron and nickel ions. The released nickel reacts with surrounding pyrrhotite to form additional violarite, and the released iron precipitates mainly as siderite. At higher Eh residual pyrrhotite oxidizes to form pyrite or marcasite and this assemblage of supergene violarite and pyrite remains stable below the water table. Above the water table all the sulphides decompose, and oxides and hydrous oxides of iron are precipitated. Nickel ions leached during sulphide decomposition percolate below the water table where they replace iron in minerals such as violarite, or where they form supergene millerite, thus enriching the ore grade. The effect of the decomposition of violarite and pyrite when exposed to the atmosphere or disturbed by blasting in mining operations often leads to spontaneous combustion in an exothermic reaction. At Selibi Pikwe, Botswana (Lear, 1979) this had an adverse effect on handling of ore, which was aggravated by the cementing properties of the oxidic decomposition products in the crushed ore and explosions were experienced in the drying plant during the early life of the mine.

#### Beneficiation

Nickel in magmatic ores is primarily won from nickeliferous pyrrhotite and pentlandite. For beneficiation purposes the ratio of pyrrhotite to pentlandite is usually determined in the ores, as ores with similar nickel contents may have vastly different sulphur contents (Harrison, 1983). Nickel is present in small amounts in solid solution and as pentlandite exsolution flames in pyrrhotite. As pyrrhotite is the dominant sulphide mineral in these ores a significant amount of nickel may be locked up in the pyrrhotite. Fine grinding of the pyrrhotite may be necessary to liberate the pentlandite and can lead to sliming.

Both hexagonal and monoclinic pyrrhotite occurs in the ores. Hexagonal pyrrhotite, which is magnetic, is removed from the concentrate by magnetic separators but monoclinic pyrrhotite is not easily removed. This may lead to excess sulphur in the concentrates which may be

deleterious, particularly if a smelter is situated in an area where environmental controls are strict. The presence of gersdorffite (45% As) and niccolite may also pose an environmental hazard.

A feature many nickel sulphide deposits have in common, that is not shared by most other deposits, is the high content of the desired metal in gangue. In disseminated ores a large quantity of nickel may be present as silicate nickel (in olivine) and is therefore not recoverable. At Trojan Mine, Zimbabwe, mill head grade is 0.51% of which only about 50% is recovered, the bulk going to waste as silicate nickel (Milne, 1981).

A common problem in ores from low grade metamorphic terranes is the presence of talc, chlorite, anthophyllite or tremolite in the ultramafic rocks which have an adverse effect on flotation.

#### Discussion

Orthomagmatic oxide deposits form part of the crystallization process of a magma and therefore larger orthomagmatic deposits can be expected in the larger magmatic systems. This is also true for endomagmatic sulphide deposits that form in a closed system, where large magmatic systems are required for concentrating processes to operate efficiently before an economic deposit can form, such as the Merensky Reef. Archaean komatiite associated nickel deposits also show a tendency to develop within or as part of a large magmatic system, such as the large greenstone belts of the Eastern Goldfields Province of Western Australia. Magmatic deposits also show a tendency to be associated with large scale deep seated intracontinental rifting or similar structures as seen at the Noril'sk deposits, the Leonora-Wiluna belt of dunitic deposits in Western Australia, and the nickel deposits occurring in the major structural boundaries separating tectonic provinces in Canada.

Because magmatic oxide deposits of chromite and magnetite form an intrinsic part of the crystallizing process of a magma, the metal content in these deposits will be determined by the composition of the minerals (e.g. 30 to 60%  $\text{Cr}_2\text{O}_3$  in chromite) and by the amount of discrete cumulus

or intercumulate silicate phases co-precipitating with the chromite or magnetite. If the conditions of precipitation of the ore minerals change rapidly, then the boundaries between ore and waste will be sharp. The boundaries are usually determined by a phase contact marked by the abrupt appearance, or disappearance, of a cumulate phase, or by a ratio contact marked by a sharp change in the proportion of two cumulus minerals (Cox, 1979).

The separation of an immiscible sulphide liquid in the endomagmatic environment leads to co-precipitation of sulphide minerals and results in an orebody with diffuse or gradational boundaries. Like the orthomagmatic oxide deposits, the endomagmatic sulphide deposits are also extensive and have a constant grade, but show a greater variability in metal content on a small scale.

Heterogeneous orebodies, often very rich and with a massive sulphide component, form in an open system where sulphide immiscibility is triggered by the environment into which the magma is emplaced. Grade distribution may be zoned vertically, as found in many komatiite deposits, and the shape of the massive sulphide zone determined by pre-existing footwall irregularities. The attitude and inclusions of reactive country rock may influence the distribution of mineralization and the richness of the deposit is overall governed by the amount of magma reacting with the country rock.

Many of the problems encountered during beneficiation of the magmatic ores are related to the mineralogical characteristics of high temperature ores. Although being potential ores of vanadium, titanium and iron, the Ti-V- magnetite ores are normally not used for this purpose due to the micro-intergrowths of ilmenite and other phases in the magnetite. Likewise nickel in solid solution and present as exsolution flames in pyrrhotite is often not recoverable. As nickel partitions into the silicate and sulphide phase under magmatic conditions a large proportion of nickel is not recoverable from the disseminated ores.

SUBVOLCANIC PARAMAGMATIC SYSTEMS

The grade of ore deposits that formed during the end stages of felsic magmatic activity is characterized by the strong influence of the environment in which they formed. The deposits formed by the crystallization of minerals from solutions generated directly or indirectly from magmas and channelled along fractures into spaces in host rocks and precipitated epigenetically. The ore forming mechanisms include pegmatitic-pneumatolytic-hydrothermal processes (figure 16) in subvolcanic environments and operated most efficiently where multiple pulses of solutions or late stage melts have been introduced. The uraniferous alaskitic pegmatitic Rössing deposit, porphyry-type deposits and primary tin-tungsten deposits are to be discussed as examples.

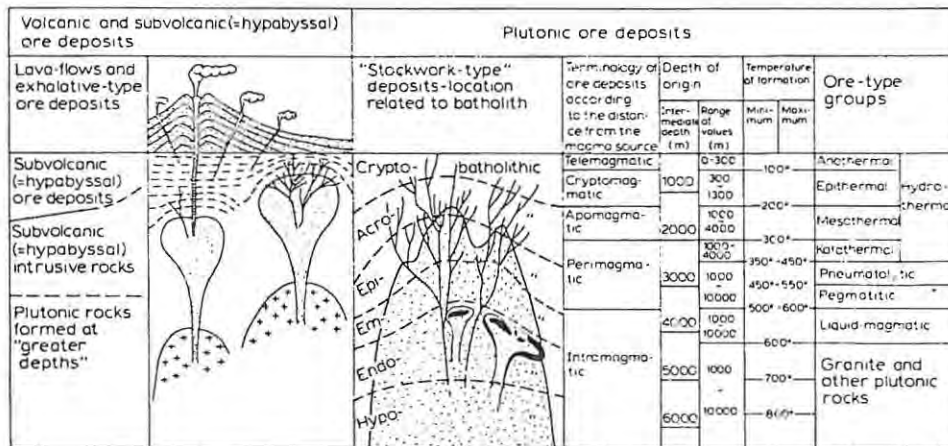


Figure 16: Schematic overview of the subdivision and terminology of the magmatic deposits, after Schneiderhöhn, 1961. (Wolf, 1981)

Pegmatitic-Granitic Deposits

As crystallization of a granitic magma proceeds the water content of the remaining magma increases, producing a residual melt of low melting silicates rich in volatiles and incompatible elements such as Li, Be, Nb, Ta, Sn and U which cannot be accommodated in the crystal lattices of quartz and feldspar of the granite. Pegmatites crystallise from this melt as late stage products of the granitic activity associated with plutonic intrusions from which the volatiles could not readily escape.

Depending on the tectonic environment of emplacement, pegmatites may crystallize within the parent granitic body or the residual melt may be injected into country rock, often in multiple phases, giving rise to pegmatitic bodies with complex internal structure. Pegmatitic crystallization can be seen as an aqueo-igneous stage or a transition between an igneous and a hydrothermal stage. The Rössing uranium deposit in South West Africa is described below and can be seen as a pegmatitic deposit emplaced into reactive country rocks. The mineralized Alaskitic Pegmatitic Granites ("alaskites") at Rössing are, apart from uranium, relatively enriched in incompatible elements and Von Bäckstrom and Jacob (1979) suggest that they are crystallization products of highly fractionated residual melts.

#### The Rössing Uranium Deposit

The Rössing uranium deposit is the largest known uraniferous granitic deposit, containing about 300 million lbs  $U_3O_8$  at an average grade of 350 ppm (Nash et al., 1981). The deposit occurs in the central part of the Damara Mobile Belt, part of the Pan-African system of metamorphic belts and is emplaced into sediments of the Late Proterozoic Damara Group which were deposited on, and partially melted with, early Proterozoic gneisses. Uranium occurs as uraninite, betafite and various hexavalent secondary minerals, mainly in the alaskite which was emplaced into calcareous rocks and a variety of mafic gneisses (figure 17). The geology and postulated origin for the deposit is described by Jacob, 1978; Berning et al., 1976; Von Bäcksbrom and Jacob, 1979; and summarized by Nash et al., 1981.

Emplacement of the alaskite was structurally and stratigraphically controlled and is restricted to anticlinal structures at or below the level of the Nosib Sub-group (figure 17). The alaskite and metamorphosed country rocks show concordant, discordant and gradational relationships. The alaskitic rocks range from small quartzo-feldspathic lenses to large bodies differing widely in texture, size and emplacement habit (figures 17 and 18). During the open-cast mining operations the alaskite/xenolith arrangement as shown in the section in figure 18 was found to be far more complex, complicating grade control. The alaskite as a whole is late tectonic and different ages of alaskite intrusion can

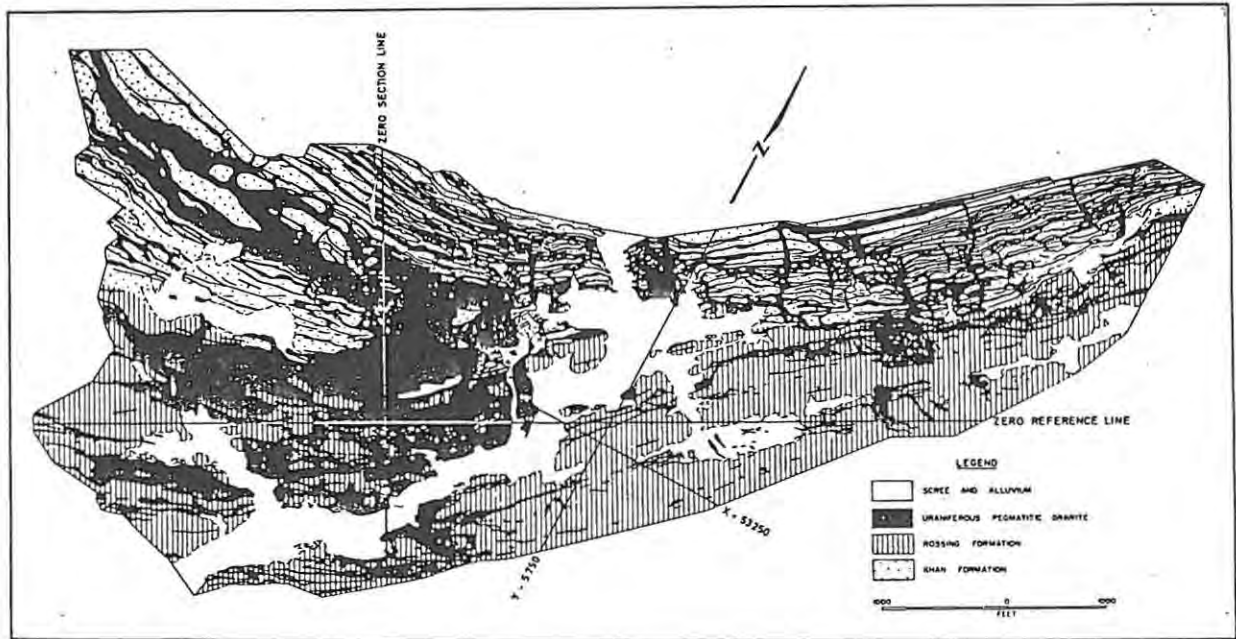


Figure 17: Generalized geological plan of the Rössing uranium deposit (Berning et al., 1976)

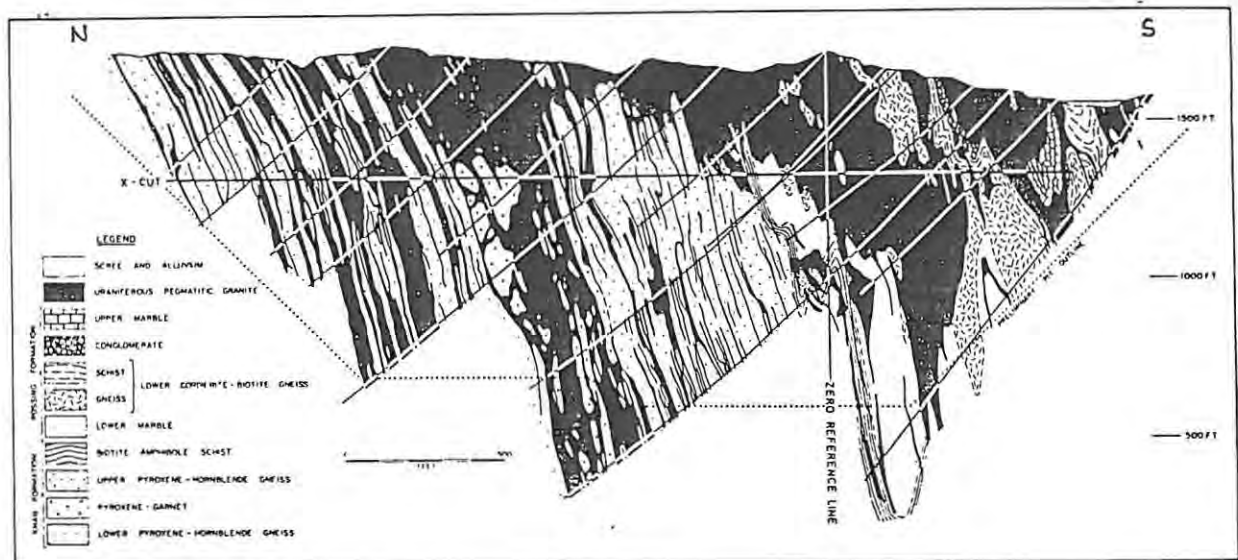


Figure 18: Drill section zero (see figure 17) showing geology, boreholes, and bulk sampling crosscut. Rössing uranium deposit. (Berning et al., 1976).

be identified. Some of the alaskites are syntectonic and have been folded whereas others, generally better mineralized, are later (Jacob, 1978; Von Bäckstrom and Jacob, 1979).

Uranium may have been precipitated from the granitic melt by one or more process. One is reduction by iron in mafic xenoliths and wall rocks, resulting in the association of uraninite with hematite and enrichment in biotite-rich selvages of the alaskite (Von Bäckstrom and Jacob, 1979). Another process is decrease of Eh and increase in pH caused by assimilation of basic country rock (Berning et al., 1976). Nash et al., 1981, regard graphite as a probable reductant in other similar deposits.

Mineralogically the alaskite consists of quartz, abundant perthitic microcline and subordinate plagioclase. Minor and accessory minerals include biotite, muscovite, chlorite, apatite, monazite, zircon, sphene, garnet, magnetite, illmenite, hematite and fluorine. Minor sulphide minerals are also found. Alaskite is not uniformly uraniferous, most is entirely unmineralized and some only leanly. Alaskite hosts all the primary uranium minerals and most of the secondary. The latter does in certain localities show spread into the country rock. The primary uranium minerals are uraninite and betafite which occur as tiny grains (<0,3 mm) both interstitially and in quartz, feldspar and biotite. They are preferentially associated with zircon and biotite. Approximately 40% of the uranium is present in secondary minerals such as uraniophane, beta-uranophane and other hexavalent minerals. The secondary enrichment could be due to hypogene or supergene activity, and it is possible that the climate of the Namib Desert played an important part in this enrichment, where nightly fog provides small amounts of moisture (Von Bäckstrom and Jacob, 1979). Supergene enrichment could also have been as a result of the extensive jointing, faulting and folding of most of the deposit. Secondary enrichment is particularly well developed in the northern mafic gneisses where brittle deformation probably provided pathways for circulating ground water.

Mineralization is strongly controlled by the geology of the lithologies into which the alaskite has intruded. Biotite schist xenoliths in mineralized alaskite bodies are normally better mineralized than the surrounding alaskite and acted as precipitants of radioactive minerals. Similar effects characterize the immediate country rock (Jacob, 1978). Likewise uranium is enriched preferentially along contacts of marble xenoliths. As described by Berning et al., 1976, the bulk of the economic mineralization in the Rössing uranium deposit is contained in alaskite that is preferentially emplaced into the mafic gneisses comprising the northern ore zone (figure 17), and also in the alaskite intrusive into the mafic gneisses, lower marbles, and lower cordierite-biotite-gneiss that comprises the central ore zone located in the northern limb of the mine.

A hot sulphuric acid leach forms part of the process during which approximately 90% of the  $U_3O_8$  in the ore is extracted. Acid consumption is the largest single cost on the mine and therefore the grade of the ore is largely determined by both the uranium content of the ore and its acid consumption. Due to the large size of the mining operation and the distribution of uranium which may not only be confined to the alaskite, up to 15% of the ore treated may be barren metasedimentary waste. Where 10 to 15 kg  $H_2SO_4$  per ton and 20 kg  $H_2SO_4$  per ton is required to treat alaskite and amphibolite schist respectively, about 200 kg  $H_2SO_4$  per ton of marble is required. As a result the ore body can be subdivided into a northern relatively 'inert' half, mainly confined to the Kahn Formation (figure 18), and a southern reactive half, mainly confined to the Rössing Formation (R. Murphy, pers. comm. April, 1982). The alaskite emplaced into marble, although containing high uranium contents, may therefore not be the most lucrative ore. On the other hand, pyrrhotite and pyrite contained in cordierite gneiss is a useful addition during the extraction process. The well mineralized amphibolitic schists, containing abundant easily leachable secondary uranium minerals, may contain large amounts of biotite which are deleterious in the extraction process.

The strong control by pre-existing lithology on the grade distribution (uranium content, acid consumption, biotite content) is currently utilized in determining practical mining boundaries between ore blocks in the open-cast. Blasting within the pit takes place across strike as this results

in a more even distribution of ore and waste available for loading than if blasting were done parallel to strike. The strong geological control on grade distribution and the fact that the alaskite/meta-sediment relationship was very much more complex than shown on figure 18 was not appreciated during early mine planning. Because of the bulk mining, which does not allow accurate selective mining of the alaskite, a significant drop in expected mining grade was experienced.

Disequilibrium problems (discussed under the Sedimentary Uranium heading) are not encountered at Rössing. The Th : U ratio of the ore changes slightly from a constant 9 : 1 to 13 : 1 towards the east of the orebody, having only a slight effect on radiometric assays (R. Murphy pers. comm.). In order to upgrade the mill-feed gamma-ray spectrometer truck scanners have been installed near the primary crushers.

Important factors controlling grade in the Rössing deposit are (a) the structural and lithological control on emplacement of the alaskite resulting in a large granitic "stock", (b) the multiple intrusion of the alaskite, each intrusion having a different uranium content probably reflecting an advanced degree of differentiation of the melt, (c) uranium content and distribution, although locally highly variable and erratic, is strongly controlled by the pre-existing lithologies, (d) carbonate host-rock lithologies are unavoidable deleterious contaminants in the ore and (e) supergene enrichment occurs preferentially where the ore body was deformed by folding, jointing and faulting in the more brittle lithologies. The high variability and high nugget effect of uranium content in the Rössing ore is therefore as a result of a late stage residual melt entering a complex environment in which reactive and non-reactive rocks, structural complexities, and lithological contacts play a role. These factors are in addition to the fact that the alaskite intrusions themselves are very erratically mineralized.

### Primary Tin-Tungsten Deposits

Primary tin-tungsten deposits comprise a continuous spectrum that range from endogranitic, through pyrometasomatic and hydrothermal, to distant zenothermal. Variables that control grade in these deposits can therefore be considered in terms of the successive stages in the evolutionary processes that took place during formation of the deposits. Primary stratabound Precambrian synsedimentary tin mineralization which is part of the family of massive sulphide deposits (Lehman and Schneider, 1981), is not discussed under this heading.

The genesis of primary Sn-W deposits is related to the fractional crystallization of residual liquids that form during the final solidification of granitic magmas. During crystallization of the granitic magma volatiles and incompatible elements such as Sn, W, U, Th, Be, Mo and rare earths are concentrated in residual fluids that separate from the rest liquid. The fluids so formed generate the hydrothermal systems that transport and deposit metals in both endogranitic and exogranitic environments (Taylor, 1979; Archer, 1981). Irrespective of whether the deposits are endo- or exo-granitic, regional and local structural controls play a dominant role in their location and morphology. Metal distribution in these deposits is also largely controlled by structural elements and reactive host-rocks may play an important role, particularly with skarn- and replacement-type deposits. Structural elements control the concentration of Sn-W mineralization because they disturb solution equilibria. Metal zoning is common in these deposits on both regional (figure 19) and local scale and is controlled by factors such as the distance from the igneous source, pressure, pH and host rock composition.

Primary Sn-W deposits also illustrate that the variables controlling grade become more numerous and more complex progressing away from the magmatic environment. Disseminated endomagmatic (closed system) deposits tend to be large tonnage, low grade, and have good continuity and simple mineralogy. Exogranitic deposits (open system) such as tin-vein occurrences tend to be small tonnage, higher grade, very erratic and are characterized by more complex mineralogy. The style and type of mineralization related to a crystallizing granite is controlled by the

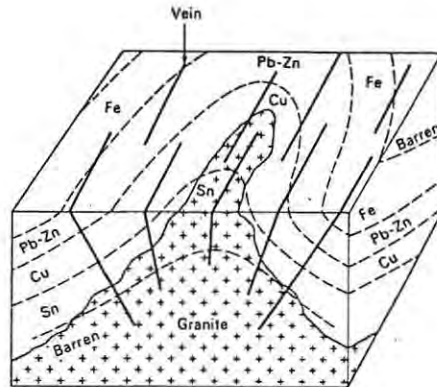


Figure 19: Diagrammatic illustration of district zoning in the orefield of south-west England showing the relationship of the zonal boundaries to granite-metasediment contact. (Evans, 1980)

stability of the confining roof rocks. In a study of Bushveld Complex tin-fluorine deposits Crocker (1979) showed that the release of pressure in a crystallizing granite caused by the fracturing of roof rocks, resulted in the volatilization and pneumatolytic fractionation of enriched residual phases. This resulted in the deposition of fluorite-actinolite (or fluorite- siderite-magnetite) mineralization separate from cassiterite-tourmaline mineralization (e.g. Rooiberg) in the roof rocks. In the closed system where no volatilization occurred due to a competent confining roof, the entire suite of residual volatiles and accessories resulted in 'syngenetic' endogranitic cassiterite-tourmaline-fluorite-type mineralization in deuterically altered granite (e.g. Zaaiplaats). Telescoping of mineralization may occur if fracturing of the roof is late.

#### Disseminated endogranitic deposits

Large tonnage low grade disseminated deposits include greisen hosted and deuterically altered granitic deposits and form part of the pneumatolytic-hydrothermal system that is also responsible for exogranitic tin deposition. The important constraint on the endogranitic ore forming process is that a trapping mechanism of some sort must exist in order to impound the upward migrating magmatic and hydrothermal fluids. The most favourable sites for mineralization are apical roof zones of granites,

particularly cupolas, cusps and ridges (Archer, 1981). The tonnage and morphology of the deposits are controlled by the shape of the apical roof zones and the interaction between the regional stress field in the country rocks and stress created by fluid pressure related to the cooling pluton (figure 20). Greisen deposits usually consist of disseminated cassiterite together with wolframite, fluorite, tourmaline and arsenopyrite. Large tonnage deposits result when the apices of some cupolas are completely greisenized.

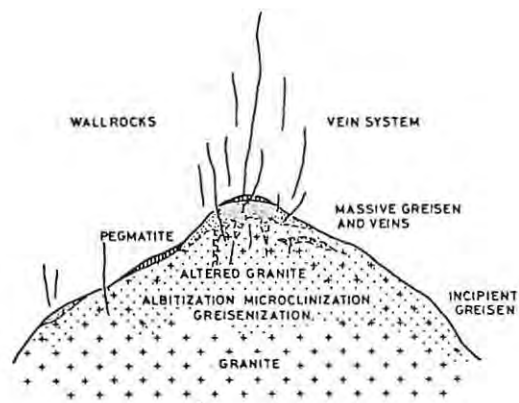


Figure 20: General model of a greisen deposit.  
(Taylor, 1979)

At the Anchor Tin Mine in Tasmania the mineralized zone is some 250 x 650 m in extent and comprises a series of subhorizontal, lenticular, disseminated cassiterite sheets of varied dimension as shown in figure 21 (Taylor, 1979). At Zaaiplaats a small stock of the late stage altered Bobejaankop granite is emplaced into earlier granitoids related to the acid phase of the Bushveld Complex. Emplacement of the Bobejaankop Granite was structurally controlled by a pre-existing antiformal structure plunging to the north-west. The mineralization is restricted to the upper portions of the stock occurring as ill-defined disseminated zones and pipe-like bodies of mainly disseminated cassiterite, tourmaline and fluorite. The low-grade disseminated bodies are irregular tabular bodies 0 to 30 m thick and extensive down-dip, parallel to the upper contact of the Bobejaankop Granite. The high-grade pipe-like bodies (up to 60% Sn) show great complexity of shape and attitude, their location being completely unpredictable, and average 1 to 2 m in diameter. Both the

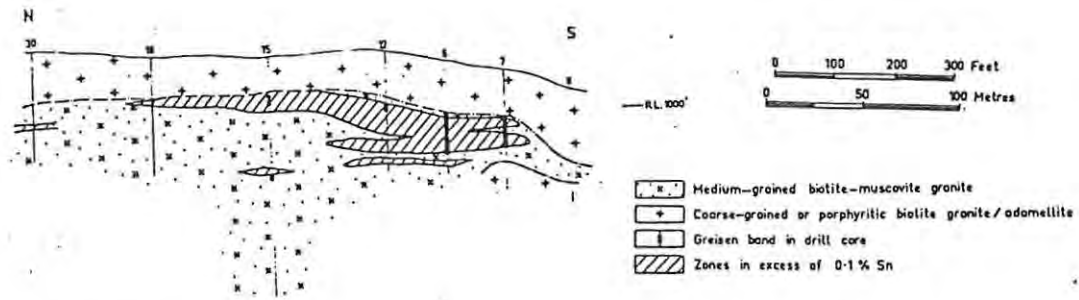


Figure 21: Sections showing relationships between granitic rocks, position of mineralized horizons and greisen bands in Anchor mine area. (Taylor, 1979).

disseminated and the pipe-like bodies show a crude north-westerly plunge suggesting that the mineralization was introduced during very late stages of consolidation of the Bobejaankop granite when the granite was consolidated far enough to exhibit some jointing to control migration of fluids.

The important control on grade in these deposits is therefore the chemical reaction of tin-rich late stage fluids with already crystallized or semi-crystallized granite beneath an impounding structure. The throughflow of mineralizing fluids due to sporadic fracturing and resealing of the roof rocks may however lead to the enrichment of tin mineralization (Taylor, 1979). The alteration process and mineralization are pervasive so that sharp cutoffs do not usually occur. The mineralization zones generally consist of fine grained cassiterite (0,2 to 1% Sn) and wolframite, minor chalcopyrite, pyrite, bornite, molybdenite, fluorite and pyrite. Mineralogical zoning is generally not pronounced because discrete volumes of mineralizing fluids concentrate and spread out under a barrier and over a limited vertical distance.

Large low grade endogranitic deposits that can be mined by open-cast or bulk underground methods are more attractive propositions than the tin-vein systems that are mined on a smaller scale and have erratic mineralization. Endogranitic deposits are often enhanced by adjacent high grade tin-vein mineralization or the presence of rich pipe-like bodies as at Zaaiplaats. Often W, F, B or Be is recovered as a byproduct. The endogranitic disseminated cassiterite deposits commonly have simple structures with more or less continuous mineralization in specific

homogenous areas. The upper contacts of mineralization are likely to be bounded by a lithological contact forming a natural limit to mining. The lower contact may be irregular or diffuse in the case of massive apical zone deposits, whilst sub-horizontal zones may have relatively sharp contacts. Due to the alteration effects accompanying the deposits, e.g. kaolinization, they weather easily and if an exposed host granite is deeply weathered the granite can be mined cheaply by water extraction techniques such as high pressure water jets to recover the resistate cassiterite.

#### Skarn associated Sn-W deposits

Skarn deposits are important sources for tungsten and are only in exceptional cases primarily mined for tin. Tin skarn deposits are characteristically small, irregular, of complex mineralogy and low grade. Skarn associated deposits are pyrometasomatic and develop within the metamorphic aureole of granitoids where, in an open system, the hydrothermal fluids escape into the exogranitic environment where they may impinge upon reactive country rocks such as limestone and dolomites to form typical skarn assemblages. A complete spectrum exists from high temperature calc-silicate skarn deposits to low temperature carbonate replacement deposits.

The attitude of the contact between the igneous and enclosing rocks, the bedding of the country rock, and fractures intersecting both igneous and country rocks are important in determining the shape of the deposit. The morphology of skarns at discordant contacts is more complex than at concordant ones (Smirnov, 1976). Mineralization is localized by chemical controls in a structurally favourable environment. The availability and density of fractures and the reactivity of the country rock control the quantity of incoming fluid. Temperature plays a critical role in controlling reaction rates in the suitably responsive lithologies.

Figure 22 illustrates some of the variables responsible for the complex mineralogy, paragenesis and zoning characteristics of skarn deposits. The evolution of skarn deposits begins with the shallow intrusion of a granitic magma leading to isochemical contact metamorphism. Reaction occurs with carbonate rocks to give calc-silicate and the loss of volatiles

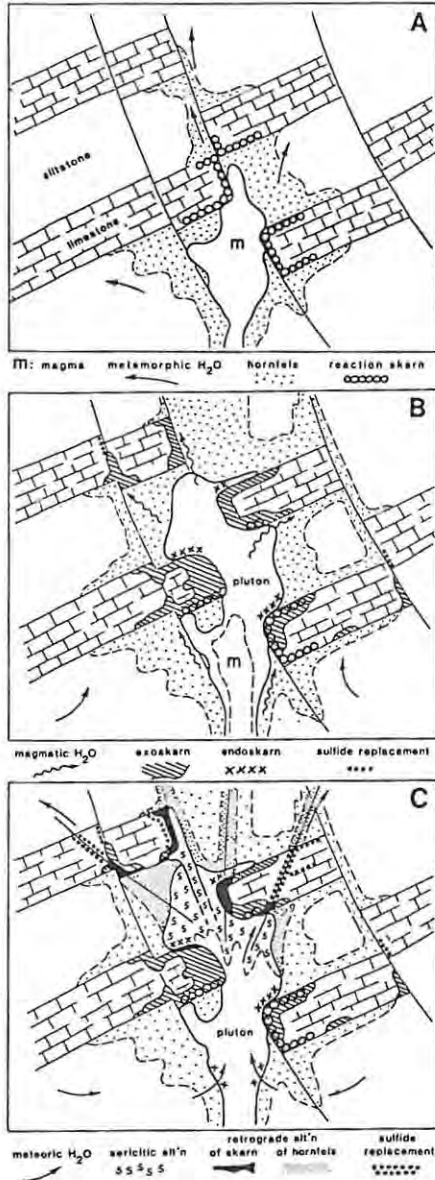


Figure 22: (Einaudi et al., 1981)

Stages of evolution of skarn deposits. A. Initial magma emplacement drives off connate and ground waters and produces a metamorphic aureole and local reaction skarns. B. Crystallization of the melt is accompanied by generation of a magmatic fluid that forms exoskarn in limestone beds along stock and fault contacts and local endoskarns where the fluid flow is into the stock. Some peripheral sulfide replacement bodies in limestone may belong to this time frame. C. Cooling of the system allows the progressive influx of lower temperature meteoric waters, which leads to sericitic alteration of the stock, retrograde alteration of skarn and hornfels, and sulfide-silica-carbonate replacement along major structures and bedding in limestone.

(CO<sub>2</sub> and H<sub>2</sub>O). The loss of volatiles leads to increased porosity, vugginess and brittleness which acts as ground preparation for later skarn and ore deposition. Accompanying further crystallization of the magma, metasomatism and iron-rich skarn formation takes place with contributions from hydrothermal fluids and possibly meteoric ground water. With time the fluid becomes enriched with sulphur and metal. Retrograde alteration of early skarn minerals together with continued ore deposition accompany the final cooling of the system. (Einaudi et al., 1981; Barnes, 1979). The complex replacement reactions involved in the skarn forming processes result in very complex mineralogy that is not always amenable to beneficiation.

Taylor (1979) distinguishes two groups of tin skarn deposits. Both are iron rich but one contains significant iron oxide whilst the other contains sulphide. In general the tin of magnetite skarns is not recoverable and it is very fine grained and occurs as inclusions and exsolutions in iron minerals. Sulphide rich skarns usually contain early oxide phases superimposed by late sulphide-cassiterite-stannite phases. Deposits of this type are also mineralogically complex and most tin is tied up in skarn and silicate minerals such as malayaite. Another complication characteristic of tin-skarn deposits is their complex zonal mineral arrangement due to multiple phases of fluid introduction. The zonal arrangement may further be complicated by replacement during introduction of late phases.

Tungsten skarns which form from impure calc-silicate marble tend to be coarse-grained, vuggy and of uneven grades. Tungsten skarns formed from pure marble tend to be medium grained, compact, and possess more uniform grades. The abundance, grain size and molybdenum content of scheelite present in the skarns varies with associated calc-silicate gangue and early anhydrous skarn contains moderate and relatively consistent grades of fine grained, high molybdenum scheelite. Skarns possessing significant amounts of retrograde alteration are particularly amenable to small scale selective mining because they are characterized by erratic high grade veins and alteration zones (Einaudi, et al., 1981).

#### Tin-tungsten vein deposits

Tin-tungsten fissure lodes are pneumatolytic-hydrothermal deposits that form at any favourable site from within the endogranitic environment to the distal exogranitic environment. Generally they are related to apical roof zones of granitoids and either emanate from the cupola or lie on the flanks of cupolas. Tin-tungsten vein deposits are extremely diverse in shape and highly variable in metal distribution and concentration (Archer, 1981). Because these deposits form by open space filling and in part by replacement, the location and morphology of the vein systems are controlled by structural and lithological factors. Replacement bodies develop where fractures intersect horizons such as shale or carbonate that are susceptible for replacement. Deposits of this type may form large economic deposits such as Mt Bischoff, Cleveland and

Renison Bell in Tasmania. A combined case of chemical reactivity with specific mechanical response of a litho-stratigraphic unit is represented by the Rooiberg tin district, where mineralized arkosites display replacement phenomena superimposed on a local fracture pattern.

Geological structure controls the plumbing system through which the hydrothermal fluids escape and determines where the tin-veins are formed, the length and thickness of the veins, the overall distribution of mineralization, final shape of the vein and the position of the ore shoots in the vein. The extent of mineralization is therefore controlled by the nature of the country rock, degree of fracturing, age of fracturing, rate of fluid flow, and temperature-pressure conditions.

Both primary and secondary structures control the morphology and tonnage of vein Sn-W-deposits. Primary structural controls are those that form at the same time as the host rocks and include structures that control fluid distribution and localization, e.g. porosity, permeability and bedding plane contacts. Secondary controls are those that make the host rock receptive to fluids, e.g. faults and fractures. The competency of a host rock to allow fracturing is important for ore localization. A competent brittle rock, e.g. silicified siltstone will fracture easier and will be better mineralized than an unaltered less competent siltstone. Ore shoot control within veins is extremely variable and is controlled by: (a) Variations in lode structure, e.g. movement along irregular fissure planes; (b) Lode intersections; (c) Lithological contacts or bedding planes may act as zones of weakness along which open space dilational features may form under compression; (d) Structure and metal content of a lode may change when intersecting a dyke because of the contrast in rock competency, e.g. the Wheal Jane deposit (figure 20), where extensive shearing between feldspar-porphyry dykes and slates coupled to the impermeable barrier formed by the dykes have resulted in excellent sites for Sn-deposition; (e) Ore zones change upon intersecting faults which act as restraining barriers that pond mineralizing fluids to form enlarged ore bodies.

The geological controls of grade variation in vein systems are highly complex and result in grade distributions that are always erratic. Initial input of tin into the hydrothermal system is subject to natural

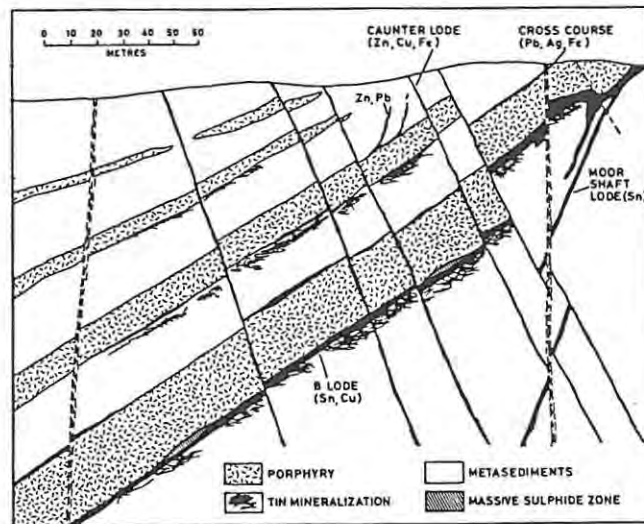


Figure 23: Idealized section through Wheal Jane, South West England, Cornwall, showing complex vein pattern. (Taylor, 1979)

randomness, and superimposed on the random influx are the structural and lithological controls and the influence of temperature and pressure gradients. The highly complex and multiphase nature of the veins are also as a consequence of continual reopening of the veins over a long period of time. This structurally controlled reopening controls the deposition of successive phases of mineralization and because only parts of the vein may reopen at different times the distribution of tin (or tungsten) is likely to be highly irregular. Not all successive phases will be ore bearing and dilution of grade may occur due to the introduction of a late gangue phase.

Lithological control on grade may be two-fold. Firstly different chemical compositions of alternating lithologies result in selective alteration, leaching and precipitation so that there is a distinct chemical control on the position of the ore shoot in a vein. In the second case there may be a structurally induced fluctuation in values produced by changes in lithology. Lithology controls the variation in joint pattern and the ease of opening of bedding planes and partings (Garnett, 1966 a; Archer, 1981).

Some of the factors affecting grade such as lode infilling, width, dip and strike, and wall rock composition are shown in figure 24, where data from an exceptionally well mineralized lode from S.W. England has been plotted onto longitudinal sections. Tin veins are typically highly irregular in all their geological features. In particular, morphology is complex and this influences grade and tonnage distribution. Tin veins may incline structurally at any angle, are generally not continuous and mineralization may only appear in selected portions. Mining methods have therefore to be adaptable to suit local conditions. The vein deposits are normally high grade low tonnage deposits and not amenable to high production mining. Larger tonnages are occasionally found in closely spaced sub-parallel tin vein swarms as at the Van Rooi's Vlei, Upington and Hemerdon, S.W. England prospects where bulk mining methods could be applied.

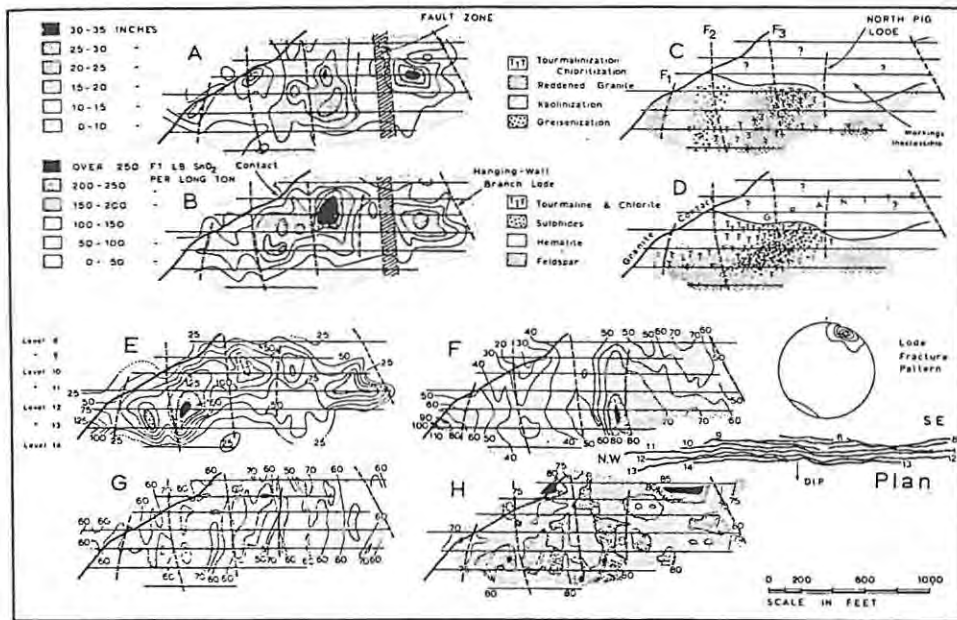


Fig.24 No. 3 Branch lode, showing in longitudinal section the following: A—lode width contour diagram, contoured in inches; B—lode value contour diagram, contoured in ft lb SnO<sub>2</sub>/ton; C—variation in wallrock alteration; D—variation in lode infilling; E—lode grade contour diagram, contoured in lb SnO<sub>2</sub>/ton; F—Conolly diagram; G—lode strike contour diagram, contoured in degrees West of North; and H—lode dip contour diagram, contoured in degrees  
(Garnett, 1966a)

## Discussion

The increase in complexity of tin deposits in the open exogranitic environment relative to the closed endogranitic environment is due to the increase in the number of variables that influence the deposition of minerals from the hydrothermal fluid phase. The large, low grade, disseminated endomagmatic deposits form by pervasive alteration processes in a closed system giving rise to continuous fine grained cassiterite (+ wolframite) mineralization. Due to confining structures in the roof zones of the deposits they may have sharp hangingwall cutoffs but other boundaries are gradational and have to be determined by assay. Zoning is not pronounced in the endogranitic deposits and structurally controlled richer zones may be present within the orebodies. The orebodies are generally amenable to bulk mining methods and evaluation by drilling.

Deposits in the exogranitic environment are still closely related to granitic intrusives, although ore deposition is controlled chemically and/or structurally by specific lithostratigraphic units. The stratigraphic control reflects high permeability of the host rock during mineralization, which is provided either by chemical reactivity or by mechanical properties of the host rock. The former case is realized in skarn horizons, where permeability is increased principally by the transformation of calcareous material into denser calc-silicate phases. Successive pulses of high temperature hydrothermal fluids and the composition and attitude of reactive country rock play a dominant role in determining the characteristics of skarn deposits, leading to complex mineralogy, paragenesis and zoning. A large proportion of tin in skarn deposits is tied up in skarn and silicate phases which cannot be recovered during beneficiation processes. A significant amount of magnetic cassiterite is also often present in skarn assemblages which is also lost during beneficiation in the magnetite concentrate (Archer, 1981)

Tin-tungsten vein deposits are characterized by their inherent irregularity and are dominantly controlled by primary and secondary structural features. They vary in shape from tabular to cylindrical pipes formed at the intersection of two fractures, they are likely to change rapidly along their course and often assume the form of disseminated pods and irregular bulging zones. They frequently change character at lithological boundaries and often switch from one fracture to another.

Due to the erratic nature of mineralization it is almost impossible to drill sufficient boreholes to calculate ore reserves and the best method of obtaining grade information is by trial mining (Archer, 1981). Drilling is used in locating the position and monitoring the persistence, structure and mineralogy of the veins. The inherent random nature of the mineralizing fluids superimposed onto the variable structural sites of ore deposition cannot be accommodated by geostatistics for ore reserve estimation.

Cassiterite in tin deposits is recovered primarily by gravity separation and the average recovery is only between 60 and 65 percent (Taylor, 1979). The low recovery is due to the large grain size variations present, particularly in vein systems where cassiterite is frequently very fine grained and intimately associated with other minerals. Cassiterite is often also present as fine intergrowths in sulphide minerals and can be lost during sulphide separation. A significant cause of losses through sliming is due to the variability of crystal forms. Cassiterite often occurs in different habits at the same site, particularly if successive phases of mineralization have occurred. It is often difficult to find an optimum grinding size that will liberate most of the cassiterite without the occurrence of sliming (Taylor, 1979; Archer, 1981). Coupled to the inherent variability of exogranitic tin deposits is the wide variability in specific gravity within the ore. Gangue material often contains very variable amounts of sulphide and other heavy minerals and often is also porous so that a constant density contrast does not exist in the ore. The specific gravity of each sample is therefore usually combined with its assay to arrive at a properly weighted average value.

#### Porphyry-Type Deposits

Porphyry-type deposits are the products of large, intrusion-related hydrothermal systems that resulted from the emplacement at shallow depths and the subsequent cooling of porphyry plutons. These phenomena resulted in the extensive evolution of secondary permeability (i.e. fractures) in both pluton and host rocks which promoted the circulation of water from various sources through both the pluton and its wall rocks. The result

was to produce large volumes of altered rock often containing economic quantities of copper, molybdenum, gold, or tin mineralization. The broad geological setting, tectogenesis, alteration and mineralization of porphyry systems are reviewed by Titley (editor, 1982); Titley and Beane (1981); and Hollister (1978). In addition to giving a short summary of their main characteristics Reichardt-Barends (1980), also emphasises the factors affecting evaluation of porphyry deposits.

A unique feature of porphyry-type deposits is their large tonnage and low grade. Most porphyry copper deposits have grades of 0,4 to 1% Cu and total tonnages range up to 1000 million tons and some even greater (Evans, 1980). Porphyry deposits are associated with intrusives, emplaced near to surface, that are related to the roofs of granodioritic batholiths. The intrusives are acid to intermediate, have a porphyritic texture and a fine grained phaneritic to aphanitic matrix. Ore bodies outlined are elliptical to circular in plan with generally an outcrop of about 1300 to 200 m in diameter. The orebodies contain disseminated and stockwork mineralization in the intrusive as well as in wall rocks. Alteration pattern and sulphide mineralization are zoned relative to the intrusive porphyries and supergene enrichment of the upper portions of deposits is often present. Intrusions with porphyry-type mineralization differ from non-productive plutons by having persistent and pervasive hydrothermal alteration effects that extend into the surrounding wall rocks.

Commonly a number of other types of mineral deposits are related to the same igneous centre that generated the porphyry deposit. These include mineralized vein systems, pegmatites and skarn deposits.

The location, differentiation of the calc-alkaline magma, and the level of exposure determine the style and types of mineralization present in a porphyry deposit. Factors that make a deposit viable are, the intensity of the porphyry system controlling the quality and metal content of the deposit, and the extensive nature (magnitude) of the system controlling the size of the deposit.

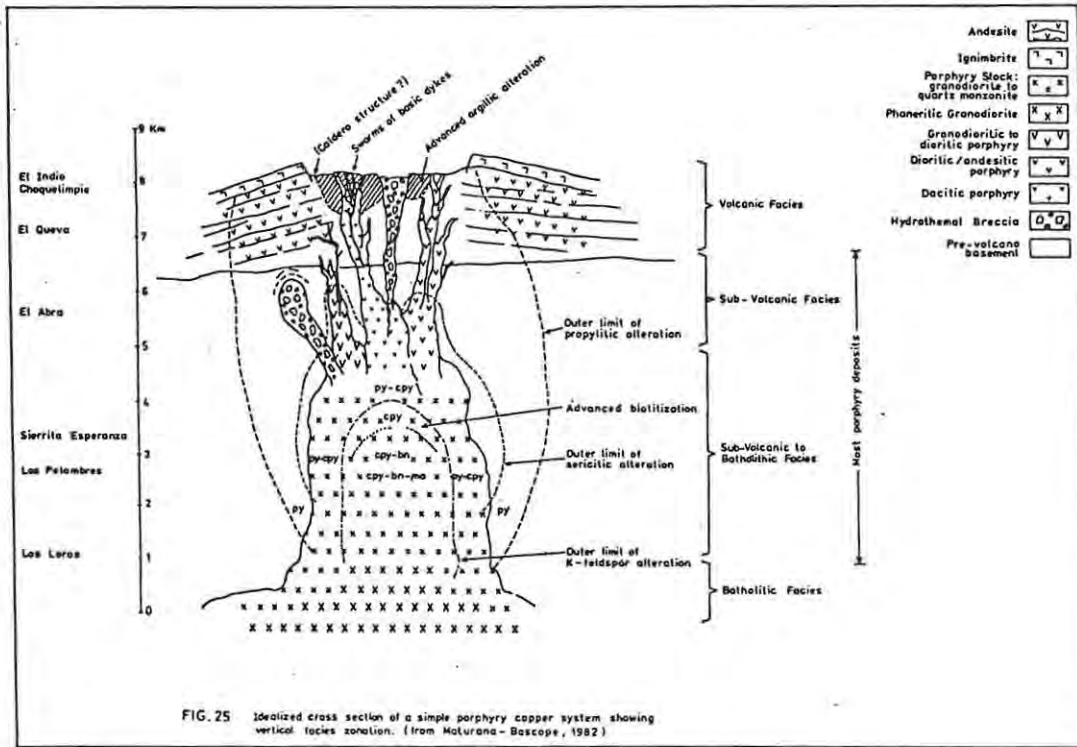
### Regional control

On world-wide scale there are differences in the ratios of metals present in the porphyry deposits. Traditionally two principal types of deposits have been distinguished, the granodioritic to quartz monzonitic intrusives hosting Cu-Mo mineralization (Lowell and Gilbert model) postulated to have developed within a relatively thick continental crust, and the syenitic-monzonitic intrusions hosting Cu-Au mineralization mainly found in island-arc environments. Titley and Beane, 1981, have however shown that the differences amongst groups of deposits cannot clearly be related to specific geotectonic settings and contend that the character of a porphyry deposit may more strongly be affected by the immediate environment than by its parentage.

### Level of exposure

Porphyry copper systems effectively span the boundary between the plutonic and volcanic environments. Sillitoe, 1973, suggested that typical porphyry copper deposits grade downward into stockwork mineralization and potassium silicate alteration in a phaneritic intrusive, which in turn is transitional downward to an essentially unaltered pluton of considerably larger dimensions than the stock. Upwards the porphyry deposits grade into a comagmatic volcanic pile, transected by a column of hydrothermal alteration representing the upper parts of the system. The level of exposure of a porphyry system is therefore an important variable as it has a direct bearing on the mineralogy and style of ores present near the surface amenable to mining.

Based on Sillitoe's model Maturana-Bascope, 1982 distinguishes different 'facies' in the magmatic systems producing the porphyry copper deposits. The facies, summarized in figure 25, each correspond to a distinctive style of intrusion, alteration and mineralization all becoming more complex away from the plutonic towards the volcanic environment. In the 'volcanic facies' intrusive activity into an andesitic volcanic centre consists of dacitic/rhyolitic plugs, the necks of andesitic and ignimbritic volcanic activity and late swarms of basic dykes. Argillitic alteration and silicification is superimposed on weak propylitic alteration, mineralization is dominantly epithermal veins, and



some disseminated Au-Ag low-temperature mineralization may be present. Pyrite mineralization may be related to the dacitic and rhyolitic plugs.

The complicated relationships found in the 'sub-volcanic facies' are the result of different small intrusives generated during the cooling and differentiation of the main porphyritic intrusive. Distribution of ore is irregular as it is controlled by the local intrusives, each superimposing its own style of intrusion, hydrothermal alteration and mineralization on the previous igneous events. For their correct evaluation unravelling of the geology in these deposits is essential as shown in figures 26 and 27.

In the deeper 'sub-volcanic to batholithic' facies the alteration patterns, mineralization and intrusion history are more simple and dominated by the main porphyry (figure 28). One major granodiorite to quartz monzonite porphyry is usually recognized, with K-alteration in its core, a halo of quartz-sericite alteration affecting the outer edges of the intrusive and the nearby country rocks, and propylitic alteration further away. The ore bodies are larger, lower grade and mineralization

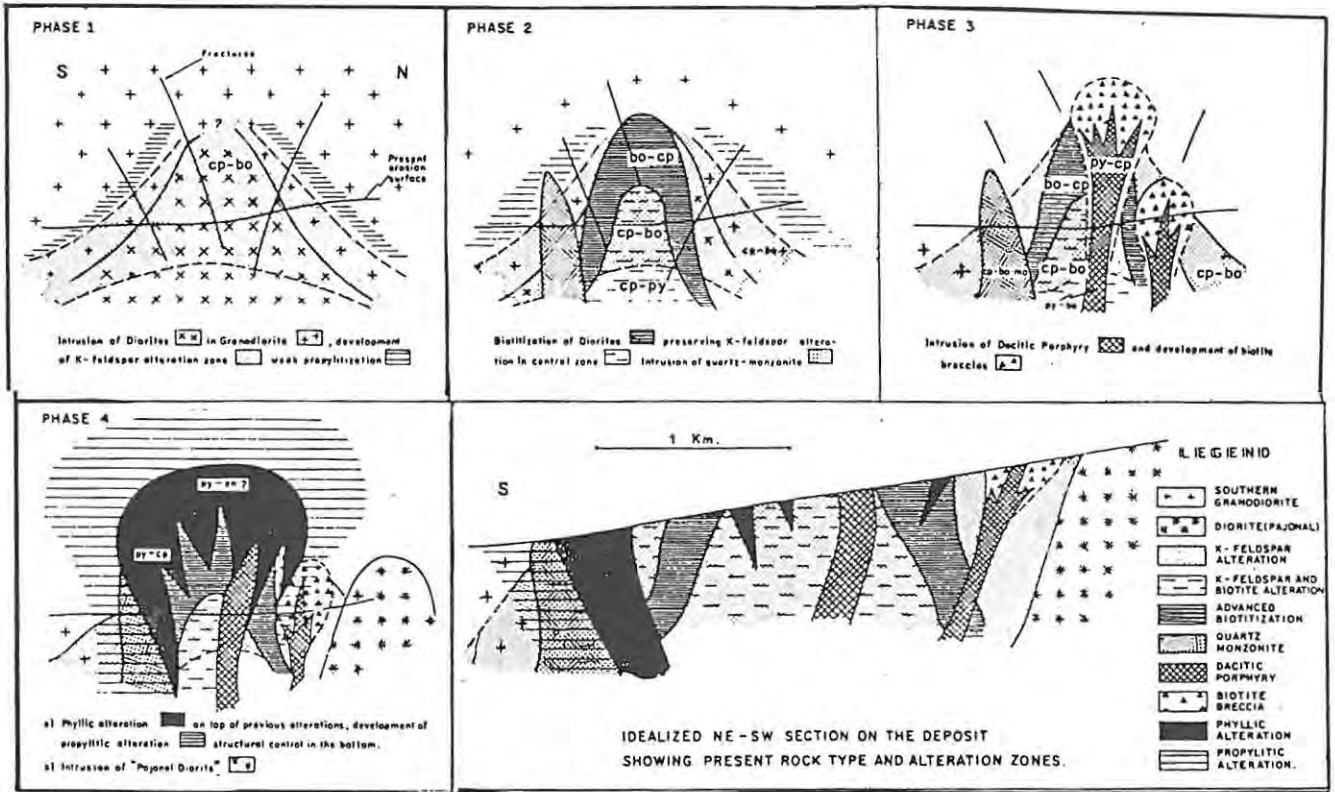
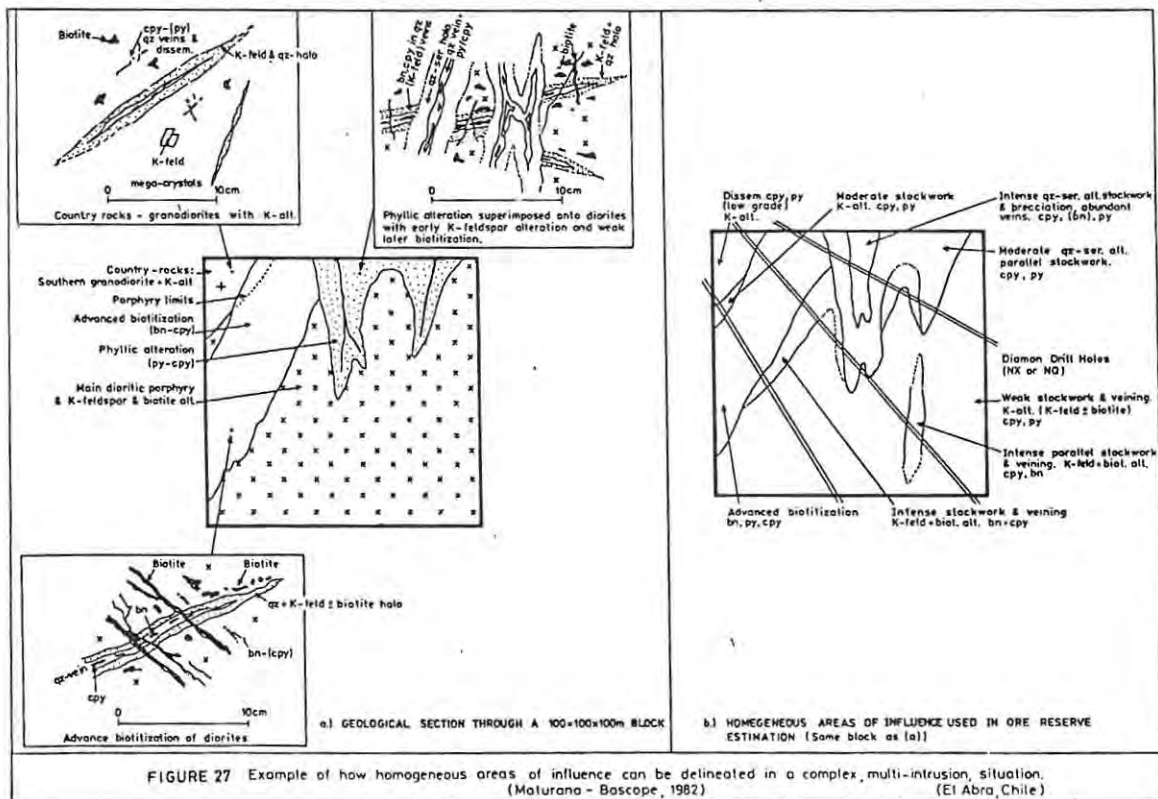


Figure 26: El Abra alteration and primary mineralization (Ambrus, 1977)



more homogenously distributed. The development of secondary enrichment is often critical to make the 'subvolcanic to batholithic' deposits viable. The deeper portions of porphyry systems are preserved in the 'Batholithic facies' and are generally subeconomic.

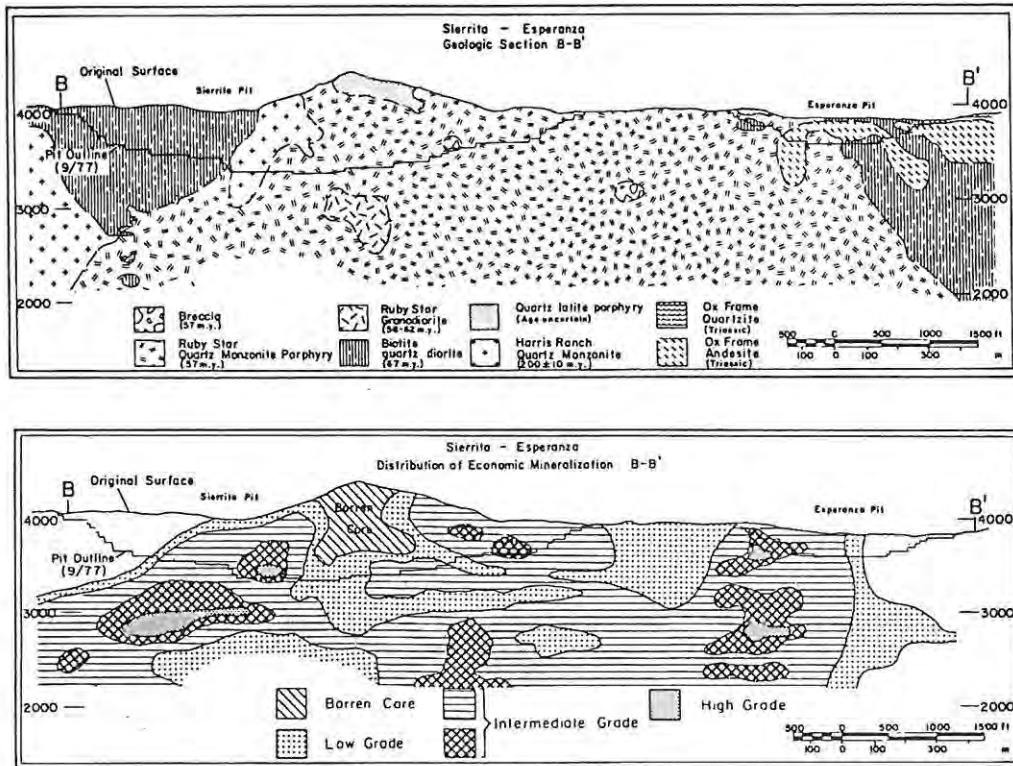


Figure 23: Geologic section (top) showing copper-molybdenite grade (bottom) at Sierrita and Esperanza. (West and Aiken, 1982)

Superimposed on the vertical facies zones of porphyry deposits is also the effect of the mode of emplacement of the porphyry bodies (Maturana-Bascope, 1982). A fast intrusion produces a rapid saturation of water and volatiles resulting in high hydraulic pressure and is therefore characterized by intense fracturing, hydrothermal alteration and mineralization. Mineralization may also be erratic and structurally controlled. A slowly intruding porphyry would have time to re-adjust itself to the pressure and temperature changes as it approaches the near-surface environment. Rather than a rapid increase in volatile build-up fluids would gradually be released upwards through the porphyry, resulting in a lower intensity of hydrothermal alteration and mineralization but with a more even distribution.

### Magnitude of a porphyry system

Porphyry type deposits are host (or wall-rock) as well as structurally controlled. The host-rock provides a regional constraint for the mineralization, and structural and alteration features provide more local constraints. Porphyry deposit boundaries represent the outer limits of the effects of mineralizing processes. These processes may produce protore grades of up to 1% Cu. Beyond the deposit boundaries the rocks usually contain 5 to 150 ppm Cu (Singer, et al., 1975).

Large copper deposits are commonly related to relatively large intrusions or intrusive complexes, although the intrusive mass within the complex genetically related to mineralization may be small. Small complexes give rise to relatively small concentrations of metals and are generally uneconomical (Titley and Beane, 1981).

Porphyry-type deposits with mineralization restricted to an intrusive body yield a mineralized tonnage that is controlled mainly by the volume of the intrusion. In deposits where favourable wall rocks are mineralized the size of the ore bodies may be dependant on the stratigraphic thickness of the favourable beds or the width of the mineralized zones surrounding the porphyry deposit. The width and shape of the mineralization in the wall rocks are dependant on the temperature of the intrusion, pressure, hydrothermal conditions near the intrusion, and the physical and mineralogical-chemical character of the adjacent host rock. At contacts with carbonates chemical and probably thermal gradients are so telescoped that sudden precipitation of metals commonly produces high-grade narrow skarns.

The initial function of structural control in porphyry-type hydrothermal mineralization is to increase the permeability of the rock that will host the mineralization. This form of ground preparation is represented by tensional openings, either as breccia columns and/or stockwork fracture systems. The localization of these structures will affect the distribution of the hydrothermal alteration and mineralization. The stockwork system in a porphyry may be of a tectonic or hydraulic origin. Hydraulic stockworks and breccia columns are produced in response to the build-up of hydraulic pressure of the residual gaseous phase during the cooling of the near surface magmas. Complex stockworks may be produced

if the fracturing is as a result of repeated pulses of hydraulic pressure, e.g. the Red Mountain porphyry Mo-deposits in Colorado (White et al., 1981). Stockworks of tectonic origin in porphyries are developed in regionally localized areas in response to pressure of regional nature. Stockworks of tectonic origin tend to present regular and continuous fracture patterns, e.g. the Haib porphyry copper prospect, South West Africa (Reichardt-Barends, 1980). The presence of tectonic stockworks may indicate lower hydraulic pressures and probably weaker hydrothermal activity. A combination of both tectonic and hydraulic stockworks exists in some deposits, often the hydraulic stockwork is superimposed on the tectonic stockwork producing a richer ore body, for example, Chuquicamata, Chile.

Post ore porphyry intrusions may partly destroy pre-existing ore bodies. A part of the Urad orebody was destroyed by a later porphyry intrusion in the Red Mountain complex in Colorado (White, et al., 1981).

#### Intensity of a porphyry system

Hydrothermal alteration and mineralization zones usually show a concentric pattern in relation to the intrusive stock. A typical porphyry copper deposit has a central economic portion characterized by concentric shells of potassium silicate, sericitic, and argillic zones, and an outward propylitic alteration zone, figure 25. The Fe/Cu ratio of the sulphide minerals also increase towards the marginal alteration zones in copper porphyries, with high concentrations of bornite and/or chalcocite grading through chalcopyrite to pyrite in the outer fringes. The grade depends on a combination of factors relating to the intensity and number of phases in the mineralizing process, the concentration of the mineralizing solutions, the rate of change of the concentrations in the depositional process and the availability of sites of deposition. The most important sites for deposition are those related to the processes giving rise to breccia and stockwork systems discussed in the previous section. The ground preparation provided by the intensity and abundance of hydrothermal fractures in a stockwork can be related to the intensity of mineralization. Sites for disseminated mineralization in host rocks include carbonate wall rocks (skarn-type), dispersed iron oxide in iron-magnesium silicate minerals,

sites around the margins of sericitized feldspars and micas and prior sulphide mineralizations that act as nuclei of deposition for later stage sulphides (Reichardt-Barends, 1980).

Grade is also affected by repeated hypogene and supergene mineralization processes superimposed on each other. The latest of the igneous intrusions and related hydrothermal events can in some cases remobilize the early mineralization and upgrade the metal content, e.g. the Henderson ore body. Successive pulses of mineralization could also give rise to separate, stacked ore bodies related to one intrusive centre, e.g. Climax orebody, (White et al., 1981). With each pulse of mineralization superimposed on a previous pulse, a complex pattern of mineralization may develop. A second pulse may follow a different fracture pattern and if not recognized can lead to a bias in drilling and lead to incorrect ore reserve estimation. Figure 27 illustrates the importance of unravelling the sequence of events related to the various minerals and alteration phases and the classification of ore types. Ores in these different zones are classified separately due to differences in by-product content, pyrite content, comminution, metal recoveries and rock mechanical properties.

Most high grade primary porphyry deposits have strong alteration zones. In lower grade deposits the potassic alteration, for example, is widespread, is spotty and not as pervasive. The size, grade and regularity of the mineralization-alteration zones decreases as the intensity of hydrothermal processes also decrease. As alteration zones become more diffuse the grade of the mineralization tends to become more dependent on the composition and textures of the host rocks. Consequently the separation of high from low grade zones, such as potassic from propylitic, becomes less distinct, and the application of selective mining methods more difficult (Reichardt-Barends, 1980).

Leaching and supergene enrichment are important processes in many porphyry copper deposits containing low grade primary mineralization and form an important component in making the deposits viable. Factors which assist the secondary enrichment process include inert wall rocks, a warm climate, a deep fluctuating water table and a high proportion of pyrite in the leached rocks (Reichardt-Barends, 1980). Supergene ore is

normally classified separately from the primary or hypogene ore, due to its different chemical and physical properties. As supergene mineralization is related to a present or former erosion surface, its distribution pattern is considerably different from that of the primary ore.

Porphyry copper deposits commonly contain minor amounts of other metals. Due to the large scale of mining it is often economical to recover some of these metals. In many instances the presence of molybdenum or gold may make the difference between a viable or a sub-economic proposition. The degree of recovery of each metal during metallurgical processing is a function of many variables, e.g. the recovery of molybdenite varies with the abundance of the mineral, grain size and composition of the associated sulphides. Gold in porphyries commonly present recovery problems, because it is usually present as very fine particles of native metal or in solid solution with sulphide minerals. Sulphide grains in supergene enriched zones may also have an oxidized plating inhibiting their flotation.

#### Discussion

The variety and quantities of metals present in a porphyry system are determined to a large extent by the regional setting, and the composition and crystallization history of the calc-alkaline magma that gave rise to the porphyry system. The level of exposure of the porphyry system is directly related to the style of the intrusions, mineralizing patterns and complexity of the alteration zones.

Porphyry copper deposits illustrate the increasing complexity of factors determining the viability of a deposit in the transition from plutonic to volcanic environments. Factors affecting tonnage and grade at deeper levels of exposure, closer to and related to the magmatic environment, are more simple and lead to larger, more homogenous ore bodies. Factors controlling tonnage and grade at higher subvolcanic levels are more numerous and lead to complex mineralization and alteration patterns. Larger porphyry deposits are associated with the larger intrusive complexes (or systems). With an increase in the intensity of a porphyry system better mineralization can be expected, but on the other hand more

complex mineralizing patterns evolve as the intensity increases, adding to the difficulty in evaluating the deposits. Estimation errors in porphyry deposits usually arise because the complexity of stockwork veinlets, variations in zoning and grade distribution patterns which are not fully appreciated.

Even in the low level 'sub-volcanic to batholithic' porphyries, figure 28, in which grade distribution tends to be uniform or shows only gradational changes on a large scale, considerable variation on a small scale (tens of centimeters) is present. Within e.g. the phyllic zone where mineralization is controlled by stockwork veinlets, core samples tend to overestimate high grade mineralization and underestimate low grade mineralization due to a nugget effect. Since the low grade blocks are excluded from ore reserve calculations, this effect can lead to an overestimation of the grade and an under-estimation of the tonnage of a deposit.

Several porphyry case histories show that the distribution pattern of ore and waste in the deposits was neglected during the feasibility stage where an appropriate mining scale had to be chosen. This inevitably resulted in poor recovery and high dilution during mining (Reichardt-Barends, 1980). Porphyry deposits seldom show precise boundaries of mineralization and mining limits are determined by assay. The cut-off grade may vary within a deposit, being dependant on such factors as metal recoveries in different ore types and different waste-to-ore ratios (Empsall, 1981).

#### VOLCANIC- AND SEDIMENTARY- EXHALATIVE SYSTEMS

Deposits in this group are conformable, frequently banded massive sulphide deposits. The principle ore constituents are usually pyrite (pyrrhotite) with varying amounts of copper, lead, zinc and barite minerals and minor precious metals. The deposits are formed by syngenetic submarine exhalative processes and two distinct types are recognised, those formed by exhalations of hydrothermal solutions in a volcanic environment, and those formed in a sedimentary environment without evidence of direct volcanic activity. Grade characteristics in the

deposits are largely determined by the rate and volume of mineralized hydrothermal exhalative activity, relative to precipitation of chemical phases such as cherts and deposition of fine grained clastic material. Secondary geological processes are important in upgrading many of the deposits.

#### Volcanic Associated Massive Sulphide Deposits

Volcanic associated massive sulphide deposits are stratabound and in part stratiform accumulations of sulphide minerals which formed on or near the sea floor by precipitation near the discharge site of hydrothermal fluids (Franklin, et al., 1981). In their stratiform portions the deposits are normally composed of massive sulphide (usually more than 60% sulphide minerals), but many deposits have a substantial component of discordant vein-type sulphide mineralization, the stringer ore, mainly in the footwall strata. The mineralogy of the deposits is simple considering their diversity in size, geological setting and post ore metamorphism. The iron sulphides, particularly pyrite and pyrrhotite, characteristically comprise at least half of the total sulphide content. Sphalerite, chalcopyrite and galena, in widely varying proportions, constitute most of the remaining sulphides (Sangster, 1972). The ores occur predominantly in volcanic environments and are an integral part of, and coeval with, the volcanic complex in which they occur. Several ore bodies usually occur at or near the same stratigraphic horizon over large areas, displaying a consistent relationship between stratigraphy and zoning of the ores. The orebodies are commonly associated with pyroclastics containing massive sulphide clasts. Alteration of the footwall rocks of the orebodies is common, and they are characterized by sharp contacts between the massive sulphide and overlying chemical sediments, which are preserved as iron formations, chert or barite beds.

On the basis of their mineralogy the ore deposits fall into two distinct groups, a Cu-Zn and Zn-Pb-Cu group determined by their geological setting (Franklin, et al., 1981). Many of the Cu-Zn groups such as those in the Canadian Shield are contained in compositionally bimodal volcanic sequences with felsic rocks predominant near the deposits. The ophiolite Cu-Zn deposits such as those in Cyprus occur at the contact between two pillowed, mafic volcanic sequences and the Besshi-type Cu-Zn deposits occur

in areas of both mafic and sedimentary rocks. Deposits of Zn-Pb-Cu are in stratigraphic settings dominated by either felsic volcanic rocks (Kuroko) or by sub-equal amounts of felsic and sedimentary rocks (Bathurst, New Brunswick).

#### Primary factors controlling grade

As the volcanic associated massive sulphides were formed at or near the discharge sites of submarine hydrothermal systems, the size of the hydrothermal system and the nature of the exhaling brine would determine the tonnage, metal zonation and spatial position of the orebody relative to the vent. Ore deposition was from hydrothermal solutions which ascended along fractures or other zones of weakness, the passageway now preserved as an alteration pipe stratigraphically beneath the massive sulphide orebodies. The orebodies have a tendency to occur in clusters, which makes them an attractive proposition as more than one body could be mined in a single operation.

The strength and duration of the hydrothermal discharge is the most obvious factor determining the ultimate size of a massive sulphide deposit. This can be correlated with the strength and duration of the preceding volcanic activity, which implies a large volcanic centre. A larger heat source would probably involve greater amounts of metal bearing hydrothermal fluids (whether magmatic or not) resulting in larger and a higher frequency of deposits. The Noranda area (figure 29) with a 16 000 m thick pile of volcanics has about one deposit per 2 to 3 sq km, contrasting with the Sturgeon Lake 8 000 m thick pile of volcanics with one deposit per 320 sq km (Venter, 1981).

The conditions under which fluids can transport appreciable volumes of metals are limited and changes in temperature, pressure, oxygen fugacity, pH or Eh will cause rapid deposition of metals from the fluids. Sato (1972) believes that the salinity and temperature of the ascending fluid governs its mixing behaviour with seawater, and he distinguishes three types of behaviour (figure 30). A lower temperature brine, with a high salinity would tend to flow down slope from the vent and collect in a depression, resulting in a relatively thin and widespread ore deposit removed from the vent (type I). On the other hand a low density high temperature

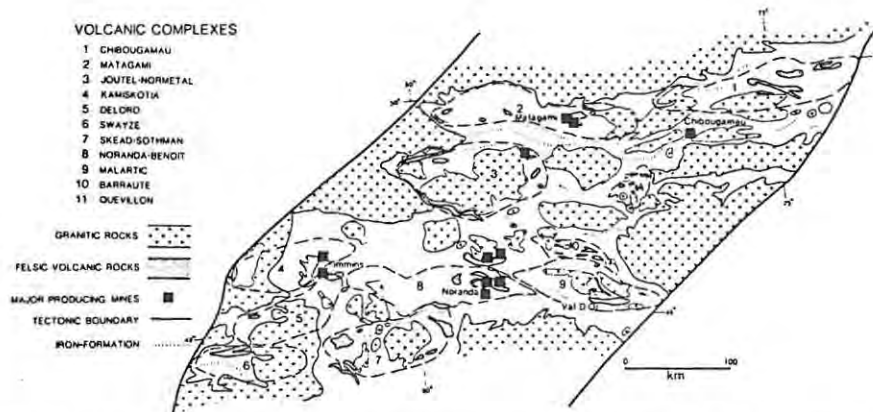


FIG. 29 The Abitibi belt, part of the Superior province of the Canadian Shield, modified from Goodwin and Ridler (1970) and Sangster and Scott (1976) to show the close spatial relationship of massive sulfide deposits to felsic volcanic centers. Note also that iron-formations are most commonly outside the major volcanic complexes and are not close to massive sulfide deposits.

(Franklin et al., 1981)

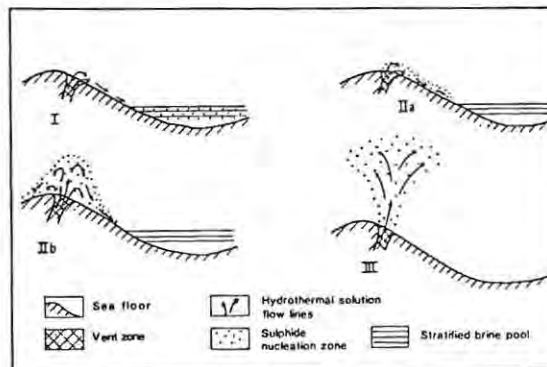


Figure 30: Probable behaviors of the four types of hydrothermal solutions discharging into a submarine environment, defined according to their initial temperature and the salinity relationships.

(Franklin et al., 1981)

brine can be expected to float up, mix and disperse rapidly without forming concentrations that might constitute ore (type III). Brines with intermediate densities and temperatures can either expect to form a thick ore mass with little topographic control (type IIa) or could result in deposition anywhere in the vicinity of the vent (type IIb). This may lead to deposition in gravitationally unstable positions and the unconsolidated ores may be reworked by submarine sliding, leading perhaps to turbidity current transportation and deposition.

Shown in figure 31 are the different types of ore that are associated with an idealized, undeformed volcanic associated massive sulphide deposit. The massive ores formed from chemical precipitation, and as a result the layering and two longest dimensions of the massive ores are parallel to bedding planes or flow contacts in the host rocks.

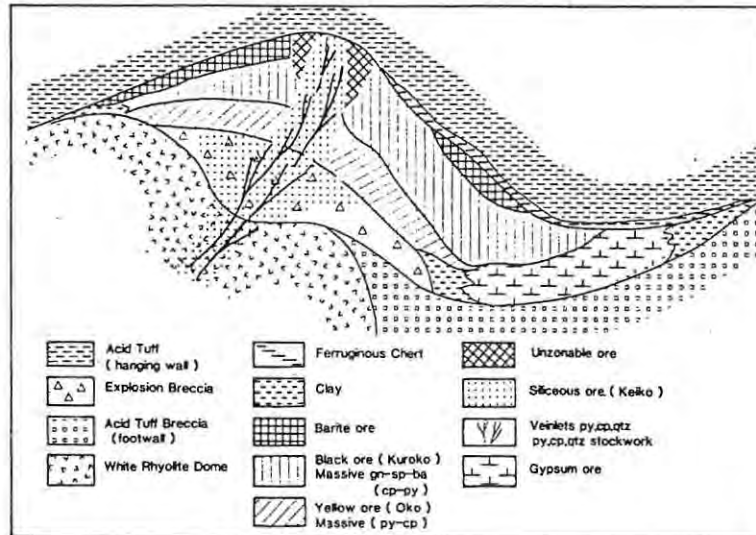


Figure 31: Idealized cross section of a typical Kuroko deposit. (Franklin, et al., 1981)

Sharp contacts of the sulphide body hangingwall with country rock are the rule, while footwall contacts are generally more diffuse and can often only be determined by assay. The more 'distal' (type I) orebodies tend to be blanket shaped within layered rocks such as tuffs, while those in volcanic rocks (type II) tend to be more ovoid in plan.

The massive ores are commonly underlain by bedded and banded ores. The bedded and banded ores resulted from the gradual buildup of mineralization preceding the voluminous exhalation of brines to give rise to the massive sulphide ores. Ores formed on or close to a central volcanic vent (type II) tend to be hosted in strata beneath a cherty capping while the more distal types (hydrothermal centre associated) tend to be hosted in, or associated with, chert or banded iron-formation. In both cases the ores have sharp hangingwall contacts and a diffuse footwall. Stringer ores, when present, are always in the stratigraphic footwall of the massive sulphide ores and formed by fissure filling, dissemination or replacement of ascending ore

forming fluids in pre-existing rocks. Total sulphide content of stringer ores seldom exceed 25%, and is variable. The stringer ore, when undeformed, consists of anastomosing veinlets, veins and irregular disseminations cutting across stratigraphy and is funnel shaped beneath the massive ore. Successive emanations of ore forming fluids could result in phreatic-type explosions and the brecciation of pre-existing ores and host rock. Although the distal type I (figure 30) orebodies are thought to have formed away from the main vent, and therefore do not have an associated stringer orebody, some 'distal' deposits, e.g. Rosh Pinah, South West Africa, have minor stringer zones associated with the massive ore indicating that they could have formed above a subsidiary hydrothermal vent or vents branching off the main volcanic centre.

Mineral zoning is typical of all volcanic associated massive sulphide deposits and is related to the relative solubilities of the metal sulphides. On the stratigraphic footwall side massive chalcopyrite-pyrite (pyrrhotite) rich ore commonly grades into pyrite (pyrrhotite) - chalcopyrite stringer ore. Within individual massive ore lenses the combined metal content usually remains constant throughout, but Cu values tend to increase towards the footwall at the cost of Zn (+ Pb), whereas Zn (+ Pb) increases towards the hangingwall at the cost of Cu. In all cases the richest ore (highest Zn (+ Pb) + Cu) occurs adjacent to the sharp hangingwall contact. In some deposits the actual amount of copper increases towards the footwall and forms high grade zones (Venter, 1981). Textural zoning is concomitant with mineralogical zoning in that the more sphalerite rich portions are generally banded, expressed as mono-mineralic layers of pyrite and sphalerite, whereas the chalcopyrite-rich portions seldom show banding and are often brecciated. The brecciated massive ore grades into stringer ore if present. The influence of ore body zonation on grade and tonnage relationships within individual orebodies is significant. Since mineable grade also depends on economic considerations such as the price structures and marketability of various mineral commodities, the influence of metal zoning and the importance of ore classification for grade control is considerable. Figure 31 shows an idealized cross section through a volcanic associated massive sulphide deposit and figure 32 the more common, deformed deposit.

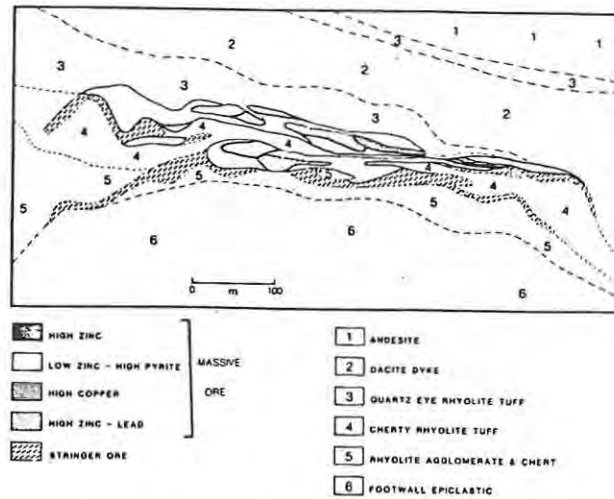


Figure 32: Plan of the compositional zoning of the Matabi mine. The stringer ore is high copper; uneconomic vein and disseminated copper mineralization extends below the stringer zone.

(Franklin et al., 1981)

Many orebodies are sharply overlain by, or grade laterally into an exhalative horizon preserved as silica rich strata, commonly iron formation. This capping formed by the variable contribution of chemical exhalative and clastic (tuffaceous) products.

Wall rock alteration commonly accompanies massive sulphide deposits. Chlorite and sericite are the dominant minerals in alteration pipes which underlie the Precambrian massive sulphide ore bodies, while clay minerals predominate in the unmetamorphosed alteration zones in the Kuroko deposits. The interaction of the hydrothermal fluids and the footwall rocks giving rise to the alteration zone and stringer ore result in the anomalous introduction of potash, aluminium and silica. During higher grade metamorphism the chloritic and other assemblages are changed to assemblages consisting of various proportions of hornblende, biotite, cordierite, staurolite and kyanite. Alteration minerals form a large proportion of the gangue minerals, particularly in the stringer zones of the massive sulphide bodies, and have an influence on the mineable grades of deposits as they (platey minerals) tend to effect ore recovery and cause bad ground conditions during mining.

### Secondary factors controlling grade

Deformation and metamorphism play an important role in either upgrading or destroying massive sulphide deposits. Because of the orogenic setting of these deposits they are usually deformed (unless very young) and their plasticity often encourages fold closures to develop in them. The ore bodies are often attenuated during mild deformation but with more severe deformation (and depending on ductility contrasts) they may become boudinaged, thickened or displaced by faulting and shearing.

In low grade areas where deformation is mainly expressed by shearing and folding, without a well-developed lineation, deposits tend to be flattened parallel to the schistosity as a result of transposition along shear planes. Shearing may have an adverse effect on small, or the more disseminated ore bodies which lack the coherence of large sulphide masses. Massive sulphides may be sliced into several en echelon ore lenses separated by slivers of highly schistose and altered wall rock. As a result minable tonnage is lowered by a reduction in size of the individual orebodies. The movement along schistosity planes rotating the alteration pipe and stringer ore to a position lateral to the massive sulphide orebody, but still in the footwall, is illustrated in figure 33.

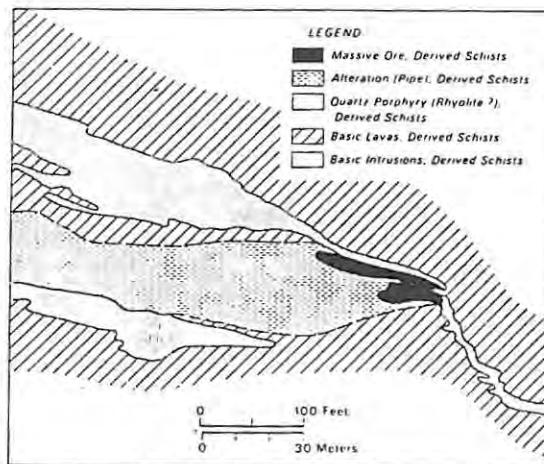


Figure 33: Flin Flon mine, Manitoba. Plan of 3000-ft level. Stratigraphic top is to the top of the diagram.

(Sangster and Scott, 1976)

In areas of medium to high metamorphic grade and intense deformation where enclosing rocks show penetrative lineations, rod-shaped orebodies form due to pinching, swelling and boudinaging of the massive sulphide orebody. Often sulphides are remobilized into crests and flanks of folds. The behaviour of massive sulphide bodies in higher grade terranes is largely controlled by ductility contrasts between the orebody and host rocks. Where the massive sulphide forms a large body or is intimately associated with more competent cherty rocks, e.g. magnetite quartzite at Otjihase Mine, South West Africa, the ore body behaves in a coherent fashion resulting in a more continuous orebody. In areas of intense polyphase regional deformation orebodies may become so distorted that their shape can best be described as amoeba-shaped (Sangster and Scott, 1976). The Rosh Pinah orebody, South West Africa (figure 34) illustrates the behaviour of an incompetent sulphide body within an area of intense regional deformation. There is a general tendency for weaker mineralized orebodies to become dismembered and destroyed by deformation and a tendency for better orebodies to be improved by deformation.

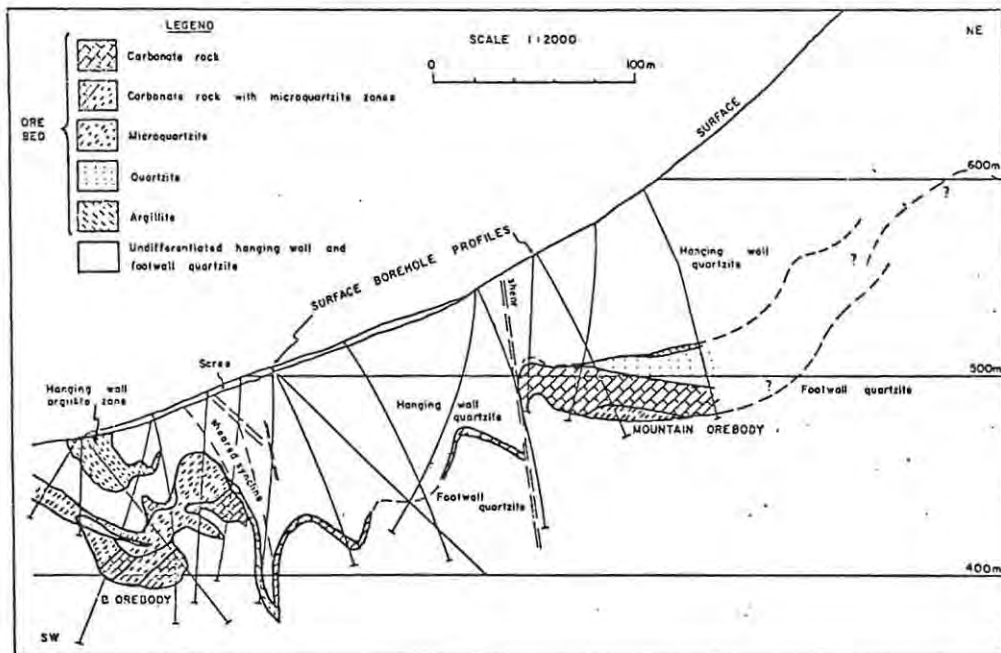


Figure 34: Section showing general fold style and lateral variation of ore bed, Rosh Pinah Mine. (Van Vuuren, 1982)

Metamorphism may modify the compositional zoning of the sulphide ores either by mass-flow or by hydrothermal dissolution and redeposition in dilatant zones (Sangster, 1972). Chalcopyrite and galena are commonly redeposited in gash veins and enrichment of copper and lead at the cost of zinc in fold hinges reflects the relatively high mobility or ductility of chalcopyrite and galena compared to sphalerite. The thickening of sulphides in the crests and troughs of folds may be the result of an attenuation of the limbs without movement of the sulphides relative to their wall rocks. On a large scale intense deformation is capable of moving the entire sulphide mass by transposition along the metamorphic foliation planes, which may result in the detachment of the massive sulphide from the stringer ore.

The main effect of metamorphism on massive sulphide ores is to increase the grain size of minerals, thus facilitating beneficiation of the ores. Mineralogical changes usually only involve the formation of pyrrhotite from primary pyrite. The conversion of pyrite to pyrrhotite results in a general increase in FeS activity (Vokes, 1979) and is in part responsible for the change in sphalerite composition after metamorphism, which is considerably enriched in iron relative to its original composition.

Various intrusives such as diabase dykes and sills are common post-ore phenomenon in volcanic associated sulphide deposits. The intrusives are probably genetically related to the magmatic event that resulted in the formation of the ore deposit. These intrusions often have the effect of disrupting the orebodies and in some cases have rendered them unmineable.

The variable effect of specific gravity on tonnage-grade relationships also applies to volcanic associated deposits. In a typical volcanogenic massive sulphide deposit consisting of layered sphalerite (+ galena) ore, chalcopyrite-pyrrhotite ore, and siliceous stringer ore, each ore type will have a different specific gravity. Given identical assays, the pay-metal content per unit volume in the massive ore would be far greater than in the stringer ore, and it would be different from that in the layered ore, depending on the amount of, e.g. galena present, or amount of interlayered gangue minerals.

## Ore Beneficiation

Major by-products won from massive sulphide ores are cadmium, silver and gold with lesser amounts of selenium, indium, bismuth, mercury and tin. Bismuth is usually considered as a deleterious element and the presence of arsenic and mercury may be environmentally toxic.

Kuroko ore which is unmetamorphosed is difficult to process because of its multiminerall content, fine-grained mineral structure, high content of clay minerals and high susceptibility to surface oxidation. Very fine grinding is necessary to achieve complete liberation of the minerals which is time consuming and costly, and recovery is poor because the very fine mineral particles lose their individual surface characteristics, which hampers selective flotation and sliming results (Venter, 1981). The opposite to this is where metamorphic recrystallization has resulted in a polycrystalline aggregate with a large average grain size and straight mineral boundaries resulting in free-milling ores. They are easy to separate and can be ground to the optimal size required for flotation.

The nature of gangue minerals is important as this may affect flotation. Micaceous minerals, clays, graphite and talc, which are common in the alteration zones of massive sulphide deposits are inclined to float mechanically. Ore minerals may adhere to the micas, graphite, and talc, or may become coated with clay and be lost into the tailings.

A thorough mineralogical study of the composition, texture and fabric of the ore is necessary before beneficiation can be attempted. The behaviour and distribution of trace elements, both deleterious and valuable have to be established. Silver, antimony and bismuth is commonly contained in tennantite-tetrahedrite; Co and As in pyrite, arsenopyrite and cobaltite; and Cd, In and Hg in sphalerite. Consequently Ag, Sb, and Bi; Co and As; and Cd, In, and Hg are inseparable in the milling circuits (Venter, 1981).

## Discussion

Whether a volcanic associated massive sulphide ore body is dominantly Cu, Cu-Zn or Pb-Zn-Cu, is largely determined by its geological setting. As the orebodies are formed from hydrothermal solutions discharging onto the sea floor, the character of the hydrothermal system will determine the position of the orebody relative to the volcanic vent, and the size and zoning in the orebody. A more intense and/or larger system will probably result in a richer orebody. Secondary factors such as deformation and metamorphism play an important role in making the deposits viable. Constructive deformation commonly results in an ore body attitude favourable to mining. Examples are sub-vertical tabular bodies like the Prieska and Geco mines, and steeply inclined lenses like the Kidd Creek deposit. Tectonic thickening of a thin widespread primary orebody is also common. Metamorphism results in the establishment of new relationships between sulphide grains and between sulphide grains and gangue minerals, which greatly facilitate the extractibility and mineability of the ore.

Mineral zonation, in both vertical and horizontal sense, is present in most massive sulphide deposits. The strong linear trends are inherent in the genesis of the deposits and therefore the use of geostatistics in the estimation of ore reserves is difficult or meaningless without close geological control. Semi-variograms, for example, are only valid for small homogenous areas within the orebodies, e.g. on the scale of a single stope. Geostatistics will therefore only work on this scale, or much smaller, if sufficient data points are available. At the Prieska Cu-Zn mine kriging is used to obtain the average grades, specific gravities and volumes of ore in 15 by 15 meter blocks, centered on grid points. Venter (1981) reports that the overall effect of this technique is to 'smooth over' any irregularities created by tight parasitic folds, boudinaging, and stretching of fold limbs. These are features of the high grade metamorphic terrane in which the ore body is located. The strong trends created by these irregularities and ore body zonation are often ignored, with the result that ore boundaries are often unknown. This leads to up to 40% dilution of the ore due to overbreaking in places, and to the leaving of ore behind in others. The problem is further aggravated by sloughing of the side walls in sheared chloritic alteration zones which are notoriously weak.

### Exhalative Sedimentary Deposits

This small but important group of deposits tend to occur in settings characterized by very thick sequences composed of fine grained, continentally derived sediments. As with the volcanic associated deposits no two are alike but certain overall characteristics are similar. Some of the world's most important base metal mines, for example, Mt Isa, Broken Hill (Australia) and Sullivan deposits, fall into this group. The Aggeneys group of deposits in Namaqualand are also considered to have close genetic affiliations with these deposits, particularly with the Broken Hill and Pegmont deposits of Australia (Ryan, et al., 1982). In contrast to other types of massive sulphide deposits they exhibit little or no relationship to volcanism tend to exhibit extremely well-defined mineral banding, and contain significant amounts of lead and silver (rather than gold). The sulphide occurrences usually occur within a sedimentary unit and where a number of deposits occur in a single district they show a clear affiliation with one or two specific horizons and usually for a specific lithological environment within or adjacent to the horizon. Wherever the sedimentary associations are clear, sedimentation can be seen to have taken place under fairly shallow conditions near a shoreline, with a reducing environment or biological activity (e.g. Mt. Isa, McArthur River) playing a role in the precipitation of the metals. The ores are an intrinsic part of the geological environment (Stanton, 1972).

#### Primary factors controlling grade

Primary control of deposition in volcanic associated deposits is the direct result of the interaction of hot dense brines with seawater at or near the hydrothermal vent, which initiates the early precipitation of copper and later lead and zinc. In contrast, environmental conditions at the site of deposition of sedimentary exhalative deposits appear to have played a more important role in controlling the precipitation of sulphides. The brines behaved differently, and often metals in the brines became fractionated during their migration from the source to the depository, as illustrated by lateral zonation in many deposits. At Mt Isa, copper is deposited in a sinter-type setting adjacent to the Mt Isa fault (Mathias and Clark, 1975), while lead and zinc are precipitated

further away under reducing conditions in a restricted environment to form stratiform bedded lead-zinc deposits.

The relationship between the rate of sedimentation within the depository and brine activity is a critical factor in the formation of viable deposits. A high influx of volcanoclastic, epiclastic or shelf-carbonate detritus would result in relatively thickly bedded sediments with scattered sulphide laminae that developed during

periods and the formation of a thick, poorly mineralized stratigraphic sequence. As a result, relatively long periods of tectonic quiescence are necessary to reduce the amount of clastic influx and allow the formation of the volcanosedimentary deposit (Dingemans, 1981). The relationship between sedimentation and brine activity within a sedimentary basin is well illustrated in the Mt Isa orebodies where lead-zinc rich ore zones occur within the finely laminated Urquhart Shale. Rate of deposition of the shale was largely controlled by movement along the Mt Isa fault. Galena, sphalerite, pyrite and pyrrhotite occur as distinct laterally persistent bands in the graphitic shale. Although isolated mineralized beds occur throughout the stratigraphic sequence it is only where these beds are grouped together in sufficient density that they constitute an ore zone. Stratiform Ag-Pb-Zn mineralization similar to the Isa ore body also occurs to the north at the Hilton mine, where mineralization is identical in all respects, but is hosted in a condensed sequence due to slower fault controlled sedimentation.

At Aggeneys the depositional environment also appeared to have a strong influence on the distribution of mineralization. As described by Ryan et al., (1982) the orebodies are stratabound and in most cases stratiform and intimately associated with banded iron-formation. The iron-formation is associated with base metals sulphides and barite, and displays textural features such as fine compositional banding, thereby implying a chemogenic origin. The calc-silicate rocks and marbles within the iron-formations, are considered to represent original limestones. On a regional scale there is an apparent metal zonation over a distance of about 10 km between the four major orebodies in the Aggeneys area (figure 35). Reconstruction of the depositional environment of the Broken Hill orebody at Aggeneys (Ryan et al., op. cit.) suggests the presence of oxide, sulphide and silicate facies (figure 36),

VARIATIONS IN METAL GRADES IN THE AGGENEYS AREA

<u>Azimuth</u>	<u>Ore Body</u>	<u>Base Metal Content</u>		
		<u>% Cu</u>	<u>% Pb</u>	<u>% Zn</u>
West	Black Mountain	0,75	2,67	0,59
↓	Broken Hill	0,34	3,57	1,77
	Big Syncline	0,04	1,01	2,45
	Gamsberg	-	0,50	7,00
East				

A progressive increase in copper to the west and zinc to the east is clearly demonstrated.

Figure 35: Table showing changing grades of base metal deposits from west to east in the Aggeneys area. (Ryan, et al., 1982)

all of which are well defined by their characteristic mineral assemblages. The sulphide quartzite and ferruginous garnet quartzite are stratigraphic equivalents, probably representing a lateral facies change. The Pb-Zn sulphide development is strongest in what is thought to have been the central parts of the depositional basin.

The zoning of the McArthur River, Isa and Hilton deposits departs significantly from the volcanic associated Cu-Zn-Pb-Ag zoning. Cyclic changes occur in which Zn-Pb ratios decrease stratigraphically upward, but copper tends to be concentrated at the tops of individual cycles. Within individual lenses horizontal zoning (similar to Aggeneys but on a smaller scale) from distal Zn through Pb to proximal Cu has been recognised. Vertical cycles of decreasing Zn:Pb ratios may reflect cycles of sub-basin development and/or increasing organic activity related to episodic faulting (Rutland and Both, 1981).

#### Secondary factors affecting grade

Constructive deformation, metamorphism and supergene alteration play an important rôle in making sedimentary-exhalative deposits viable. The McArthur River deposit of Northern Australia occurs in Precambrian sedimentary rocks that have barely been affected by metamorphism and deformation and in consequence lies in an almost horizontal position (Lambert, 1976). Although the deposit has an estimated in situ reserve of 200 million tons at 10% Zn, 4% Pb, 45 ppm Ag and 0,2% Cu the exceedingly

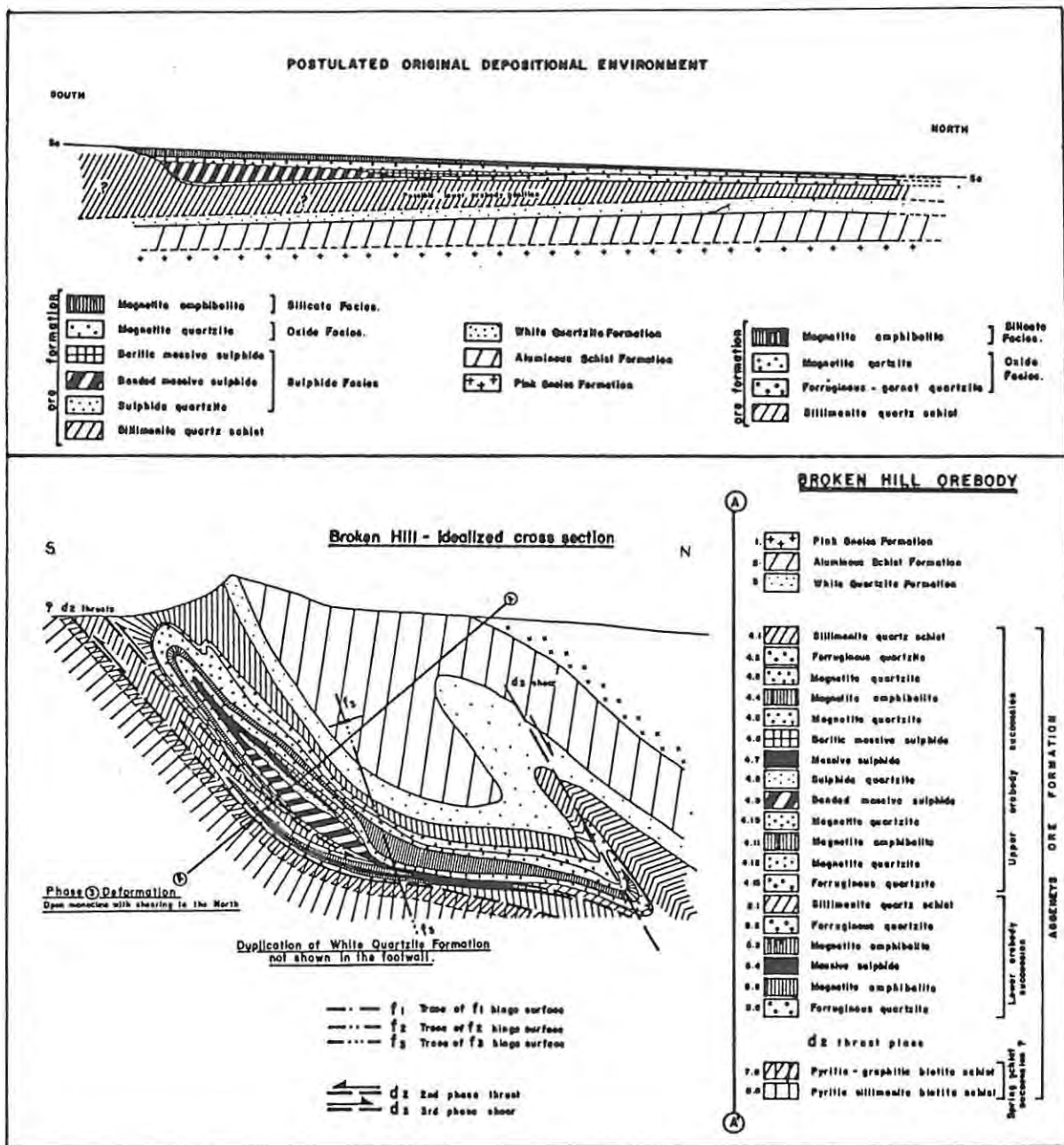


Figure 36: Simplified cross section through the Broken Hill orebody, Aggeney's (bottom), showing the postulated original depositional environment (top) (modified after Ryan et al., 1982).

fine grain size of the unmetamorphosed ore, comprising pyrite, sphalerite and galena, causes metallurgical problems and is one of the reasons why development of the deposit has been held up. In contrast the Broken Hill, New South Wales, deposit (Scott, 1981; Rutland and Both, 1981) has been complexly deformed, the steep dip facilitating mining of the deposit. The sulphides have been coarsely recrystallized during the metamorphism

accompanying the deformation and are easily processed. The deposit (figure 37) totals roughly 200 million tons of ore with an average grade of 12% Pb, 12% Zn and 115 ppm Ag. There are six separate lodes at the south end of the deposit and the upper three have distinctly higher Zn:Pb ratios. Ore is coarse grained and massive and enclosed in mica sillimanite schists, in gneiss and in quartzite. The major ore minerals are coarse grained galena and sphalerite (marmatite). Pyrrhotite is locally abundant but overall is a fairly minor constituent. Other minor sulphides are chalcopyrite, arsenopyrite, lollingite and tetrahedrite. Each orebody has its own characteristic gangue assemblage, the main gangue minerals being quartz, calcite, garnet, rhodonite, bustamite and fluorite.

Upgrading of the Broken Hill, Aggeney's, ore deposit by multi-phase deformation resulting in the production of highly complex refolded and faulted structures is illustrated in figure 36. The steepening of the

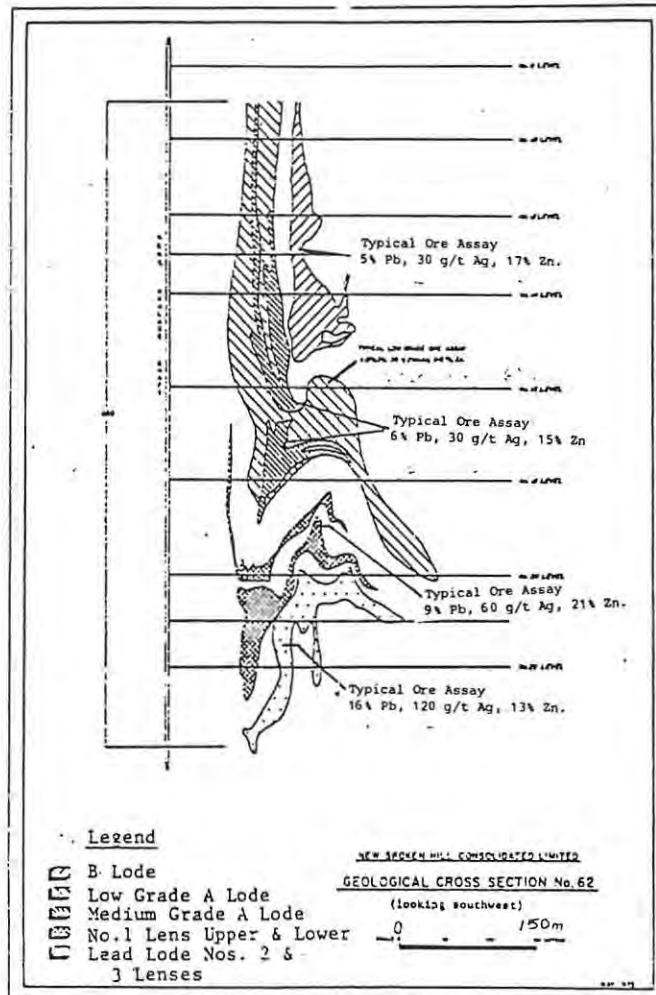


Figure 37: Cross section through Broken Hill orebody, New South Wales. (Scott, 1981)

orebody to the south has also resulted in the application of cheaper mining methods during the early life of the mine. The sulphide ores have been subjected to metamorphism bordering on granulite facies and there is evidence of an increase in base metal content in the cores of the  $F_2$  fold closures (figure 36). Whether this concentration is due to migration of base metal sulphides into fold closures, or whether the fold closures took place about the more massive sulphide sections of the orebody is not known (Ryan et al., 1982). McDonald (1970) has shown that migration of sulphides and gangue material occurred mainly by solid state processes at Mt Isa, where deformation at low intensities of regional metamorphism had affected the orebodies. The ease with which constituents are deformed increase in the order, sphalerite : silicates : carbonates : galena, and resulted in a 40 percent increase in galena in some hinge zones of folded layered sulphides.

Secondary mineralization is present above the Mt Isa orebodies in the zone of oxidation. Above the Isa copper ore body about 1 500 000 tons of secondary copper is present and is mined by opencast (Smith, 1975). The ore grades up to 40% Cu at places, but as a whole contains about 4% Cu. The zones of deep oxidation and leaching were controlled by a dense and well developed set of transverse faults and the significant downcurrent of ground water.

#### Discussion

Similar problems to those experienced in volcanic-associated ores are encountered during the mining and processing of exhalative sedimentary ores. Exhalative sedimentary ores do not have the added complication of extensive alteration causing bad ground conditions and hampering recovery of ore. The strong primary trends in the ores and superimposed structural complexity make the recognition of homogeneous zones in the ore bodies necessary for efficient ore reserve estimation and grade control purposes. At Black Mountain, Aggeneys, where the economic base metal sulphides, galena, sphalerite and chalcopryrite occur together with pyrite and pyrrhotite, at least 15 different ore zones are distinguished based on grade and lithological characteristics such as varying amounts of quartz, garnet, magnetite, plagioclase, apatite, amphibolite and biotite gangue minerals (Chunnett, 1982). For mining and grade control purposes the distribution

of lead, zinc, silver, copper, bismuth and relative density is monitored. Some of the factors important for grade control to ensure a constant mill feed listed by Chunnett are the variation in metal grades (particularly lead); the variation in lead to copper ratio; the variation in ratio of soft massive sulphide to much harder magnetite bearing ore, which affects milling; the occurrence of pyrite and pyrrhotite; and the occurrence of bismuth, a deleterious metal.

Secondary factors such as deformation and metamorphism play an important role in generating a viable deposit both by coarsening the ore and by increasing the mineable tonnage of the deposits. Metal distribution is closely tied to conditions existing in the original environment of deposition. Depending on the nature of the introduction of the brine and the rate of sedimentation, foot and hangingwall cutoffs could be diffuse and only determined by assay. Assay cutoffs are more complex when more than one metal contributes to the viability of potential ore.

#### PLACER FORMING SYSTEMS

Placers form on the surface of the earth in response to some or other tectonic activity. The environment in which the placer forming system operates has a strong influence on the morphology, payability and grade distribution of the placers. Placers form when relatively dense and durable minerals are liberated during weathering and erosion to become concentrated by sedimentary processes in a form that is economically exploitable. Whether placer deposits form by fluvial or other processes such as wave and current action on a beach, the processes of placer formation involve some or other mechanism of winnowing and removal of less dense material, or by the sorting of minerals of different specific gravity.

Concentration of heavy minerals in fluvial systems broadly correspond to spatial scales at which hydraulic sorting processes operate (Smith and Minter, 1980). On a large scale, concentrations occur on a regional scale in response to optimal combinations of average size of heavy minerals and characteristics of the fluvial environment

resulting in e.g. broad bands of placers parallel to depositional strike in alluvial fan deposits. On an intermediate scale concentrations arise from processes associated with major topographic elements within channel systems such as through winnowing by flow convergence in curved channels. On the small to very small scale heavy mineral concentrations can form by processes such as deflation mechanisms on the floor of a stream, leaving thin layers of heavy minerals on erosion surfaces, or by entrapment in the interstices of pebbles. Placer deposits are by nature very erratic and unpredictable and this is a reflection of their mode of development and the processes related to the type of sedimentary systems and environments that they occur in.

Viable placer formation is governed by variables such as, (a) a large or persistent supply of sediment containing the heavy mineral constituents, (b) the nature of transport from the source to the depository, (c) the morphology of the depository, and (d) later sedimentary processes of reworking at the site of deposition. Examples from the Witwatersrand placers discussed below will illustrate the vast differences between placers formed as a result of the interaction of these variables. The variables are all controlled by the tectono-sedimentary environment in which the placer deposits formed.

#### Witwatersrand Placer Deposits

The 2700 m.y. old Witwatersrand Supergroup is a thick sequence of shales, quartzites and conglomerates which have undergone low grade regional metamorphism and are divided into a lower argillaceous unit and an upper, more arenaceous unit. This supergroup is underlain by the Dominion Group and overlain by the Ventersdorp Supergroup. The sequences are separated by locally pronounced unconformities and in certain localities the Venterspost Conglomerate Formation is developed at the unconformity separating the Ventersdorp and Witwatersrand Supergroups. Major gold bearing placers occur in the upper Witwatersrand and in the Venterspost Conglomerate Formation. The most widely exploited auriferous placers are basal conglomerates of sedimentary cycles where gold occurs in the matrix of oligomictic conglomerates. Other sites where gold is being exploited include pyritic sands which usually fill

erosion channels; and sands, mud and carbon seams developed along planes of unconformities. Irrespective of the nature of the host lithology the association with planes of unconformity is ubiquitous (Pretorius, 1976).

#### Tectono-sedimentary environment of deposition

The Witwatersrand placers were deposited in a fluvial environment (Pretorius, 1976) and factors affecting grade in these deposits must be seen in a tectono-sedimentary context to appreciate the differences between individual placers. A number of fluvial fan deltas have been identified along the northwest margin of the Witwatersrand basin and their localization has been attributed to the periodic uplift of the margin of the basin resulting in the shedding of material into the basin between constricting granite domes punctuating the basin edge. The gold bearing placers can all be related to events, mainly due to tectonic activity, that took place on the fans. Continued but episodic uplift of the basin's source area to the north was complimented by a gradual subsidence of the basin. Each tectonic event that resulted in uplift initiated erosion of the source areas and deposition of sediments on the alluvial fan surfaces. At times continued subsidence of the Witwatersrand basin caused transgressive sedimentation between the pulses of regressive sedimentation.

Conglomerates occurring above the base of each major sedimentary cycle may be explained by one of three main processes. Firstly, minor periodic movements of uplift in the source area could result in the deposition of conglomerates on the fans, or secondly, they could be deposited by internal non-tectonic geomorphic processes occurring on the fan, such as streams on a fan surface that retrench and cut back upslope in automatic response to slope oversteepening caused by aggradation (Minter, 1978; Smith, 1982). Thirdly Mason, R., (person communication) relates the extensive thin highly payable conglomerate reefs to major basin wide events resulting in the sudden deposition of sediments onto a relatively even paleosurface

A number of different placer-types can be distinguished which can all be related to the tectono-sedimentary environment of deposition. Three of the placer-types are selected for further discussion, and are:

- (a) Placers which occur on a smooth regional unconformity, showing little variation in pebble size, generally thin, sheetlike and highly payable. These placers are probably related to basin-wide tectonic activity, e.g. Carbon Leader (Carletonville), Main Reef Leader (Central Rand).
- (b) Placers that formed in an environment of general aggradation as a result of 'within fan' fluvial activity, e.g. Elseburg Reefs.
- (c) Placers deposited on an irregular structurally controlled paleosurface immediately after or during major regional upheaval, e.g. Venterspost Contact Reef.

The three placers selected probably represent 'end-members' of the various placers found in the Witwatersrand but are selected to stress the influence of tectonic events on the grade of a placer. Most other placers within the Witwatersrand basin can be seen as gradational types between these end-members.

#### Thin extensive placers related to basin-wide tectonic activity

The Carbon Leader Reef, Carletonville Goldfield (Nami, 1981) Vaal Reef, Klerksdorp Goldfield (Minter, 1976) and Main Reef Leader, Central Rand Goldfield (Mason, R., and Hiller, N. personal communication) all possess similar characteristics in that they are thin, very persistent and consistently highly payable. These deposits are amongst the richest placers discovered anywhere in the world. They are all situated in the lowest portion of the upper Witwatersrand sequence (Central Rand Group) and occupy sizable areas in their respective goldfields. The placers generally rest on a plane of unconformity which appears to represent an angular truncation of the horizons beneath them.

Figure 38 shows the development of the Carbon Leader Reef as interpreted by Nami (1981). Two subfacies are recognized within the placer, one consisting of lenticular shaped conglomerate/quartzite units yielding

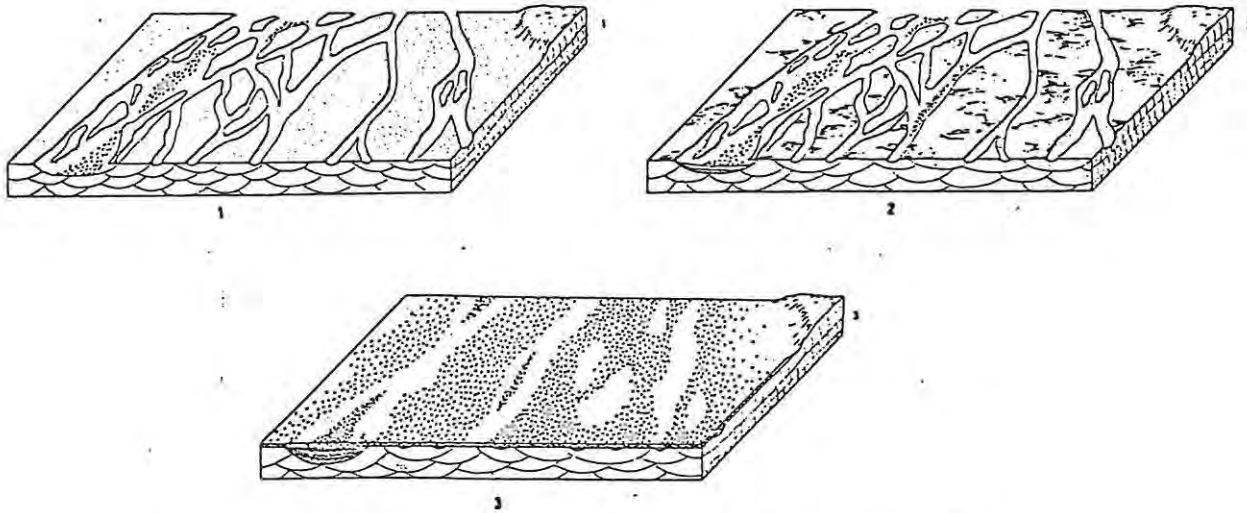


Figure 38: Generalized block diagram, illustrating the development of Carbon Leader Reef, Blyvooruitzicht Mine, Carletonville. (Nami, 1981)

erratic gold values and an overlying sheet-like conglomerate, often with underlying thin carbonaceous seams, and with consistently high gold values. Likewise Mason and Hiller (personal communication) describe the Main Reef Leader as a thin blanket-like conglomerate only a few centimeters thick with restricted linear zones in which the reef is significantly thicker. The Main Reef Leader is also interpreted as the result of two sedimentary events where earlier gravel and sand filled shallow channels are overlain by thin gravel sheets.

The thin sheet-like oligomictic conglomerate facies in these placers is poorly sorted and the pebbles are enclosed in a fine to medium grained quartzite matrix. The conglomerate is often composed of several thin consecutive pebble bands of one or two pebble thickness. The placers display neither a downdip decrease in pebble size nor a marked change in the pattern of gold or uranium content that can be related to downdip sorting. Minter (1978) also reports the absence of down-dip decrease in pyrite and zircon grain size in the Vaal Reef. A striking feature of the sheet-like conglomerate facies, both in the Vaal Reef and Carbon Leader Reef is the presence of carbon seams at their base.

There is a marked difference in the distribution pattern of gold within the two subfacies of these placers. In the thin sheetlike facies the distribution is relatively uniform and the mean gold value is high. Most of the gold is situated at the base of the sheet-like conglomerate where it is associated mainly with carbonaceous matter and occurring in the form of very fine detrital grains. A small portion of the gold is randomly distributed in the matrix of the overlying conglomerate (Nami, 1981). In contrast, the distribution pattern of gold in the channel facies is not uniform and mean gold value is low. Gold occurs in the matrix of the conglomerate together with other heavy minerals and higher concentrations of gold occur along the bottom conglomerate and along channel edges, (Nami, 1981; Mason and Hiller, personal communication).

Mason (pers. comm.) regards the preconcentration of heavy minerals in the sediment that gave rise to the sheet-like conglomerate facies as an important step prior to deposition. The preconcentration process would be related to an advancing orogenic front to the north of the Witwatersrand basin. A combination of a highly unstable environment with folding of pre-existing sediments, and crumpling of partly consolidated beds, particularly, in the upper fan areas, would create favourable conditions for concentrating heavy minerals.

During the break in sedimentation prior to deposition of the placers a broad paleo-surface of low relief developed. Streams flowed across the paleosurface, and in the areas between stream channels conditions were suitable for growth of primitive algae.

During the initial stages of sedimentation a high rate of flow was concentrated in the channels and gold particles being small in size were probably transported in suspension. Although the conditions were not suitable for concentration of gold the presence of open-framework gravels could have acted as a trap for the particles. The resulting Sediments in the channels generally have low gold content, but erratic high values do also occur (Nami, 1981). Eventually the channels filled and the overall relief of the alluvial planes was reduced still further. The second mineralizing event involved sheet floods which washed successive layers of pebbles over the entire subdued topography of the alluvial plain

in response to tectonic events. The first pulse of gravel flooded across the erosion surface with preconcentrated gold and other heavy minerals. Most of the gold within the early pulses of gravel was concentrated as a lag deposit and trapped by the algal mat. Gold also settled out on flanks of channels and over paleoridges. Subsequent poorer thin gravel sheets were not well sorted and heavy mineral particles were deposited along with the pebbles giving rise to moderate gold values (Mason and Hiller, pers. comm.). In areas where the post depositional flow was pronounced complete erosion of the sheet-like conglomerate took place (Nami, 1981).

These placers can therefore be interpreted as a result of major tectonic upheavals resulting in the deposition of large volumes of preconcentrated heavy minerals over an extensive even paleosurface. The placers are economically important because of the consistency of grade, payability and down-dip extension. Although showing relatively uniform mineralization, distinct payshoot trends parallel to the paleoslope may be present. Gold distribution can largely be related to settling out of fine gold particles in suspension with entrapment by algae mats and deposition as a lag deposit in zones of reduced flow such as flanks of channels and interchannel areas. This sheet-wash related deposition of even mineralized fine grained gold is in sharp contrast to the erratic bedform controlled gold distribution of the placers discussed in the following paragraphs.

#### Placers related to 'within-fan' fluvial activity

The Elseburg No. 5 and Leader Reefs studied by Smith and Minter (1980) on the Klerksdorp and Welkom Goldfields and the Elseburg Reefs occurring in the Western Areas and Cooke Section, Randfontein Estates, mines are to be discussed in this section. For the sake of brevity these placers will collectively be referred to as 'within-fan' placers. The placers all occur in the Central Rand Group and the Elseburg reefs, in particular, formed during the closing stages of Witwatersrand sedimentation. The within fan placers occupy relatively proximal portions of their respective fans and were deposited by shallow braided streams on aggrading fans.

The placers probably formed as a result of very minor tectonic activity on or in the vicinity of the alluvial fans, or by localised geomorphic processes of stream retrenchment on an aggrading fan. In sharp contrast to the extensive thin highly payable placers described in the previous section, within fan placers are characterized by their high variability on all scales requiring tight geological control during mining. On a larger lateral scale the within-fan placers are not continuous over the whole fan. Often, as between Western Areas Mine and Cooke Section, Randfontein Estates Mine different placers and in different stratigraphic zones of the Elsburg Reef zone are mineralized. Another characteristic of these placers is the presence of pay-shoots parallel to the paleocurrent direction separated by barren to low-pay areas controlled by the irregular braided environment in which they formed. Gold distribution even within the payshoots is erratic and in a specific mine, in sympathy with the overall trend, gold content falls away down the paleoslope.

The strong control of paleocurrent direction and proximal-distal relationships on an alluvial fan is best illustrated by the gold and uranium distribution on the Steyn and Basal placers, Welkom Goldfield (figure 39). The two coalescing placers probably also formed in response to larger scale processes of partial degradation operating on the fan and therefore show greater continuity of mineralization than the more variable within-fan placers.

The Elsburg Reefs on Western Areas Mine and on Cooke Section, Randfontein Estates have a tendency to merge towards the Panvlakte fault to the west of the mines, probably indicating the control of local tectonic activity in their deposition. This is in sharp contrast to the basin-wide tectonic upheavals giving rise to the thin extensive placers found on angular unconformities.

On a smaller scale within-fan placers show a high variability in gold and heavy mineral content in both vertical and lateral extent. The conglomerates display examples of gravel filled channels, pebble lag deposits, scour surfaces and gravel bar formation, all sites for heavy mineral concentrations. Closely spaced packing of pebbles, large pebbles and the presence of buck-shot pyrite indicates areas of high

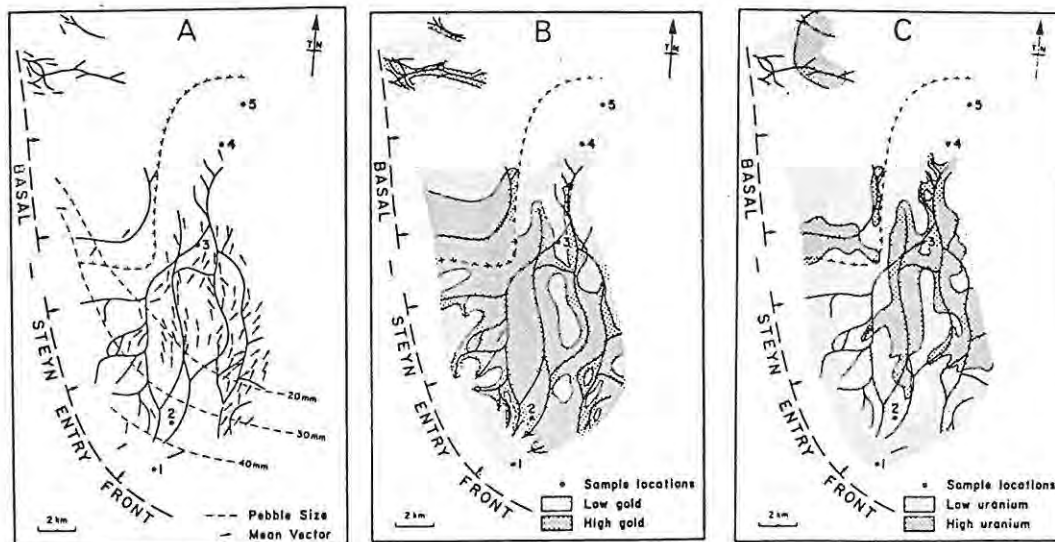


Fig. 39 A, Paleocurrent plan of Steyn and Basal placers showing: their entry positions; boundary of lateral coalescence (marked with T symbols); mean pebble-size isopleths of ten largest pebbles; main trends of best mineralization based on detailed moving-average contours; vectorial means; and the location of heavy mineral sample sites (1 to 5). B, The location and distribution pattern of the high gold content facies in the Basal and Steyn placer deposits. Upslope contour re-entrants are associated with channelways. C, The location and distribution pattern of the high uranium content facies in the Basal and Steyn placer deposits. The fit between gold distribution and paleocurrent data indicates hydraulic control. The position of the uranium facies, downslope from the gold facies, may be related to an apparent lack of coarse-grained uraninite.

(Minter, 1976)

gold mineralization. Sand filled channels are often defined at their bases by a thin pebble lag deposit containing concentrations of pyrite and gold. Pyrite and gold may also be present on foreset laminae and troughs of some sandstone crossbeds, figure 40. The various bedforms in which the heavy minerals can accumulate lead directly to the high nugget effect characteristic of many Witwatersrand-type deposits.

Noting the transient and fluctuating nature of transport in a braided stream environment Smith and Minter (1980) developed the 'point-source' concept to explain the irregular distribution of gold and uranium. Periodic reactivation will result in pulses of eroded heavy minerals being fed into the stream which will locally concentrate at favourable sites in the stream or be dispersed in other areas creating a highly variable distribution. These local concentrations, which are only temporary deposits in the braided system, such as a bar or a portion of a channel bed, will then constitute point sources of heavy minerals during subsequent periods of erosion (figure 41).

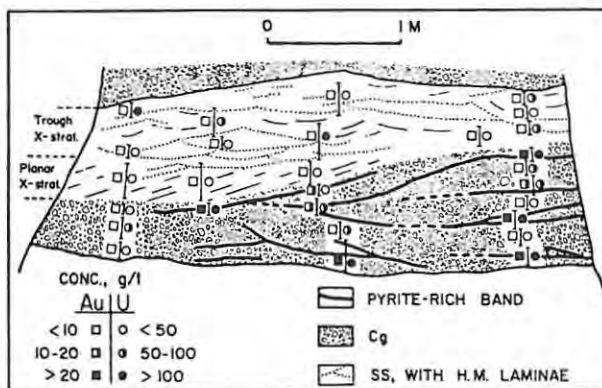


Figure 40: Cross section of gravel bar and overlying sandstones showing pyrite-rich and other heavy mineral (H.M.) bands, and distribution of gold and uranium.  
(Smith and Minter, 1980)

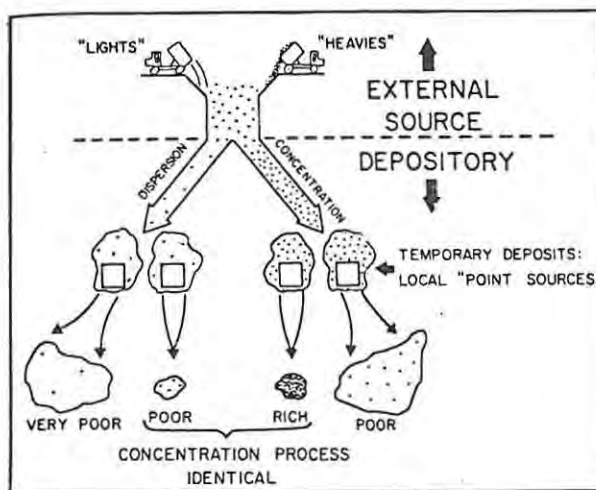


Figure 41: Schematic model showing effect of local point sources in determining local placer occurrences. Deposits rich in heavy minerals are most likely where both an efficient concentrating mechanism operated and where the upstream point source supplied abundant heavy minerals.  
(Smith and Minter, 1980)

Processes following this erosion may further concentrate the heavy minerals or disperse them. The deposits therefore contain an inherent random factor hindering exact qualification of grade prediction. These local placers are essentially transient features but in an aggrading system they may be buried and preserved. An economic deposit strongly controlled by the stream processes will only form if sufficient repeated concentrations of heavy minerals has occurred.

The association of placer mineral concentrations with bedforms and paleochannels parallel to flow makes analysis of these features essential in the evaluation and mining of the placers. Projections can be extended for greater distances in the direction of paleoflow rather than transverse to paleoflow. On the other hand, stopewide valuations would be more representative if sampling were done across paleoflow where a maximum number of relief elements such as channels and bar forms would be encountered (Smith and Minter, 1980).

Within fan placers therefore form as a result of local processes and probably to a large extent from local reworking of existing material on the individual fans. The erratic within fan fluvial activity explains the inconsistent and fluxuating behaviour of the placers. As only relatively small amounts of material are involved in the sedimentary processes giving rise to the placers, only small and poor placers result. These deposits show a high nugget effect and high variability and therefore competent geological interpretation is necessary during geostatistical and other evaluation.

Placers deposited on an irregular structurally controlled paleosurface

During the tectonic activity that preceeded the extrusion of the thick (2000 m +) Ventersdorp Supergroup lavas, a series of horsts and grabens formed along the margins of the Witwatersrand basin. Material derived by erosion of the uplifted margins supplemented with material from outside the basin were incorporated into placers differing significantly from those that formed in the upper Witwatersrand sequences. The placers were deposited on an irregular surface characterized by the development of erosion valleys, scarps and terraces. As a result they show a rapid lateral variation in thickness and character. The sediments were in transit in a relatively high energy degrading environment when they were preserved by the outpouring of the Ventersdorp Supergroup lavas as a continuous layer of gravel resting on an erosional unconformity. Normally gold content averages less than 20 ppm in these deposits with higher averages (30 ppm) in the midfan gravel bars but decreasing to less than 10 ppm distally. Conversely the low uranium content increases downslope (Tankard, et al., 1981). A number of placer deposits formed in this way and are collectively named the Venterspost Conglomerate

Formation. The Venterspost Conglomerate Reef in the Carletonville Goldfield will be discussed in more detail.

In the Carletonville Goldfield the conglomerate braid bar and channel fill deposits of the Venterspost Contact Reef (VCR) have been interpreted as intermontane fluvial accumulations (Krapez, 1979). Rivers deposited a large clastic wedge mantling at least 30 km of a paleoslope, now represented by the width of the Carletonville Goldfield. On a regional scale the VCR shows a large but systematic change in its characteristics related to the changing processes operating on the paleosurface of deposition (Dales, 1980). In the proximal localities the mean bed thickness is generally less than 4 m but decreases further down the paleoslope to about 1 m. Paleorelief above the Witwatersrand strata decreases from 30 m proximally to less than 1 m distally. The slopes of the paleotopographic highs are rarely covered with sediments, the result being that they are occasionally misinterpreted in borehole intersections as either faults or widespread barren zones (Tankard et al., 1981). A decrease in gold and gold : uranium ratio is also present down the paleoslope. Superimposed obliquely on the regional trends related to the paleoslope are large regional areas containing higher gold contents separated by areas with poor gold content. This feature is more pronounced in the relatively poorer and more distal portions of the fan and the richer areas correlate positively with the sub-outcrop zones of gold bearing Witwatersrand reefs where they truncate the VCR. Also affecting the regional trend in mineralization is a small poorly mineralized proximal alluvial fan (Black VCR) which was deposited contemporaneously with the more distal portions of the main VCR at the western end of the Carletonville Goldfield (Mullins, 1982).

On an intermediate scale the gold distribution largely parallels flow direction but is modified by the different processes operating along the paleoslope. In the upper more proximal areas the reef zone consists of an interrelated confined complex of predominantly polymictic and poorly sorted conglomeratic lithofacies. In the more distal environment the reef consists of a thinner predominantly clast supported oligomictic conglomerate deposited in unconfined braided stream flow (Dales, 1980). The five main gravel facies identified by Krapez (1979) in the proximal part of the VCR in the Carletonville Goldfield are shown in figure 42.

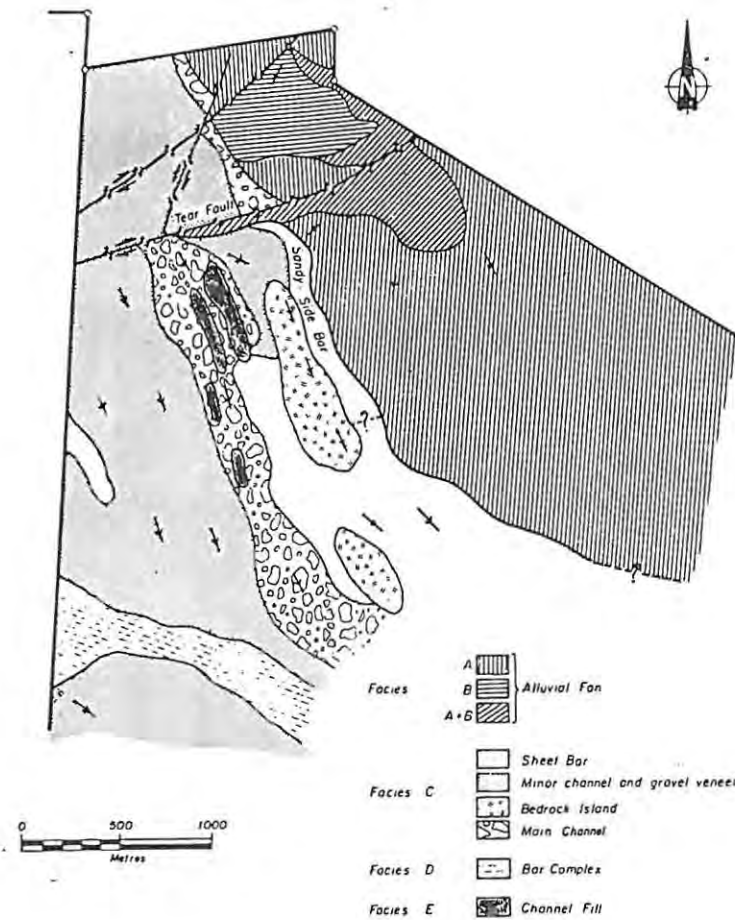


Figure 42: Plan showing facies distribution on East Driefontain mine. (Krapez, 1979)

Each of these facies formed under different conditions which is reflected in the distribution, content and grain size of the gold in the ore. These characteristics have been taken into account during tonnage-grade estimations and have resulted in a more reliable assessment (Schoeman, 1982). Facies A gravels (figure 42) are interpreted as a torrential flood or debris flood deposits and facies B gravels as sheet flood deposits. Both facies formed on the same horizon on the alluvial fan, are consistent over hundreds of meters and have erratic heavy mineral assemblages. Facies C gravels were formed by bedload traction processes in a fluvial environment, are inconsistent and influenced by the irregular floor of the paleotopography. Channels, potholes and scoured areas are common with the reef. Both facies D and E consist of polymictic clast supported conglomerates with visible gold deposited by fluvial processes and are laterally impersistent.

Material forming facies A to D was largely derived from a mixed provenance comprising erosion of pre-existing Witwatersrand strata and material from outside the basin. Facies E gravels are always well mineralized and predominantly constitute reworked facies A to D material. Although not always visible, gold is relatively coarse in the proximal areas of the VCR. All the facies-types have abundant pyrite and pyrrhotite mineralization, often in buckshot form.

On a more local scale gold is concentrated in the VCR by bedform processes with larger concentrations at the base of the reef. In the more distal small pebble conglomerates the gold and pyrite is, for example, often concentrated along foreset toes (Dales, 1980).

Gold distribution in the VCR is therefore erratic on all scales but with regional trends related to the paleoslope of deposition. Although gold distribution is erratic, the VCR at Carletonville is a highly payable reef because of the high initial input of gold into the system.

#### Ore processing

Gold and uraninite are the most important economic minerals present in the reefs. Pyrite is an ubiquitous constituent of the gold reefs and is commonly extracted for the manufacture of sulphuric acid. Other minor economic constituents are platinum group metals and silver. Most of the gold in the Witwatersrand ore is free-milling, i.e. the bulk of the gold is liberated by milling and easily recovered. This is in contrast to greenstone belt mineralization where much of the gold is refractory, i.e. gold is fine grained and forms complex intergrowths with a wide variety of sulphides and sulpharsenides like arsenopyrite and is not liberated by fine grinding. The reason for the free-milling nature of Witwatersrand ore is due to the origin of the gold as detrital fragments. Later metamorphism might have altered the shapes of the detrital grains.

After milling, and in the process of recovering gold from the gravity concentrate, gold is dissolved in a dilute alkaline cyanide solution. The rate of dissolution of gold depends on factors such as the particle size, degree of liberation, silver content and the presence

of surface coatings. The rate at which gold will dissolve is therefore largely proportional to the surface area of the gold particles. Gold is lost mainly owing to: (a) Occlusion in particles such as carbon, gersdoffite, iron oxides and pyrite. (b) As it takes a longer time to dissolve larger particles of gold, the large particles of gold are often lost if proper mineralogical work is not carried out and it is assumed that all gold is fine and will dissolve in a specified time. (c) As it takes roughly twice the time to dissolve pure silver than that required for gold, a high Ag: Au ratio in the concentrate could hamper recovery. (d) Surface coatings such as FeOH and 'armouring' of gold particles (flattened gold particles are often impregnated by minor quartz and other mineral fragments) could prevent optimal recovery (Reynolds, I.M., pers. comm.).

Where the placers are also mined for their platinum and uranium content normal problems related to the recovery of by-products from a multi-product ore are encountered. Detrital uraninite, when present is readily liberated on milling and dissolves rapidly during concentrate leaching but some uranium, mainly in the form of brannerite, is lost because of enclosure by carbon, phyllosilicates, leucoxene, and to a lesser extent quartz and pyrrhotite (Feather and Coen, 1975). The gravity concentrates prepared at the mines contain both alloys of the platinum group elements and mineral compounds such as arsenides and tellurides of the platinum group elements. The concentrates are treated with an acid leaching process in order to remove impurities such as sulphides but in the process a substantial amount of platinum is also lost (Feather, 1978). More recently substantial work, based on the fundamental understanding of the mineralogy of Witwatersrand ores has led to adapting and improving methods of recovery of the metals. For example, the strong acidity of pressure leaching for uranium leads to the dissolution partly or wholly, of most of the host minerals. Not only is the bulk of the uranium dissolved, but enclosing gold is liberated for cyanide leaching.

## Discussion

Gold deposits of the Witwatersrand Supergroup and Ventersdorp Conglomerate Formation are a prime example of the influence of tectono-sedimentary processes on the grade of placers. The extensive and thin type of placers formed in response to basin wide tectonic events when gold was deposited as part of preconcentrated material onto an unrestricted erosional unconformity of very low relief. Fine grained gold was mainly in suspension and deposited onto the smooth surface to give rise to rich placers with uniform gold content. On the other hand 'within fan' placers formed by localized processes which caused reworking of existing material on aggrading fans. This resulted in an impersistent reef with an erratic gold distribution determined by bedform processes. A high nugget effect was introduced by the various bedforms in which the heavy minerals could accumulate. As these placers are strongly controlled by fluvial processes they have better continuity in the direction of paleoflow and are affected by the changing processes occurring on the paleoslope.

The Venterspost Contact Reef was deposited on an irregular structurally confined surface. A large volume of material, possibly also preconcentrated to some extent as in the case of the thin extensive placers, coupled to reworking of pre-existing reefs on the paleosurface gave rise to relatively rich placers. Although gold concentration was also controlled by bedform processes it took place in a degrading environment involving the reworking of richer material than that of the within-fan placers. The result was to form richer deposits but still with a large inherent nugget effect and high variability. The proximal areas are characterized by coarser grained and overall richer gold than the poorer distal areas. In the distal areas the effect of reworking of pre-existing reefs is also more pronounced.

The tectono-sedimentary environment in which these placers evolved determined the content, distribution and ease of extraction of gold in the reefs. Factors like continuity (important for mine planning) and uranium content were also determined by the tectono-sedimentary processes. During the Witwatersrand times viable placer forming processes operated more efficiently in the larger sedimentary systems. Major tectonic

upheavals coupled to large influxes of sediment gave rise to the extensive thin rich placers and to the Venterspost Conglomerate Formation reefs. The erratic and poorer placers were related to localized within fan activity involving smaller volumes of material at a time.

#### LOW TEMPERATURE EPIGENETIC SEDIMENTARY SYSTEMS

Some of the major sedimentary ores are formed by the introduction of mineralizing groundwaters or metalliferous brines into a sedimentary rock. Introduction of the mineralizing fluid may occur during early diagenesis (sedimentary copper) or even long after lithification of the host rock (carbonate-lead-zinc) and deposits so formed can therefore be considered epigenetic. Conditions existing in the host rock immediately prior to entry of sufficient quantities of mineralizing fluid control the quantity and distribution of mineralization. If the composition (sedimentary structure) and hydrology of a sand body is characteristically complex then the mineralization hosted in the sand-body will be equally complex. The conditioning or preparation of the host rock is also important not only to ensure sufficient precipitation of the metals from the brines but also in controlling distribution of mineralization. Preparation of the sedimentary host may include processes such as the formation of early diagenic anhydrite (sedimentary copper) or the presence of abundant carbonaceous material (sedimentary uranium).

#### Sandstone Uranium Deposits

Sandstone Uranium deposits have an affinity for continental depositional environments, especially fluvial sandstone deposits. The deposition of uranium in the sandstone is governed by the physico-chemical composition of the host sandstone and chemistry of the mineralizing ground water. Certain sand bodies are good hosts for uranium because of their high porosity and permeability; presence of reductants such as carbonaceous substances and of absorbants such as iron oxides and clay; and frequent facies variation which may inhibit the rate of movement of ground water. Primary and secondary sedimentary characteristics of the sandstone will therefore govern the behaviour of ground water movement and precipitation

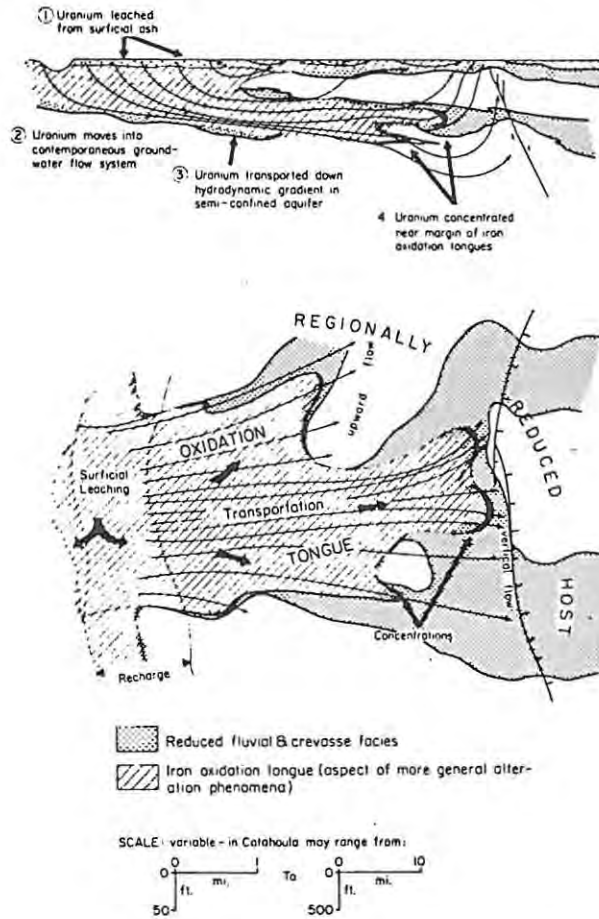


Figure 43: Diagrammatic representation of the genesis of roll-type deposits in the Catahoula Tuff, Texas. (Nash and Granger (1981))

of uranium. Mineralization may take place within a permeable host rock fairly long after the host rock had accumulated or could form shortly after deposition during diagenesis. Depending on the degree of permeability retained in a sand body after deposition, early formed uranium may be redistributed by later ground water movement.

A large variety of sandstone uranium deposits are recognised and the more common types are usually referred to as the roll-front-type (or Wyoming roll front, or geochemical cell) and the tabular peneconcordant-type (or Colorado plateau-type) (figures 43 and 44). Metals occurring in these deposits in significant quantities are: uranium, vanadium, copper, silver, cadmium, selenium and molybdenum. A deposit may contain any one or more of these metals in almost any combination except vanadium and

copper which are usually mutually exclusive. Amounts of metals vary enormously within and between deposits and many orebodies fluctuate so much in grade that a single overall average figure is not informative. Average uranium content of these deposits varies between 0,1% and 1,0%  $U_3O_8$ . In North America 99% of all known sandstone uranium deposits contain less than 1 million tons of ore with less than 3 million lbs  $U_3O_8$  (Evans, 1980; Holliman, 1981; Nash and Granger, 1981; Rautman, et al., 1980; and Thamm, et al., 1980).

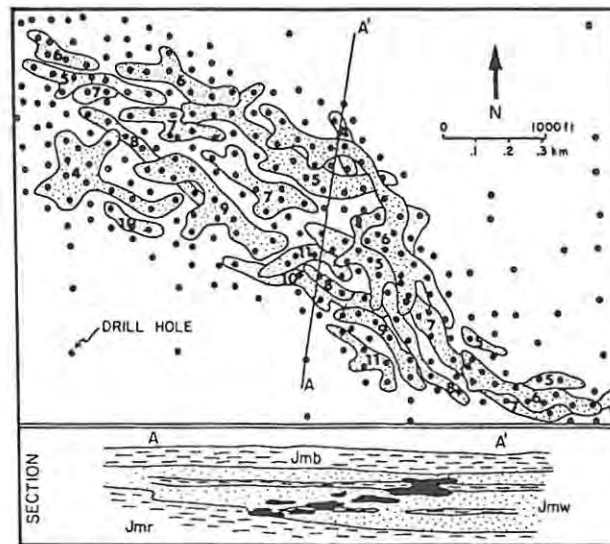


Figure 44: Diagrammatic illustration of an ore-development block showing distribution and complexity of ore horizons. (Rautman, et al., 1980)

#### Factors controlling ground water movement

The porosity and permeability of sand bodies determine the extent and rate of migration and movement of ground waters. The direction of movement is dependant upon pre- and post- deformational dips of beds, paleocurrent direction and geometry of sand bodies. The spatial arrangement above, below and laterally of associated silt and clay units also influences movement of ground water. Sand bodies formed in different depositional environments have various sizes and shapes and different arrangements of bounding lithologies. The geometry of a sand body is the large scale unified response to the depositional environment, paleoslope of the basin, and paleocurrent pattern. If, for example, the environment

was dominated by braided stream facies a tendency would be for a sand body with a high permeability to form, which could mean that the chances of uranium fixation and precipitation would be reduced. Also chances of organics being present in a braided stream environment are more limited than in a high senuosity, meandering stream environment. Characteristics of sand bodies that formed in specific environments are shown in figure 45 and an example of the influence of the geometry of a channel sandstone body on the distribution of uranium is illustrated in figure 46. The sandstone body shown in figure 46 has been interpreted by Brynard et al., (1982) to have been deposited in a lacustrine deltaic environment.

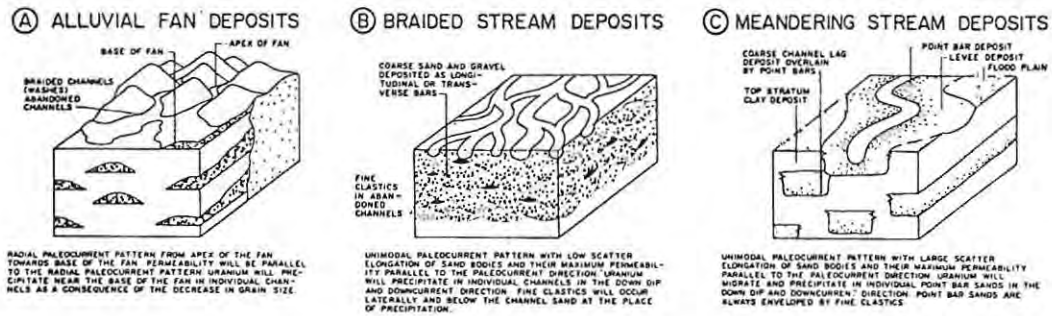


Figure 45: Major physiographic components, lithologies, shapes of sand bodies, and paleocurrent pattern for some continental depositional environments important for uranium (Quidwai and Jensen, 1979)

Features formed by primary processes controlling the hydrology of a sand body are texture, sedimentary structures and the bounding lithologies. Tilting of beds, superimposed patterns of cementation, compaction and faulting are some of the features formed by secondary processes.

Texture is governed by the grain size, sorting, packing, cementation and orientation of mineral grains and is the primary control on porosity and permeability. A good horizontal permeability in the paleocurrent direction of sand bodies is therefore a logical consequence but factors such as voids filled with primary cement will result in poor porosity and permeability.

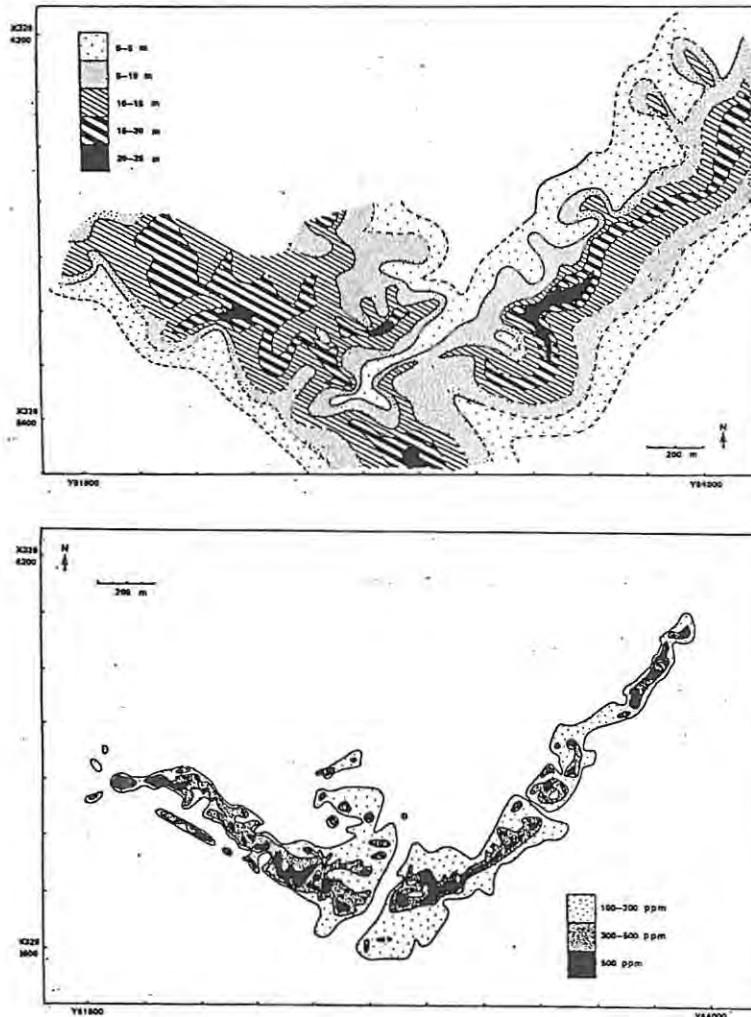


Figure 46: Mooifontein orebody (O.F.S.). Isolith map of S1 - sandstone (top) and grade contours (bottom) (Brynard et al., 1982).

Sedimentary structures such as bedding, cross bedding, parting lination and grooves also influence the localization of mineralization or ore bodies. At the Peanut mine, situated in the Salt Wash member of the Morrison Formation, Colorado Plateau, Roach and Thompson (1959) have shown that on a small scale the ore bodies conform to the outlines of trough cross beds (figure 47). The most common form is produced by the intersection of three cross beds resulting in a 'festoon solid'. Ore bodies are contained within the festoon solids and are found only in the part of the festoon solid having structural closure, forming a relatively impermeable surface. A thin clay seam is commonly present along this surface.

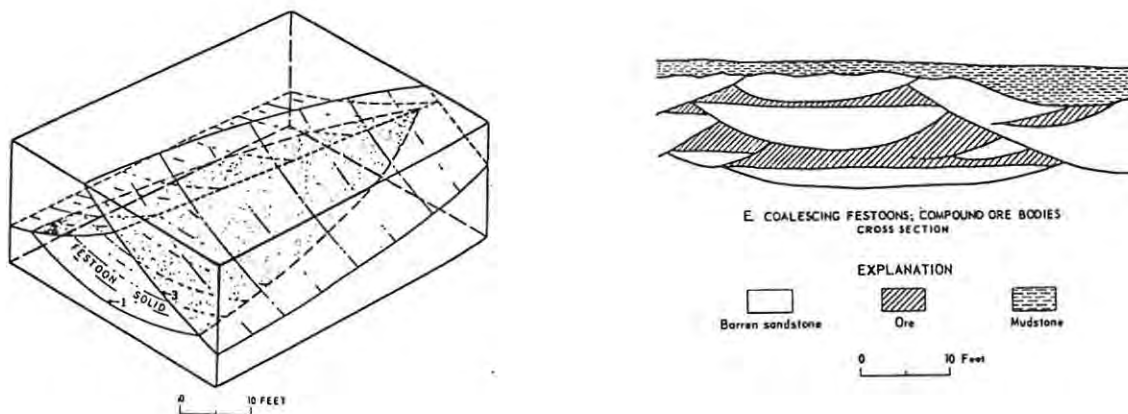


Figure 47: Diagrammatic sketch of festoon solids showing surfaces under which ore occurs (Roach and Thompson, 1959).

Fine grained rocks such as siltstone, clay and shale partings are barriers to fluid flow or ground water flow and exert a strong control on the shape and distribution of the sandstone uranium deposits. On a broad scale clusters or trends of deposits are associated with major sedimentary channels. On a more local scale individual deposits or lenses of mineralization commonly terminate against shale horizons, channel margins or any other sedimentological feature that produce permeability changes.

Permeability of a sand body can either be reduced or completely obliterated by secondary cementation. This could either effectively seal existing mineralization preventing it from redistribution or could prevent or restrict entry of late mineralizing fluids. Biogenic structures such as those produced by burrowing organisms can also reduce permeability. Faults in a sand body will have a two-way effect. If the faults are cemented by silica or some other sealing material it will act as a permeability barrier, otherwise as a porous and permeable zone (Qidwai and Jensen, 1979). Post depositional deformation of a sand body could further complicate hydrology, and the flow of ground water would be determined by the post-depositional dip and paleocurrent direction. Too steep a dip may also cause rapid ground water movement to flush uranium out of the sandstone.

## Factors controlling deposition of uranium from groundwater

Precipitation of uranium from oxidizing ground water is in response to a chemical gradient, when Eh becomes reducing. This can be brought about when ore bearing solutions move through a redox front within a sandstone body (roll-type deposits) or when oxidizing uraniferous ground waters come into contact with reducing pore-water during early stages of diagenesis (irregular peneconcordant deposits). Precipitation of uranium from solution is by mechanisms such as, (a) reduction by organic matter forming uraninite or other uranous phases, (b) adsorption of uranyl ions on organic matter, Fe-Mn hydroxides and clays followed by reduction and, (c) formation of insoluble compounds where uranyl ions combine with vanadate, phosphate, arsenate, silicate, carbonate or sulphate cations. The composition of a sandstone body will therefore significantly affect the grade of a related uranium orebody. If, for example, a minimal amount of organics were present in a sand body only a small amount of uranium would be captured, likewise sulphides are needed to create the mobile reductants responsible for the precipitation of the uranium. The clay content of the sandstone would govern its permeability responsible for reducing flow of the solutions so that uranium would have time to be absorbed onto the organics. (Holliman, 1981)

Mineralization is essentially one continuous surface which is much contorted and disrupted in response to the sedimentological features in the host sandstone. The different sandstone uranium ore deposit types are all formed by the same ore forming process, they differ only in form due to a combination of local hydrology in response to sedimentological features, timing of introduction of mineralizing fluids and possible secondary redistribution. Ore body distribution may be scattered along miles-long interfaces between altered rock, like widely spaced beads on a string, with little uranium along the interfaces between the ore (roll type - figure 43) or the distribution may be discreet and erratically distributed (peneconcordant - figures 44 and 48). In many instances tabular peneconcordant ore bodies of the Colorado Plateau are physically continuous into roll-shaped bodies. Roll shaped mineralization is more abundant where the host sandstone contains numerous shale horizons, which appear to break the mineralized horizons into a series of rolls within the intervening sands. Massive sandstones, by contrast are characterized by more tabular mineralization (Thamm et al., 1980).

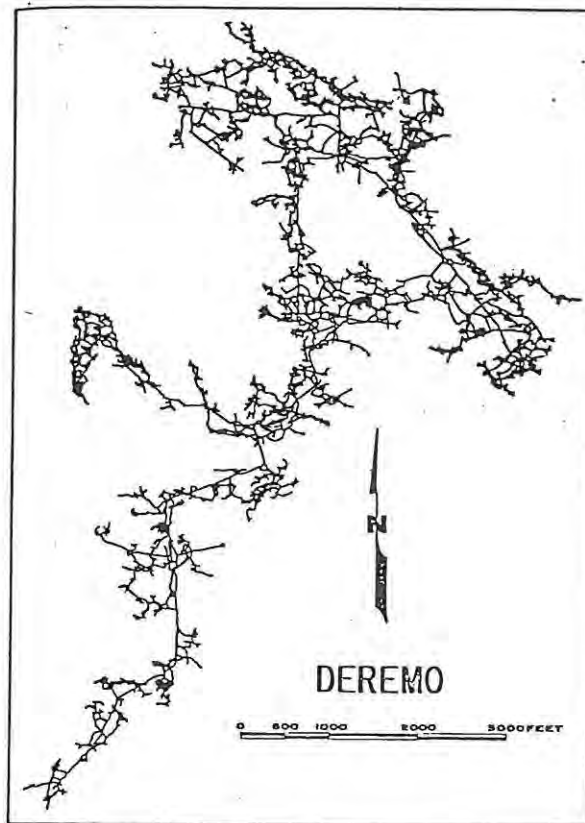


Figure 48: Plan of the Dermo Mine, Uravan mineral belt showing small size of stopes and the complexity of the workings. (Thamm et al., 1980)

Tectonic events that expose uranium deposits to atmosphere agencies, lowering of the water table, or changes in the climate are the main factors responsible for recycling of uranium. If the recycling is not in a preferred direction owing to local or regional geological factors, the uranium will be dispersed (Quidwai and Jensen, 1979). The disseminated form and microscopic size of the ore minerals increases the susceptibility to subsequent oxidation and remobilization by both alteration and weathering. Continuous or episodic introduction of oxygenated groundwater explains some of the major economic sandstone uranium deposits and is a process still affecting some deposits such as the roll front deposits where sandstones have retained their permeability and there is a flow of ground water.

## Ore mineralogy and disequilibrium

A fairly similar suite of elements and minerals is present within various sandstone uranium deposits, with small (but important) differences in accessory mineral content. Colorado Plateau peneconcordant deposits are varied uranium, uranium-vanadium or vanadium deposits with selenium and molybdenum conspicuous in only a few places. Average vanadium content of ores from Colorado Plateau peneconcordant deposits is 1,25%  $V_2O_5$ . Wyoming roll-type deposits on the other hand are consistently only uranium deposits with considerable selenium and in places also molybdenum. They have little vanadium and sparse copper.

Mineralization is both concordant and discordant with the sedimentation and occurs in sharp contact with carbonaceous free or oxidized zones. The ores occur in various degrees of oxidation depending largely upon their proximity to the surface and their position with respect to the water table. Primary ores are mainly composed of uraninite and coffinite and in the case of vanadium rich ores also montroseite and vanadium aluminosilicates. The ore mineralization impregnates the matrix of the sandstone and tends to be homogeneously distributed, except for the heterogeneities of the sandstone itself. Calcite, dolomite and barite could be present within or close to, ore as cement in the sandstone. Total carbonate contained in most Colorado Plateau ore is less than 6%. Pyrite, marcasite, jordisite galena, sphalerite, and minor copper and silver accessory minerals may be present. A zonation of minerals within ore bodies is commonly noticeable in most types of sandstone uranium deposits. In particular uranium selenium, vanadium and molybdenum are found zoned across roll front deposits (figure 49). In some cases, elements like molybdenum and vanadium are extracted as by-products and their presence consequently increases the grade of the ore. However, over the years the specification for yellow cake uranium concentrates have gradually become more restrictive. As a result elements such as molybdenum, vanadium, phosphorous and sodium are regarded as contaminants. If the amounts of the elements are sufficiently high in the concentrate resulting in further treatment or payment of penalties, then these elements would be regarded as deleterious products rather than by-products (Holliman, 1981).

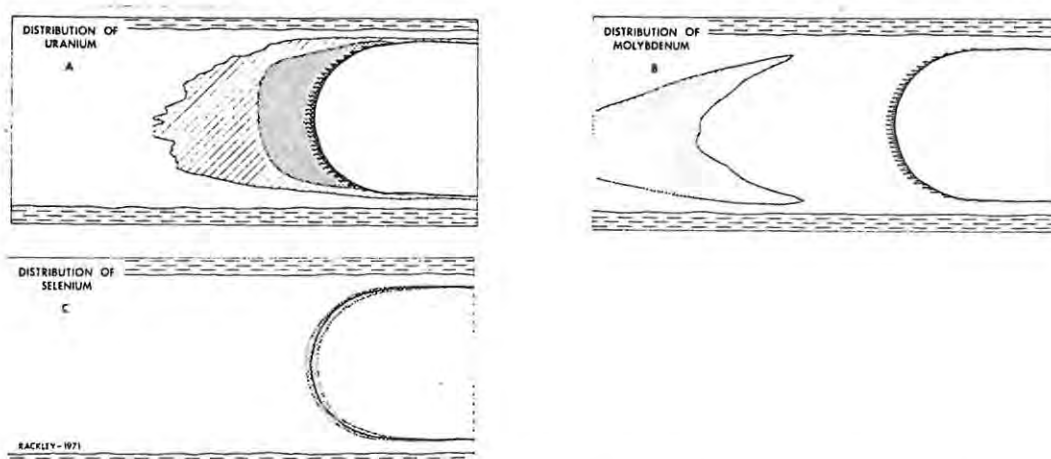


Figure 49: Characteristic zoning of uranium, molybdenum and selenium in leading edge of roll-front geochemical cell. (Rackley, 1972)

The carbonate content of the host rock also has an effect on the grade of a deposit from a metallurgical point of view. Most methods of extracting uranium from the ore incorporate an acid leach. If the ore contains a high carbonate content then more acid than normal is used, increasing the cost of processing the ore and therefore indirectly lowering the grade of the ore. If the carbonate content of the ore is abnormally high, it might necessitate the use of an alkali leach method which in cases of ore with normal amounts of carbonate (2-5% calcite) is more expensive than the acid leach method (Holliman, 1981).

Secondary oxidized ores are dominated by carnotite and tyuyamunite (V-rich ores). Virtually all the uranium oxidized from the primary vanadium-uranium ores is protected against leaching and mobilization by incorporation into insoluble secondary vanadate minerals. The deposits, therefore undergo essentially no loss of uranium during secondary processes (Thamm et al., 1980).

Disequilibrium is a prime factor controlling the estimation of uranium grade and it is unlikely that it will be constant throughout a deposit. Uranium is geochemically very mobile in the oxygenated ground water, especially in the absence of vanadium. Compared to parent uranium isotopes, their long lived daughter products, such as  $\text{Pa}^{231}$ ,  $\text{Th}^{230}$ ,  $\text{Ac}^{227}$  and  $\text{Ra}^{226}$  are more resistant to weathering and erosion.

This greater mobility of uranium in contrast to its daughters, creates disequilibrium conditions in sandstone. Disequilibrium at a particular site will either be in favour of the parent or in favour of the daughters. The former implies accretion of uranium and the latter removal of it, (Qidwai and Jensen, 1979). Irregularly distributed secondary porosity, permitting entry of oxidizing solutions through a mineralized rock, may cause patchy disequilibrium in an ore body. Within dynamic systems, such as roll-type deposits, where uranium is currently still being remobilized, disequilibrium is common.

Studies of disequilibrium conditions of uranium in sandstones have to be carried out and analysis for  $^{222}\text{Rn}$  and  $^{210}\text{Pb}$  as well as for uranium have to be carried out to check the accuracy of the uranium and radioactivity analysis. Misinterpretations can be made if only the chemically determined uranium content of a sample is compared with its equivalent uranium (eU), particularly if radon loss has occurred which may mask the presence of long lived daughters that are present in greater amounts than the uranium itself (Rosholdt, 1959). Accordingly the disequilibrium factor must be determined when estimating grade in the same way that S.G. must be determined.

#### Discussion

Grade distribution in sandstone uranium deposits is highly variable and almost random. The high nugget effect in the orebodies is due to inherent variability of processes controlling the deposition of uranium from the groundwaters. On a small scale fluid flow is affected by features such as bedforms (figure 47) and secondary cementation of the sand bodies controlling porosity and permeability. On a larger scale fluid flow in the sand bodies is controlled by the paleo-environment of deposition such as channel morphology in a braided environment or point-bar deposits in a meandering stream. Coupled to the highly irregular hydrology, characteristic of terrestrial sediments, are the highly variable processes controlling deposition of uranium from the oxidizing ground waters. Distribution of adsorbents and precipitants, related to the environment of deposition, may be erratically distributed throughout the sandbodies resulting in highly variable changing chemical environment controlling

precipitation of the uranium. Of the various types of sandstone uranium deposits the solution front deposits, related to the furthest down dip or outer penetration front of oxidizing ground water, appear to have the most regular features. Nevertheless the roll front deposits are usually fairly complex due to their often having several mineralized zones and the mineralization being quite variable in both grade and thickness. Because of the many variables involved in precipitation uranium the fronts of uranium are quite irregular with poor continuity. In the roll front deposit studied by Sandefor and Grant (1976) located in the Shirley Basin, Wyoming, each disconnected stringer typically measured less than 2 m in thickness and 5 m in width perpendicular to the strike.

#### Sedimentary Copper Deposits

It is generally accepted that the metals in sedimentary copper deposits were introduced as a component of an aqueous fluid which permeated the sediment before or during diagenesis. Therefore the variables controlling the mineralization will be, as in the case of sandstone uranium, related to the composition and hydrology of the host sediment and the nature of the ore forming brines. Some of the outstanding features of sedimentary copper deposits are the persistency and uniformity of the metallization parallel to the depositional strike over a uniform width, their fine dissemination in sediments, and their relation to certain restricted stratigraphic sequences. The sulphides are mainly conformable pyrite-chalcopyrite-bornite-chalcocite assemblages often with exploitable cobalt, silver and uranium mineralization. Minor lead, zinc and other metal sulphide mineralization has been reported from these deposits. Both vertical and lateral sulphide mineral zoning occurs and appears to be related to the interaction between the brines, the various mechanisms of precipitating metals from the brines and the depositional environment of the host rocks. Mineralization is not as laterally extensive as the favourable sedimentary host.

The deposits world over, appear to display similar geotectonic settings and paleoenvironmental conditions during sedimentation and metal accumulation. They all occur in continental yoked reductate basins (Bowen and Gunatilaka, 1977) which are either shallow lagoonal and lacustrine

type settings in cratonic basins, or marine to marginal marine environments with mainly terrigenous accumulations that are indicative of extensive subtidal to supratidal flats and shallow enclosed embayments. Though the deposits vary greatly in age, geographic location and extent, the ores are hosted by carbonaceous shales, sandstones, conglomerate and dolomites. The ores are often underlain by oxidized continental clastic sediments and overlain by evaporitic lithologies.

The Upper Proterozoic White Pine, Coppermine and Seal Lake deposits are the most important stratabound copper deposits in North America. They are hosted in continental clastic sediments which together with subareal tholeiitic volcanics accumulated in rift bounded basins. The copper deposits are preferably hosted by carbonaceous shale horizons developed above thick tholeiitic volcanic piles. At White Pine the copper mineralization is confined to five stratigraphic horizons in the Nonesuch shale and shows a broad scale vertical and lateral native copper-chalcocite-pyrite zonation (Brown, 1979).

Late Proterozoic stratiform copper deposits in Africa occur in the basin margins adjacent to Archaean cratonic nuclei. The most important copper deposits are those of the Zambian Copperbelt ( $\pm$  900 m.y.) where mineralization is confined to the Lower Roan Group which was deposited on an irregular basement paleotopography. Mineralization occurs disseminated within both argillaceous and arenaceous horizons (Mendelsohn, 1961).

From the analysis of sediments hosting numerous stratiform sedimentary copper deposits, Brown (1978) and Bartholomé (1974) have indicated that mineralizing processes can be sub-divided into a pre-ore stage followed closely by the influx of economic base metals. The pre ore stage is characterised by the conditioning of the sediment by the extensive enrichment in syngenetic or very early diagenetic sulphur, generally in the form of iron sulphides or anhydrite. The sediment is then amenable to metal enrichment especially during its succeeding early diagenetic history when porosity and permeability are high. This two step process explains the observation that mineralization is not always as laterally extensive as the favourable sedimentary horizon.

Evidence for reaction of introduced metal with original sulphur is given by Annels (1974) who proposed that sulphur from anhydrite was extensively consumed in the formation of sulphide in the Copperbelt bodies. Whether the ore bearing host rock be arenite, argillite or siltstone, an antipathetic relationship can be demonstrated between copper and iron sulphides on the one hand and anhydrite on the other. Anhydrite formed during early diagenesis under conditions of supersaturation of  $\text{CaSO}_4$  in a sabkha-type environment. During advanced diagenesis, still under relatively low temperature conditions, the anhydrite was replaced by carbonate, thus liberating sulphur which was then utilized in the precipitation of diagenetic sulphides, initially pyrite. The Kamoto ore of Shaba in Zaïre also bears evidence of mineralization following one or more prior diagenetic events. Brown (1981) has shown that a diagenetic event involving pyrite preceded the deposition of copper. At Seal Lake mineralogical studies (Brown, 1979) indicate that iron-rich sulphides were progressively replaced by copper rich sulphides and at Klein Aub, South West Africa, the replacement of early formed diagenetic pyrite cubes by chalcocite is present along the fringes of the orebodies.

In general metal transport is attributed to metal solubilities in chloride rich brines of various origins and to the favourable degree of permeability through the surrounding sediments (Brown, 1978). The pre-conditioning of sediments is a critical factor in determining the preferential concentration of copper sulphide mineralization in the sedimentary copper deposits and therefore the stratabound mineralization has a character controlled more by the host sediments. The proposed source of metals is commonly thought to be from selective leaching of the basin strata themselves or from weathered basement rocks. The presence of low grade alteration zones and the introduction of anomalous trace element concentrations suggested to Dingemans (1981) that the mineralization was associated with magma-derived hydrothermal brines.

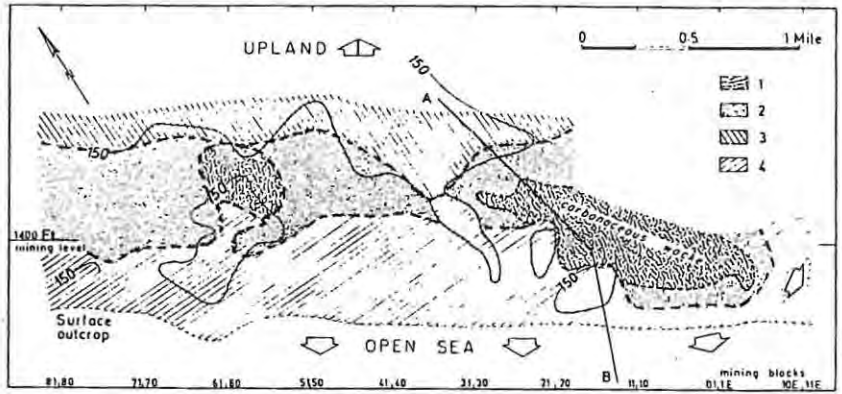
### Primary factors controlling grade

There is not an obvious relationship between grade of mineralization and host lithology in the sedimentary copper deposits. The distribution of copper at particular sites must therefore have been controlled primarily by the availability of metal in solution at these localities and the degree of conditioning of the host sediments. In the Zambian Copperbelt variations in orebody morphology, metal distribution and mineralogy indicate that the migration and fixation of copper and cobalt did not take place in exactly the same way at all the Copperbelt orebodies. Even at the scale of the width of an orebody or lesser distances it is likely that different fixation mechanisms operated to produce the relatively heterogenous grade distributions commonly observed (McCulloch, 1981).

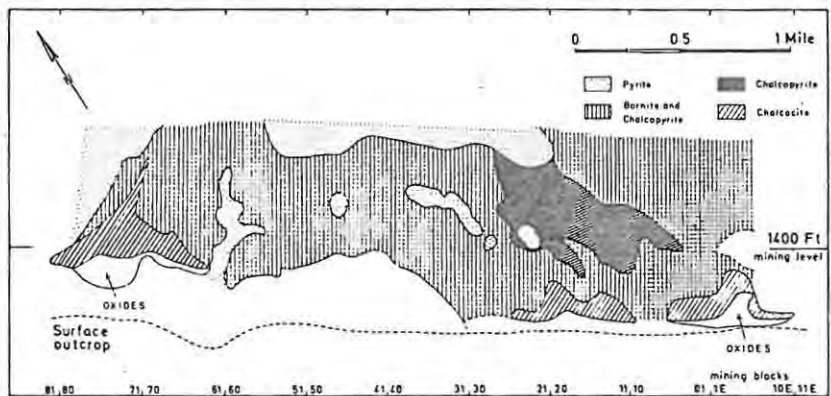
The environment of deposition of the host rock is important as it determines the degree of conditioning. The degree of conditioning of a host rock will, to a large extent, control the intensity and distribution of mineralization. For example, if the conditioning of a host sediment involved the formation of widespread disseminated diagenetic pyrite, later replaced by copper sulphide, mineralization can likewise be expected to be extensive and disseminated, etc.

In the Zambian Copperbelt basement paleo-topography played a role in restricting currents and circulation, and creating anoxic basins that were conducive to metal precipitation. Orebodies show a change in grade from the crestal regions where the ore is thin, absent, or pyritic, to the paleoslopes where the ore is very high grade (figure 50). The ore becomes sub-economic or absent in the paleovalleys. The so called 'barren-gaps' in many of the Copperbelt orebodies are related to pinch-outs of ore strata against paleo-highs or due to the presence of biohermal reefs that occupied the higher lying ground.

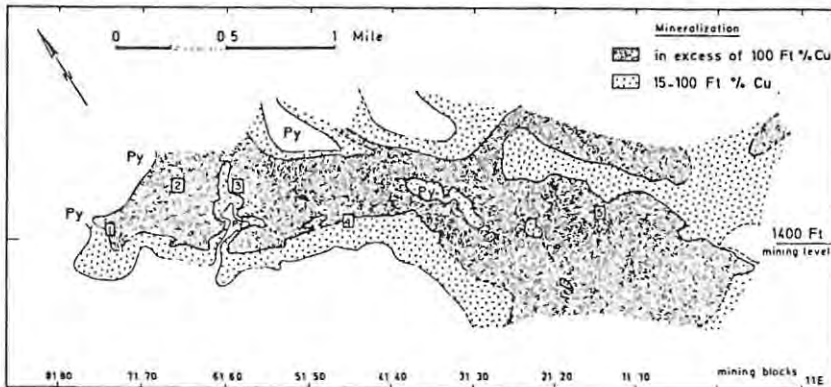
On a smaller scale copper mineralization is preferentially hosted by certain stratigraphic horizons although in detail the mineralization transgresses bedding and lateral facies changes (figure 50). On an even smaller scale, accumulation of copper minerals on bedding planes and the even dissemination in more massive lithotypes are described by Binda and Mulgrew, 1974. In calcareous schists which form the hosts for the



Elements of the paleogeography during C Orebody sedimentation: (1) carbonaceous wacke and (2) mottled argillitic sandstone, both (1) and (2) represent a low-energy depositional environment in which syndimentary or diagenetic copper sulfides could have formed; (3) and (4) coarse, often cross-bedded, sandstones of a higher energy depositional environment, littoral and off shore, respectively:



Unrolled map of C Orebody showing generalized zones of dominant sulfide minerals.



Unrolled map showing C Orebody mineralization in percent copper:

Figure 50: Maps showing distribution of mineralization and related metal content relative to paleotopography, Mufulira, Zambia. (Van Eden, 1974)

basal parts of the orebodies at Rokana, Chambishi and Luanshya, it is often difficult to distinguish the original bedding, and the copper minerals usually occur as augen-like blebs, veinlets, and concentrations that rather reflect the metamorphic than the sedimentary history of the rock. In the bedded argillite there are concentrations of sulphide grains along bedding planes, whereas in the more massive argillite the

ore is evenly disseminated, and the grain size is directly related to that of the rock. Likewise ore-bearing arenaceous rocks on the Zambian Copperbelt display concentrations of copper sulphides on bedding surfaces, in erosional potholes and in a variety of other sedimentary structures.

Mineral zoning in sandstone copper deposits occurs laterally as well as stratigraphically. At White Pine native copper is concentrated in underlying sandstones and grades abruptly upwards into a chalcocite-native copper zone in the Nonesuch shale followed by a chalcocite zone that is in turn overlain by an extensive pyritic zone (Brown, 1979). The Oamites deposit in South West Africa is characterized by a silver enrichment in the fringe zones of the orebody. In the Zambian Copperbelt, the vertical sequence is generally basal chalcocite, followed by bornite, chalcopyrite and topmost pyrite. Laterally the order is bornite, chalcopyrite, chalcocite and pyrite. This zonal sequence is variable at different mines and cannot be tied to a specific facies in the host rocks (Bowen and Gunafilaka, 1977).

Broadly there does however appear to be some relationship between the sulphide minerals and lithology at some Copperbelt mines. At the Mufulira mine, pyrite and chalcopyrite have the strongest affinity with a reducing environment (carbonaceous quartzites), chalcocite is most common in the highly porous conglomeratic sandstones, and bornite and other sulphides in the argillitic sandstones (figure 50). At Baluba mineral zoning has been explained by the changing Eh-pH conditions with time due to fresh waters entering a hypersaline basin (Bowen and Gunatilaka, 1977).

A knowledge of the mineral zoning within the orebodies is important for grade control purposes. Even though a homogenous persistent metal content is present within an orebody ores with the same metal content may have different mineral assemblages (figure 50) affecting plant efficiency. Grade control becomes more complex when more than one metal is to be recovered from the same orebody. Figure 51(A) shows the complex copper-cobalt zonation within the Chibuluma West orebody.

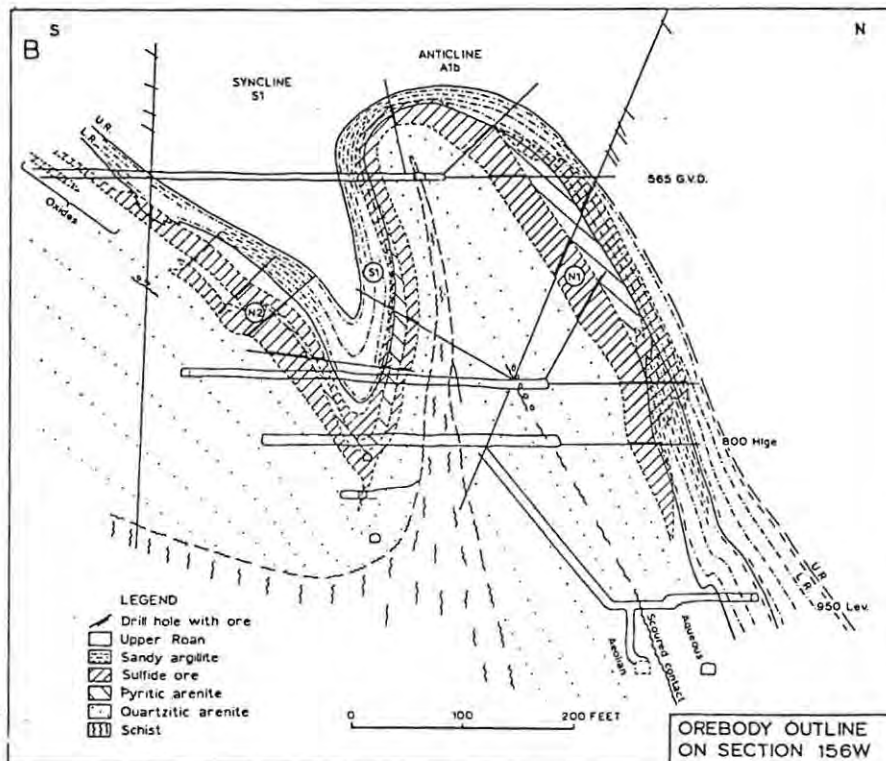
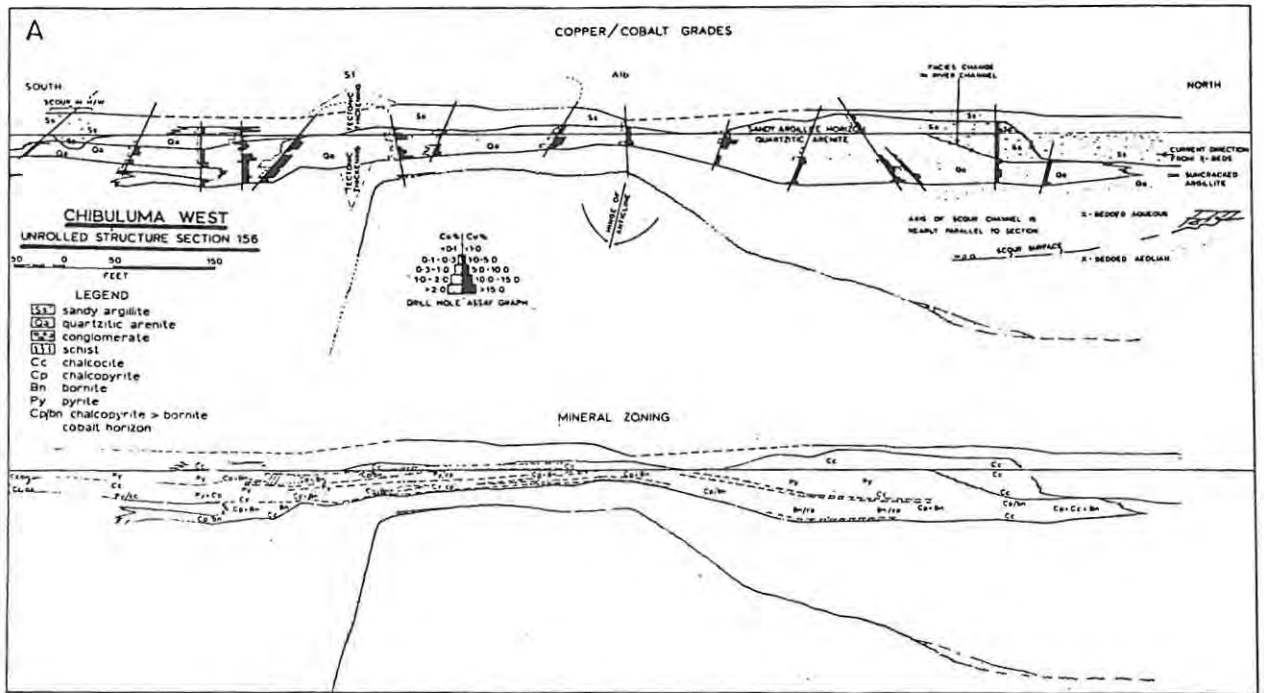


Figure 51: Maps showing zoning and deformation of the Chibuluma West orebody, Zambia. (Whyte and Green 1971)

The extractive properties of copper and cobalt minerals found in the Zambian Copperbelt ores greatly affect the amount of metal that can be recovered. A total copper or cobalt assay is not necessarily indicative of the amount of metal ultimately extractible from an ore. Sulphides are normally recovered by grinding of the ore and flotation. Ore containing both copper and cobalt sulphides are treated by using a differential flotation process to recover two separate concentrates. Problems are encountered in separating copper from cobalt and include: (a) Where carrollite occurs as fine veinlets traversing chalcopyrite and bornite grains, much of the carrollite floats with the sulphides to which it is attached. (b) Where carrollite is mantled by chalcopyrite or bornite, these grains float in conditions designed to produce a copper-rich concentrate despite being mainly composed of carrollite. The effect is again to produce a loss of cobalt to the copper concentrate (McCulloch, 1981). (c) The cobalt content of cobaltiferous pyrite must exceed 10% Co before the cobalt can successfully be recovered from the ore. Therefore even though an ore may have a high cobalt content because of a concentration of cobaltiferous pyrite, it may not be extractible because the cobalt content of the pyrite itself is less than 10% (Mason, R., pers. comm., 1982).

The multi-product problem is well illustrated at the Chibuluma (East) mine, Zambia. The copper and cobalt sulphide orebody at Chibuluma is contained in a lensoid pyritic sericitic sandstone body. A strong mineral zonation is present in the orebody with the occurrence of cobalt mineralization fringing the orebody. Cobalt occurs mainly as cobaltiferous pyrite in the same lithological unit as the copper (chalcopyrite-bornite) mineralization, partially overlapping it both laterally and vertically. In addition to the vertical and lateral chalcopyrite-cobalt-pyrite zonation, a high concentration of sulphides occurs over a wide zone at the base of the orebody. This basal massive sulphide zone comprises mainly chalcopyrite, linnaeite and carrollite (McCulloch, 1981) and rests with a sharp contact on the footwall lithologies. Because of the differential treatment required to recover copper and cobalt from the ore, the ore is classified into copper-sulphide

ore (main part of orebody), copper-sulphide- carrolite massive ore (10% Cu, 2% Co), and copper-sulphide- cobaltiferous pyrite 'fringe' ore (1,5% Cu, 0,2% Co). Because cobalt is present in cobaltiferous pyrite of which the cobalt content is less than 10% the 0,2% Co in the 'fringe' ore cannot be recovered. Likewise, although due to other metallurgical problems described above, all the cobalt from the massive ore cannot be recovered (Mason, R., pers. comm. 1982).

#### Secondary factors affecting grade

Ore bodies of the Zambian Copperbelt illustrate very well the effects of varying intensity of deformation on shape. At places where the ore horizon has been tightly folded there has been intense deformation about protuberances in the granite that had earlier formed the basement of the Roan sedimentation (figure 51 B). In such placers the ore bearing sediments are heavily deformed and conspicuously drag-folded, and the outlines of the orebodies, in conforming with the corresponding structures, are correspondingly complex. Tectonic thickening of portions of the orebodies has occurred at places such as the western extremity of Luanshya mine and at the Mufulira mine (figure 51 B).

The less competent members of the Lower Roan sequences were deformed by planar shear, with resultant development of cleavage. Fairly extensive remobilization of ore minerals into cleavages is evident in some of the deposits and in other cases considerable redistribution of metals over small distances have resulted (McCulloch, 1981). At the Klein Aub mine finely disseminated chalcocite has been remobilized into fracture cleavages transposing bedding. This remobilization has resulted in making the ore amenable to easier beneficiation.

Other metallurgical problems commonly encountered are related to outcropping orebodies where supergene effects alter the character and mineralogy of the orebodies causing metal migration and fixation in non-sulphide minerals. Oxidized zones may constitute an important part of ore reserves in some mines, particularly on the Copperbelt mines where oxidation to levels in excess of 200 m are common. Minerals commonly present are malachite, chrysocolla, cuprite, cupriferous wad, tenorite

and native copper. Often a zone of supergene enrichment occurs above the unoxidized ore. As most non-sulphide minerals cannot normally be recovered by flotation, their extraction usually involves a sulphuric acid leaching process, and therefore non-sulphide mineralization is calculated separately during ore reserve estimation.

According to McCulloch (1981) determination of sulphide and oxide copper is normally carried out by means of assays for total copper and acid soluble copper, using cold dilute sulphuric acid saturated with sulphur dioxide for the acid soluble copper determination. The difference between these values is taken to be the amount of copper present in the sulphides. However, values for sulphide and oxide copper obtained by this method can be misleading. A small percentage of the copper present in chalcocite and bornite reports as acid-soluble or oxide copper, but would be recoverable by flotation. Native copper is not soluble in cold sulphuric acid and therefore reports by assay as sulphide copper. Massive native copper can cause problems because it will not grind, and coarse grains of native copper will not float. Fine-grained native copper appears to float readily with sulphides and thus presents no metallurgical problem. Chrysocolla, malachite and pseudomalachite, plus various minor cupriferous phases, none of which are really oxide minerals, are all completely soluble in cold sulphuric acid. Cuprite is the only true oxide present in Copperbelt ores but is not completely soluble when leached by sulphuric acid. A portion of malachite may be induced to float by the use of sulphidizing reagents.

#### Discussion

The viability of a sedimentary copper deposit depends on the degree of conditioning of the host sediment and the nature of the mineralizing brine. The conditioning of the host sediment determines to a large extent how much of the copper (or other metals) will be precipitated from the brine. The paucity of abundant free pyrite at White Pine and Klein Aub relative to the Zambian Copper Belt ores, suggests that the better the conditioning of a host sediment, the greater is the potential for a large ore deposit. The finely disseminated nature of the ores are probably also related to the conditioning of the host sediment where, for example, the distribution of early diagenetic anhydrite throughout a

sandbody determines the distribution of later mineralization.

The composition and quantity of the mineralizing fluid would obviously also be a factor in determining whether a viable ore deposit would form. Some brines appear to have U, Co or Ag in addition to copper. In some cases as at Oamites and Klein Aub a limited volume of mineralizing fluid probably coupled to a poorly conditioned host sediment and a small environment resulted in the formation of a relatively small deposit. Although hosted in a large extensively conditioned sequence the White Pine copper occurrence is of limited size due to the small volume of mineralized fluid that entered into the depositional environment.

In sandstone uranium deposits which are hosted in sediments formed under fluvial conditions the uranium mineralization occurs in multiply sealed porous sandstone bodies of braided or meandering stream origin. The hydrology and also the presence of variable amounts of reductants in the fluvial environment is responsible for the complex morphology of the uranium deposits. On the other hand in sedimentary copper deposits the sandstone bodies, controlling the distribution and to a large extent the quantity of mineralization, formed in lacustrine or shallow restricted marginal marine environments. The sedimentary host would therefore laterally have uniform hydrology and reductant content. This coupled to the early timing of entry of the copper brines, before porosity can be blocked by secondary processes, would result in a relatively continuous orebody. Mineralization in argillaceous and carbonate hosts tends to be more evenly distributed, whereas in an arenaceous host the presence of irregularly distributed structures such as foresets and scour channels have an influence on the distribution of reductants, such as detrital pyrite, or have an influence on the hydrology of the sand body.

Vertical continuity, hanging-, and foot-wall cutoffs are dependant on the way the mineralizing system developed. Hangingwall boundaries to the mineral deposits may be diffuse due to the waning of influxes of mineralizing solutions into the host rocks, resulting in an assay cutoff to define ore bodies. Footwall boundaries may be similar, but due to a gradual buildup of mineralization. More commonly however the footwall

contacts are sharp and probably related to the sudden influx of large volumes of mineralizing fluids into an early diagenetic porous sandbody resting on older impervious sandstone or bedrock.

#### Carbonate Hosted Lead-Zinc-Copper Deposits

Carbonate hosted Pb-Zn-Cu deposits are characterized by their extreme variability both on a large and a small scale. The ores were deposited from low temperature chloride brines and are hosted in shallow water platform carbonates. The carbonates and their contained mineralization are related to paleoshorlines and are associated with reefs, facies changes, and unconformity features. Often superimposed tectonic features control the localization and geometry of the deposits. Depending on the timing of entry of the ore forming solution into the host rock and the presence or absence of post-ore forming deformation these deposits have traditionally been called Mississippi Valley-, Alpine-, or Appalachian-type deposits. This discussion will mainly centre on Mississippi Valley-type deposits.

The deposits are formed by precipitation of metals from a brine within a porous carbonate host. The origin of the brine and mechanism of precipitation of the metals from the brine is still debated. Brines forming the deposits usually occur far from any obvious igneous activity and if the brines were generated by diagenetic processes within the sedimentary basin they must have migrated over long distances to their sites of precipitation in shallow environments. The processes creating open space or porosity in the carbonate within which metal deposition occurs are controlled by complex features of diverse origin. The mineralizing fluid does not 'dump' its contained metals, as in the case of sandstone uranium deposits, but may only precipitate one or more metals at a time in a specific place. Brines forming carbonate-lead-zinc deposits may also be introduced in a number of separate pulses, in some cases, over a considerable time span. All these factors lead to extremely complex deposits being formed which are difficult to locate and difficult to evaluate.

### Factors controlling porosity in carbonate sequences

The porosity in the carbonate host rock is the common factor to all types of carbonate Pb-Zn deposits which dictates the depositional site, volume and quality of ore. It may be a primary sedimentary or diagenetic feature or could be related to secondary processes such as dolimitization, folding, faulting, jointing or fracturing and, very importantly, karsting. Porosity in limestones is rarely homogenous and as a result permeability trends are often formed. The trends will not be haphazard and in many cases are broadly geologically predicable. The arrangement of permeability trends in carbonate reservoirs will determine the relative flow of inter- and intraformational fluids. Factors controlling porosity in carbonate sequences are discussed in detail by McDonald (1980).

Some of the sites of primary porosity in host carbonates are shown in figure 52 (A1 to A4). These sites are directly related to the depositional environment of the carbonate sequences, and as a result of an interplay between paleotopographical features and the various facies of deposition.

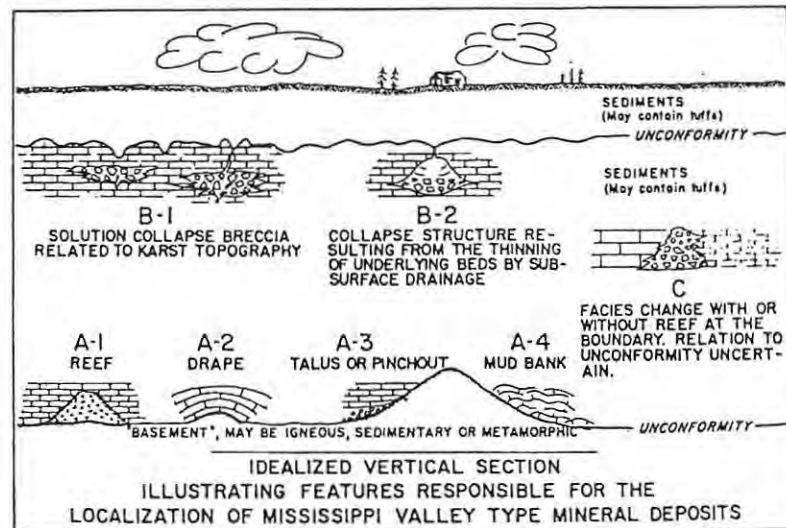


Figure 52: Idealized vertical section illustrating the range of geological situations in which limestone lead-zinc deposits are known to occur. (Callahan, 1967)

Figure 53 shows the facies distribution of the ore bearing Bonneterre formation in Missouri which is controlled by a circular positive structure of Precambrian age. The form of orebodies in the Bonneterre formation

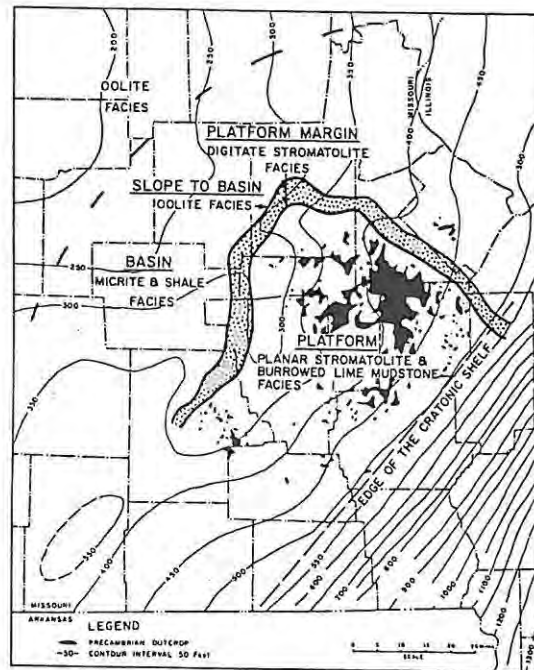


Figure 53: Relationship of Bonneterre facies distribution to isopach of the Bonneterre Formation and depositional Framework. (Larsen, 1977)

are mainly those of sedimentary depositional structures related to the topographic highs. Elongation of the ore bodies is parallel to the contours of the topographical features. The geometry of algal reefs, for example, are determined by the geometry and internal features of the biotic complex. This in turn determines the characteristics of ore deposits hosted in such structures. A typical biohermal complex is shown in figure 54 where later sediment filled surge channels, representing the end stage of a carbonate cycle, are porous sites for good ore development (figure 55). Repetitive biostromal cycles can be developed within a digitate stromatolite facies. The stromatolite or coral growth lines are also sites of increased porosity.

Disconformities may provide an avenue for fluid migration, giving rise to blanket type mineralization. Likewise unconformities, especially if a breccia is developed, may be mineralized. Ore may be found along stylolites, bedding planes, or an impermeable cap rock may act as a trap to mineralizing fluids. Facies change with different compositions may directly affect relative porosities. The deposits located at facies

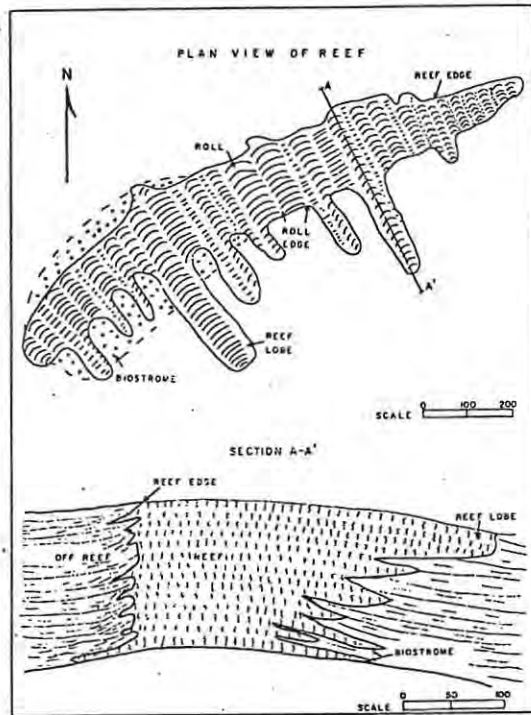


Figure 54: Bioherms of the Old Lead Belt, Southeast Missouri. (Larsen, 1977)

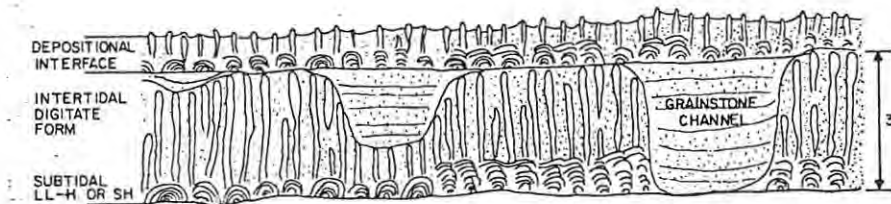


Figure 55: Biostromal stromatolite cycle, Ozark Mine. (Larsen, 1977)

changes or localized by old shore lines are usually strikingly linear. They may extend for kilometers in a relatively narrow zone and do not have great areal extent.

A wide range of structurally controlled sites resulting from a combination of faulting, fracturing, jointing, folding etc., may form open spaces for deposition of ore. Figure 56 shows the pinching, swelling and irregularity both vertically and laterally in the dimensions of gash vein and joint controlled ore bodies. Structure can be constructive in a

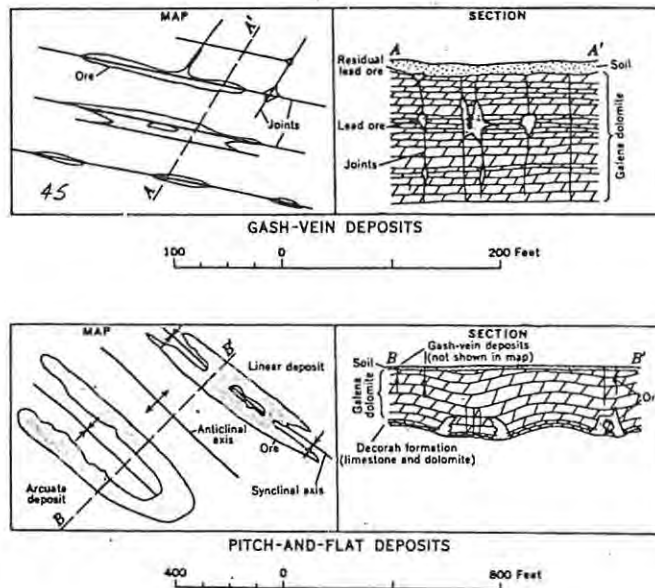


Figure 56: Diagrammatic Plans and Sections, showing typical patterns of gash-vein lead deposits and underlying pitch-and-flat deposits and their stratigraphic positions relative to one another. (Heyl, 1969)

sense that protore is remobilized and recrystallized in economic concentrations. At the Namib Lead Mine, South West Africa, galena-sphalerite ore is concentrated in elongated steeply dipping, plunging, boudins representing parasitic folds of a regional refolded structure. Structure may also be destructive and in stead of upgrading a deposit an orebody may either be dismembered through shearing or faulting, or the ductility contrasts between galena, sphalerite, pyrite and pyrrhotite or between silicified and unsilicified carbonates can result in very complex configurations.

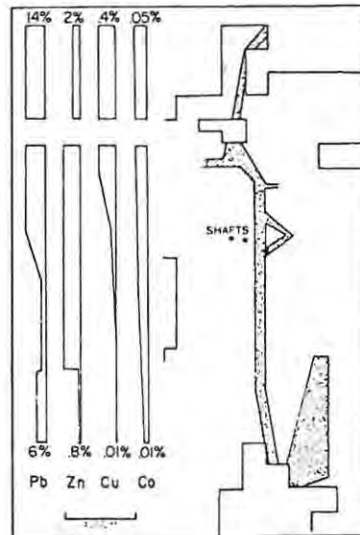
Numerous ore bodies are related to an erosion surface or unconformity, where in the past a karstic topography was developed by chemical solution during subareal exposure (figure 52). Karsting may also be associated to a paleoaquifer system where solution collapse breccia bodies are common. Primary and tectonically induced porosity may also be enhanced by karsting. Karst associated deposits are commonly integrated into a dendritic pattern reflecting control by a subsurface drainage system and can have substantial areal extent, up to hundreds of square kilometers (Callahan, 1977).

### Factors controlling intensity of mineralization

Whereas the size of a carbonate hosted polymetallic ore body is directly related to the size of the entrapping structures in the host, the quantity and distribution of the ore minerals in the entrapping structure are largely controlled by the relative porosity of the host rock, nature of the mineralizing fluid (resulting in the zonation of minerals in the orebody), and by supergene alteration.

Carbonate hosted lead-zinc ores were probably precipitated from concentrated sodium, calcium, potassium chloride brines at temperatures of between 70 to 160°C (Barnes, 1979) derived from adjacent basins. Two main theories have been proposed to account for the transport and precipitation of the ore minerals, either precipitation took place from a single fluid system or, alternatively, it was associated with the mixing of at least two subsurface fluids. Ore transport routes were lateral up-dip and precipitation took place at the flanks of the sedimentary basins. Whatever the transporting and precipitation methods were they must have been affected by a series of stratigraphic restraints described above and precipitation of the minerals from the solution was probably as a result of, or a combination of, temperature decrease, pH decrease, dilution, or reduced sulphur content.

Differences in the stabilities of metal carrying complexes in brines result in sequential precipitation of metals thereby inducing lateral and vertical zonation in an ore deposit. The zonation is however not very well defined in carbonate hosted Pb-Zn deposits due to the multiple mineralizing phases associated with deposition. Numerous overgrowths of different sulphide minerals in vugs, leached and etched crystals, pre-breccia ore in a matrix of post breccia ore, and complex zoning of individual sulphide minerals point to several mineralizing pulses with varying chemical conditions in the fluid (Barnes, 1979). Knowledge of zoning in a deposit is critical in order to accurately control grade. The breccia bodies of the Buick Mine of the Viburnum Trend (figure 57) display a well developed north-south metal zoning while on a smaller scale significant zoning is also present as shown in the cross-section through the orebodies (figure 58). This example shows the introduction of fluids from the north resulting in what appears to be a fairly regular zonation on a large scale but with extreme variability in cross section on a small scale.



Buick property map showing the relative metal abundance along the trend of the orebody.

Figure 57: Map of the Buick Mine, Southeast Missouri, showing the relative metal abundance along the trend of the orebody. (Rodgers and Davis, 1977)

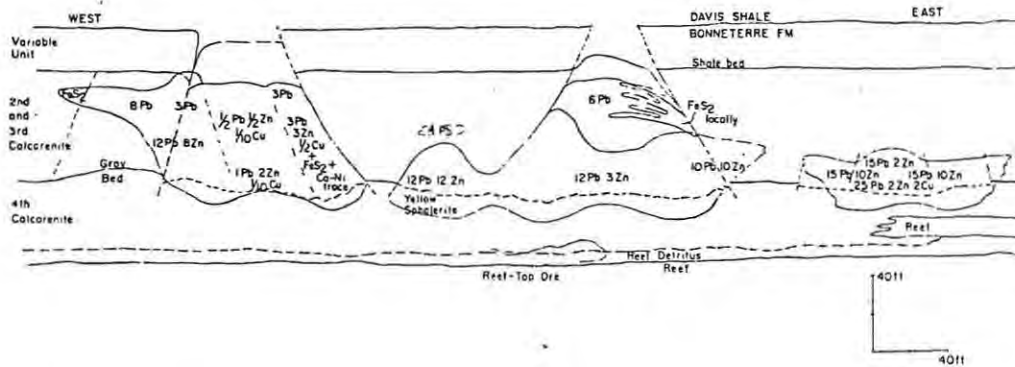


Figure 58: Section of the breccia bodies, Buick Mine, showing typical metal zoning. (Rodgers and Davis, 1977)

Ore mineral distribution in a carbonate rock is determined by the relative porosity in the rock and the degree to which the voids have been filled by ore minerals. Sites for deposition have been discussed in the earlier paragraphs. In a barrier reef environment, for example, porosity is created by biota, recurrent dolimitization of the reef, and evaporitic brecciation during emergence of the reef. Ore minerals filling the voids may, as at Pine Point, crystallize as colloform sphalerite, often enclosing idiomorphic galena. The remainder of the open spaces, if filled, contain dolomite, quartz, calcite, fluorite and barite (Jackson and Folinsbee, 1969).

As porosity varies considerably in the ore, porosity factors are applied to ore reserve estimation calculations.

Mineralization in breccia bodies is also characterized by open space filling of vugs and fractures. At the Buick mine (figure 57) the grade in the breccia bodies is directly influenced by the quantity and size of the barren breccia fragments as well as the gangue and porosity percentage. As shown in figure 58, grade through a breccia body is erratic and patchy (Rodgers and Davis, 1977).

Supergene alteration is commonly present in many near surface ore bodies. Three zones of supergene alteration are often distinguished. A zone of leaching and oxidation usually occurs at surface depleting tonnage and grade. This is followed by a zone of enrichment containing secondary oxidized ores. Due to a decrease in S.G. of the oxide minerals, relative to the unoxidized minerals, the enrichment is often false. Below the secondary oxide zone, a zone of secondary sulphide mineralization is present in ore bodies containing copper minerals as co-products e.g., Tsumeb and Kombat Mines. Secondary ore is normally separated from primary ore in ore reserve estimation as the S.G. is different, mill head treatment differs, mining conditions are different, and the oxidized zones are much less stable and more water ridden.

Primary sulphides of carbonate hosted ore deposits occur mainly as open-space filling and replacement of suitable host rocks. The ore show several varieties of textures dependant upon the process of deposition, structural control, and wall rock alteration. Ore texture varies from coarse and fine crystals lining open cavities to massive replacement of host rocks, and from colloform masses to pseudomorphic replacement of earlier formed minerals. The granularity varies from coarse grained to fine grained and is rarely microscopic. The simple grain boundary relationships and the relatively coarse grained nature of the ore minerals and gangue facilitate their liberation during processing. Due to the low temperature, epigenetic unmetamorphosed character of the ores a simple ore/gangue relationship exists (McDonald, 1980).

The polymetallic ores at the Tsumeb Mine are more complex. Compact intergrowths of galena, sphalerite and copper minerals are typical but do not pose a serious problem in extraction. In addition minor economic

constituents of the carbonate hosted lead-zinc and copper minerals are mainly silver, cadmium and germanite. Quality in carbonate hosted Pb-Zn-Cu ores is generally high, the main detrimental impurities being iron and arsenic. The contacts of the ore bodies are generally sharp, contrasting with the lighter coloured dolomitic wall rocks and assay contacts are a rarity.

The highly variable specific gravity of ore in these deposits is another characteristic that has to be accommodated during evaluation. Fluctuations in grade of the three main metals in the Tsumeb orebody (which occurs as a flat cylindrical pipe in karsted dolomite) is wide and ranges from 0 to 55 percent for copper, 0 to 75 percent for lead and 0 to 45 percent for zinc (Söhnge, 1966). The various metal ratios vary with depth, and horizontally, and the metals are contained in over 100 different minerals. Oxidation is present to 300 m below surface and again along a fracture zone below a depth of 850 m (Söhnge, 1964). The gangue may be any combination of quartz, calcite, dolomite and "pseudo-aplite". Subterranean water channels lead into as well as away from the orebody and the ores so modified are cavernous and more often leached than enriched. The density for use in ore reserve estimation can therefore vary according to metal content, metal ratio, degree of oxidation, density of the metal bearing mineral, type of gangue and the presence of vugs. This results in a range of ore specific gravities from 6.0 to 3.0. At Tsumeb a formula, explained by Söhnge (1966), is used taking into account the specific gravity of the gangue, presence of porosity, and percentages for copper, lead and zinc to arrive at a specific gravity for each sample, which is combined with each assay, to arrive at a properly weighted average for a group of assays before applying a weighting to an area of influence for use in ore estimation.

#### Discussion

Carbonate-lead-zinc deposits may take on many forms depending on the relative chronology of the porosity creating process and the arrival of the mineralization. The numerous variables that have an influence on the shape, size and grade of carbonate hosted ore deposits are almost unique in each individual deposit and ore reserve estimation is adapted

to suit the individual conditions. Average ore grades in the larger mineralized districts, for example, Pine Point, Canada, or the Upper Mississippi Valley, U.S.A range between 3 and 10 percent combined lead-zinc, with individual ore bodies or zones running as high as 50 percent lead-zinc. Where it is possible to distinguish individual deposits, tonnages vary between a few tens of thousands to perhaps 10 or 20 million tons (McDonald, 1980).

The extreme irregularity of mineralization both vertically and laterally within an orebody, the absence of an alteration halo surrounding the orebodies, as well as the discontinuity of mineralization within a favourable depositional environment, e.g. along a reef or on strike within a slump breccia zone, may necessitate very close spaced drilling and complicate ore reserve estimation. The extremely erratic lateral and vertical distribution of mineralization has resulted in many companies abandoning actual sampling of the deposit as a means of grade control (McDonald, 1980). The application of statistical and geostatistical methods to try and predict variability of grade in any ore deposit has to date not proved to be very successful.

Carbonate hosted ore deposits owe their remarkable irregularity to two main variables, the extreme diversity of sites of deposition and the unpredictable fluctuating behaviour of the mineralizing fluid from which the ore minerals are precipitated. Even if suitable sites for precipitation of ore minerals are available the rock may have limited permeability, or earlier formed gangue phases may fill potential sites for mineralization. Mineralizing fluids may under certain conditions only precipitate one metal, e.g. Cu. During a later influx of fluid under differing conditions, either in the composition of the fluid, or at the site of deposition, different metals may precipitate e.g. Pb and Zn. After each mineralizing pulse permeability in the host rock probably changes due to either clogging of available open spaces or solution of new paths of permeability. Later pulses precipitating different metals or different ratios of metals may therefore affect different parts of the orebody. An added complexity is that mineralization coats or replaces wall rocks in three dimensions and gradual filling of open spaces from bottom to top does not occur. In some deposits superimposed folding or brecciation of already formed ores by secondary karsting, followed by

renewed mineralization adds to the variables that have to be dealt with during evaluation. As shown in figure 58 only two features appear to have some form of predictable trend. Overall zoning of metals may be present ranging from the scale of a mine to the scale of an orefield and porosity may show a predictable trend as it is usually related to primary depositional features or to structural trends.

## DEPOSITS OF DIVERSE ORIGIN

### Unconformity Related Uranium Deposits

Unconformity related uranium deposits are high grade, economically important, vein-type deposits. Those located all occur in metamorphosed early Proterozoic rocks below unconformably overlying unmetamorphosed Middle Proterozoic fluvial red sandstone sequences in Saskatchewan, Canada and Northern Territories, Australia. The deposits are structurally controlled by basement topography and are commonly hosted by pyritic, graphitic, chloritic and calcareous schists. Detail descriptions of these deposits are provided by Ferguson and Goleley, 1980; and Dahlkamp and Adams, 1980. Nash et al., 1981 and Dabrowski, 1980, summarize the main characteristics of the deposits and give a review of the proposed genetic processes that gave rise to these deposits. The deposits seem to have formed from various combinations of geological conditions ranging from synsedimentary uranium precipitation through some combination of diagenesis, metamorphism, metasomatism, weathering and deep burial diagenesis.

The most striking economic characteristic of the unconformity type deposits is their high grade compared to most other types of uranium deposits. There is an apparent inverse relationship between tonnage of the deposits and their grade, and a great range in tonnages and grades between the deposits, e.g., Ranger One-100 350 tons  $U_3O_8$  with an average ore grade of 0,2007%  $U_3O_8$  and Cluff Lake D-orebody-6,600 tons  $U_3O_8$  with an ore grade of 10.43%  $U_3O_8$ . The Jabiluka II deposit is the largest known uranium deposit, containing more than 225 000 short tons  $U_3O_8$  at an average grade of 0,39%  $U_3O_8$  plus about 350 000 ozs of recoverable gold (Nash et al., 1981). From an investment point of view the unconformity-

type deposits are extremely attractive due to their comparatively low tonnages for similar uranium contents, compared to most other types of uranium deposits. Their attractiveness is enhanced by the fact that all of the presently known deposits are situated close to the surface (Dabrowski, 1980).

#### Geological control on localization, morphology and tonnage

Unconformity related deposits are often elongated, forming disconnected pods, with clustering and periodicity of the pods very common. They are strongly controlled by structural and lithological characteristics of the basement rocks. Structures such as faults and breccias probably provided channelways for mineralizing solutions and sites for precipitation of uranium and other metals, while the favourable host lithologies provided the necessary precipitants for the uranium.

The localization of mineralization in individual deposits is primarily dependent on porosity features such as breccias, faults, fractures and shear zones. Breccias are particularly well developed at the Ranger Jabiluka and Koongarra deposits in Australia and may be related to solution and silicification of dolomite at or near the unconformity. Likewise structural control of mineralization is pronounced in all the Canadian deposits. Fractures and breccias associated with major faults and shear zones are most commonly mineralized. The textures of the uranium ore minerals indicate that most of the mineralization is of the open space type which accounts for the almost ubiquitous association of the unconformity type deposits with structural features. Folding appears to have localized mineralization at Jubiluka and some of the deposits at Rum Jungle, Australia.

In both Canada and Australia graphitic and chloritic schists are the most favourable host rocks. On a regional scale carbonate and carbonaceous schists are characteristic lithologies of the uranium bearing formations in Australia. The predominant host rock-type in northern Saskatchewan appears to be pelitic schists, but calcareous metasediments and quartzites are also hosts to some of the deposits. In Australia the Kombolgi Sand-Stone overlying the deposits is rarely mineralized. In contrast the

the overlying Athabasca Sandstone in Canada is often ore bearing (Dabrowski, 1980). Diagrammatic sections through two unconformity related uranium deposits are shown in figure 59 and 60.

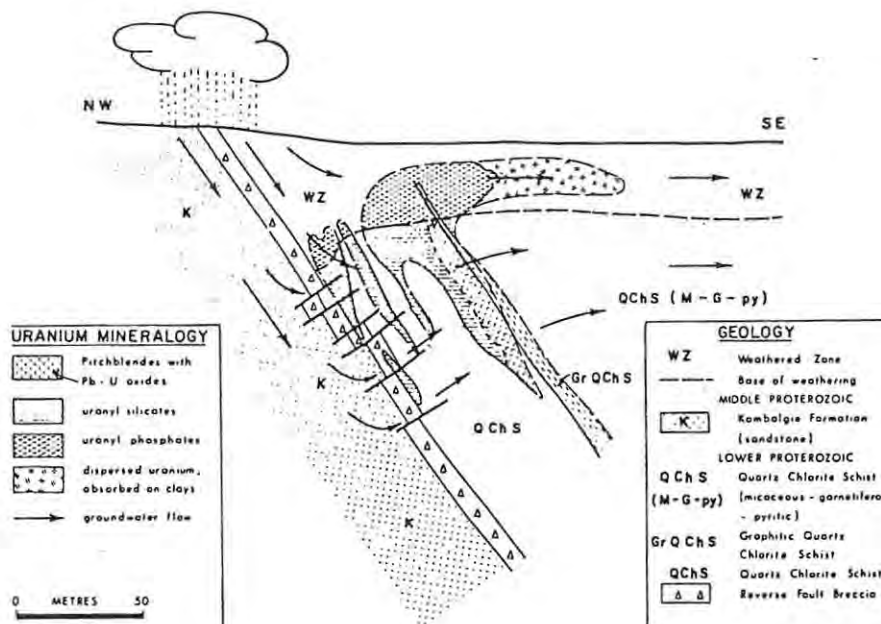


Figure 59: Simplified cross section through the Koongarra No. 1 Orebody. The distribution of the various uranium minerals and the paths of groundwater circulation at the present time are shown schematically (Snelling, 1980).

Two separate ore bodies, about 200 m apart, are present at Koongarra, Australia. Both contain primary zones of pitchblende veins conformable with the steeply dipping quartz chlorite schists. They wedge out at a depth of about 100 m. The No. 1 orebody, figure 59, also contains a tongue-like, tabular dispersion fan of uranium mineralization in the 30 m thick weathered zone above the orebody. The deposit therefore consists of an unweathered deep zone and a weathered shallow zone. The primary ore zone forms an elongate orebody about 350 m long with an irregular width varying from a few metres to 60 m. Uranium mineralization of the two Koongarra orebodies also shows distinct structural and chemical lithological controls. The structural control is expressed as, (a) a northeast striking breccia zone associated with a reverse fault, which displaces the Lower Proterozoic metasediments over the Middle Proterozoic Kambolgi Formation, marking the foot-wall of the orebody and, (b) strong

shearing and fracturing of the overlying quartz-chlorite schists of the ore zone. The chemical-lithological control is suggested by the occurrence of ore in strongly chloritized schists, immediately below a graphitic-bearing horizon. Dolomitic rocks are an integral part of the schist sequence. No mineralization occurs in the Kombolgie sandstone which, due to the reverse fault, is situated in the footwall of the ore body (Dahlkamp and Adams, 1980).

The two Key Lake ore bodies in Canada, probably continuous for nearly 5 km prior to glacial scouring, occupy a northeast striking fault where it cuts graphitic metapelite at a low angle (Kirchner et al., 1980). The two very high grade ( 2%  $U_3O_8$  ) deposits are 800 and 1400 m long, average about 15 m in width and average 50 m in thickness below the unconformity. The ore bodies are therefore elongate and trend parallel to the trace of the intersection of the fault zone and the unconformity, figure 60. Offshoots from the main ore body also occur along and adjacent to the unconformity. The ore shoots start in the lower basement as vein-like features conformable with the foliation. Their thickness increases upward and finally they develop into more irregular bodies. Within the Athabasca Sandstone the orebodies are mainly confined to shear and to complicated joint systems (Dahlkamp and Tan, 1977).

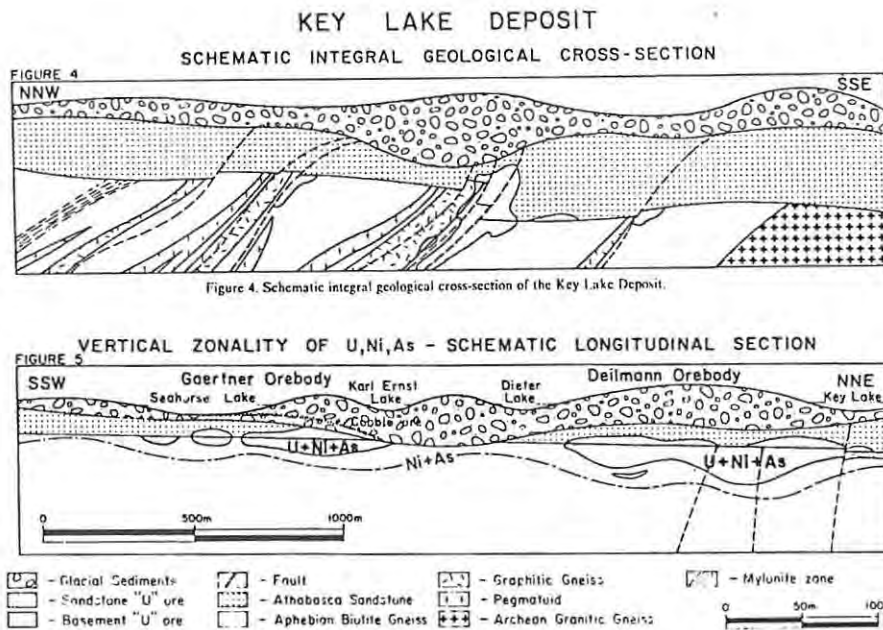


Figure 60: Schematic longitudinal section of the Key Lake Deposit. (Kirchner et al., 1979)

### Characteristics of mineralization

Uraninite (pitchblende) is the most important ore mineral in unconformity related deposits, often accompanied by coffinite and rarely brannerite. Gold is a byproduct at Jubiluka in Australia and economic nickel grades are present at Key Lake and Midwest Lake in Canada. Accessory minerals include a wide variety of sulphides, sulpharsenides, selenides and others. These vary amongst the deposits and probably reflect compositional differences in the country rocks (Dabrowski, 1980).

In most deposits uranium mineralization fills a variety of open spaces and is associated with chloritic and graphitic assemblages, indicating that both structure and chemical controls are important for its location. Most deposits show evidence of redistribution of the uranium and this is reflected by variable ages for the mineralization. Uranium mineralization is always accompanied by some form of alteration of the host rocks; the most common products being chlorite and hematite, with lesser amounts of kaolinite and sericite.

The main features of the mineralization at Koongara are indicated on figure 59. The primary uranium mineral is uraninite which occurs in both crystalline and sooty amorphous forms. The crystalline variety both parallels and transgresses the schistosity, and also occurs as euhedral grains and botryoidal masses within a chloritic matrix in breccia bodies. Trace amounts of gold and minor sulphides are associated with the higher grade portions of the orebody. The secondary mineralization in the near surface dispersion zone is predominantly controlled by the depth of weathering and ground water flow. An additional ore control is the nearby Middle Proterozoic unconformity which is postulated to have been situated just above the present land surface (Dahlkamp and Adams, 1980; Snelling, 1980).

At Key Lake mineralization in both ore bodies is characterized primarily by the association of economic grades of nickel in addition to the uranium. Uranium, mainly as pitchblende, ranges up to 50 wt percent over 0,3 m. Nickel as niccolite, bravoite, gersdoffite and other Ni-As-S minerals are intimately intergrown with pitchblende but extend beyond and below the uranium zones, figure 2. Coarsely crystalline pitchblende and complex Ni-As-S minerals grade upward into fine grained minerals and

no Ni-As phases occur at the unconformity or in the Athabasca Formation (Nash et al., 1981). Two distinct types of mineralization occur within the Key Lake deposits, (a) an old (1270 m.y.) uranium oxide and nickel sulph-arsenide assemblage that is restricted to the crystalline basement; and (b) a younger ( 300 m.y.) U-Ni-bearing assemblage of different minerals which occurs in the overlying Athabasca Formation (Dahlkamp and Adams, 1980). It could be possible that U-Ni-mineralization in the Athabasca Formation was formed by remobilization of mineralization in the underlying basement.

#### Discussion

Unconformity related deposits are therefore characteristically small in size, extremely elongated and thin (Rabbit Lake 10 to 20 m by 2400 m) forming disconnected pods, and have a limited depth extent below the unconformity. This results in very close spaced drilling for evaluation due to the large variation in orebody morphology and there is a tendency to overdrill. These examples illustrate the extreme variability of the types and distribution of uranium mineralization within unconformity related ore deposits. The deposits, although having sharp cut-offs at their boundaries, display a wide range of grades, from 0.01% to over 90%  $U_3O_8$ . Due to the variable location of the ore, locally transgressive to stratigraphy, and no correlation between host rock type and uranium content within the deposit, continuity is difficult to assess. A single borehole drilled into an orebody will therefore have little influence.

As a result of erratic distribution of the grades and poor geological control on the mineralization, conventional methods lead to a large error in the evaluation of unconformity related uranium deposits. Some of the difficulties encountered include, (a) minerals with large differences in specific gravity (pitchblende 6.5 to 9.7; coffinite-variable; gersdorffite 5.6 to 6.2; millerite 5.3 to 5.6; quartz 2.65; goetnite 3.3 to 4.3); (b) varying porosity; (c) margins of error in chemical analysis; (d) incomplete core recovery in fractured zones; and (e) problematic quantitative interpretation of gamma logs in high grade ore (Dahlkamp and Tan, 1977).

The large differences in specific gravity and varying porosity cause errors in the determination of bulk density. The complex mineralogy of the ore prevents any calculation of the specific gravity from chemical composition. The specific gravity has to be measured on core and other samples during the exploration and development of an orebody. Normal margins of error in uranium assaying ( $\pm 5\%$ ) produce very large variations in tonnage calculations when dealing with the higher ore grades. Dahlkamp and Tan also report that the most severe problem in interpreting of gamma logs arises from the effect of highly concentrated uranium shielding its own radiation from the logging probe (Z-effect).

Despite the polymetallic nature of the ore, minerals containing metals other than uranium may be too difficult to extract due to their fine grained nature or the fine intergrowth between the different sulphide phases. The high arsenic content of minerals such as gersdorffite and niccolite could also pose an environmental problem. Very high grade uranium ores, particularly those of Canada, can cause dangerous radiation to mine personnel.

Unconformity related deposits as a class probably formed in many stages, spanning more than a billion years, and their genesis is probably one of the most complex of any class of metal deposit (Nash et al., 1981). A tight control on the location, size and shape of the deposits is exerted by the lithological character of the host rock, structural environment and relative position of the orebody to the unconformity. On a smaller scale the deposits have several similarities to replacement type vein deposits and have often been described as such. On all scales the mineralization is erratic and unpredictable.

GRADE IN RELATION TO NATURAL ORE  
FORMING SYSTEMS

EFFECTIVENESS OF ORE FORMING SYSTEMS

The same ore forming processes giving rise to high grade, and often also large tonnage, deposits may also give rise to deposits of lower grade and lower tonnage. The richer large deposits also tend to be more simple and easier to evaluate than the poorer deposits, which often have complex grade relationships. As stressed in the individual discussions on the various ore forming systems in earlier sections and also by Mason (1982), there appears to be a relationship between the size or dimensions of a mineralizing system, and the size of related ore deposits. In general, because an ore forming process operates more efficiently to give rise to larger deposits in large systems, the efficiency of the process will also lead to creating richer (higher tenor) deposits. While larger, more efficient processes usually create richer deposits they do not necessarily create larger (tonnage) deposits.

Ore deposits that form in closed systems, or in systems that are dominated by an ore forming mechanism in which the geological environment plays a minor role, illustrate the larger system - better deposit concept well. The total amount of metal in a closed orthomagmatic system, for example, is fixed, and for a larger magmatic oxide deposit to form, such as a chromitite layer, larger amounts of magma would be required. The endomagmatic Merensky Reef-type sulphide mineralization is also only developed in the largest of magmatic systems where the process of platinum metal accumulation could operate efficiently.

In the open orthomagmatic - sulphide ore forming systems, where the geological environment plays an important role in generating the ore deposits by either providing a structural trap for sulphides to accumulate, or in supplying constituents to cause sulphide immiscibility, the larger deposits also appear to be associated with the larger systems.

The large komatiite-nickel deposits of the Eastern Goldfields Province in Western Australia occur in very large greenstone belts, reflecting extensive mafic-ultramafic magmatic activity. In contrast, smaller nickel-deposits occur in the smaller greenstone belts of Zimbabwe and no significant nickel mineralization has yet been found in the small South African greenstone belts. A tendency also exists for the larger komatiite nickel deposits to be richer or of higher grade (Kambalda versus Windarra). Most nickel sulphide deposits, and in particular the Proterozoic komatiite nickel deposits of Canada, the Noril'sk and Duluth deposits, are associated with major intercratonic rifts or taphrogenic-type structures illustrating the association with large features. In this case a large mantle tapping structure is part of the ore forming process.

In epigenetic ores such as the hydrothermal paramagmatic and low temperature epigenetic stratiform deposits (figure 10) in which the environment plays an important role in the genesis of ore deposits, two situations can be identified. These include those systems in which the environment also has to be extensive to give rise to a large deposit, and those systems in which the environment actually plays a restricting role in concentrating, or localizing, ore formation to give rise to richer ore deposits.

The constricting role played by the geological environment in ensuring viable deposits is well illustrated by primary tin and unconformity-related deposits. Hydrothermal fluids are channelled through restricted openings to give rise to high grade tin vein systems in contrast to the low tonnage, low grade greisen deposits. Unconformity-related uranium deposits are also characterized by an inverse relationship between tonnage and grade (page 131) illustrating the role played by the structural environment in concentrating the metal.

A large, extensively conditioned environment is a necessary prerequisite for large and rich stratabound copper deposits to form. An extensively conditioned host coupled to a large influx of mineralizing fluid was probably responsible for the formation of the Zambian Copperbelt deposits. Processes operated efficiently to give rise to rich, large deposits such as the Mufulira mine (282 million tons at 3,47% Cu).

In contrast, the White Pine deposit (550 million tons at 1,2% Cu) is probably an example of an extensively conditioned environment into which either a limited amount of mineralizing fluid was introduced, or the fluid had a poor copper content. The Oamites mine, in South West Africa, (< 10 million tons, < 1,3% Cu) is an example of a small system working in a restricted environment, in which ore forming processes worked less efficiently, resulting in a small, poor deposit.

The larger and richer porphyry-type deposits (page 55) also formed from large extensive systems in which intensive multiple phases of mineralization and alteration worked efficiently. Smaller deposits that form in weaker mineralizing systems are characterized by patchy alteration and only a few pulses of mineralization in a smaller system such as the Haib deposit in South West Africa. Likewise larger and better volcanic-associated massive sulphide deposits show a tendency to develop in the larger felsic volcanic centres. In the Abitibi belt large felsic volcanic centres host deposits such as Kidd Creek, in contrast to the small felsic volcanic centres preserved in the South African greenstone belts hosting small, and often also poor, deposits. The larger volcanic centres probably generated larger hydrothermal systems which could exhale voluminous rich brines onto the sea floor.

Larger and richer placer deposits also appear to form during the larger tectonic upheavals when large amounts of sediment are reworked. In the Witwatersrand this is reflected in the extensive rich Carbon Leader-type reefs and Venterspost Conglomerate Formation reefs in contrast to the small erratically mineralized Elsburg-type placers (page 84).

The pattern of mineralizing processes working more efficiently in the larger systems appear to hold for most metalliferous ore forming systems where a considerable enrichment, particularly for the geochemically scarce metals, is required before they can be concentrated into grades high enough to be considered ores.

IMPLICATION FOR EXTRACTION OF METALS FROM ORES

A concentration of metal in the form of a mineral deposit is worthless unless the metal is extractible from the rock in which it is hosted. The ease of extractibility is controlled by the mineralogy of the ore. Generally ores contain three groups of minerals, valuable minerals of the metal(s) which is being sought, compounds of associated metals which may be of secondary value, and gangue minerals. Gangue minerals inevitably accompany the valuable minerals being either partly replaced country rock, a host rock such as sandstone hosting uranium mineralization, or an agglomeration of other minerals deposited simultaneously with the mineral(s) of interest. Gangue minerals are often important in determining the ease with which metals are liberated from ores. They may be deleterious, such as acid consuming carbonate minerals in the Rössing uranium ores, or they may be valuable, such as calcium and magnesium carbonates which impart self-fluxing properties to ores of the Khalahari Manganese Field.

Extraction of metals from ores involves a two stage process, namely concentration of the ore mineral by freeing it of the gangue minerals, and extraction of metal from the mineral concentrate. As discussed in the introductory chapter, mineralogical characteristics such as ore texture, hardness, abrasiveness and other physical properties determine the ease of concentration during comminution and the various sorting operations. Pyro- and hydro-metallurgical extractive processes are usually affected by mineralogical features such as the nature of the ore and gangue minerals, the metal content of minerals and the presence of impurities in the ore.

The behaviour and properties of minerals in ores result from their mode of formation which may either be from a magmatic melt, from gas-liquid precipitation (hydrothermal, or chemical precipitation in a standing body of water, etc.), or by mechanical concentration. These processes determine the primary characteristics of ore minerals. For example, minerals may crystallize from ionic solutions such as ground water, forming finely disseminated minerals in a host sandstone, or may precipitate from colloidal solutions and display colloform or framboidal textures. Minerals that crystallize from magmatic melts

are often characterized by micro-intergrowths of two or more phases, such as ilmenite in magnetite, or by exsolution flames of pentlandite in pyrrhotite. Unmixing is common among metal sulphides and if the scale of unmixed intergrowth is small, the separate phases cannot be liberated and separated in the beneficiation processes. In this case it has to be treated as a single mineral which may carry impurities through to the extractive process (Reynolds, 1982).

If the mineralization is emplaced in a single stage, the composition and characteristics of the minerals will usually be fairly constant, or will only change gradually in relation to the changing geological environment. Many of the magmatic and syn-sedimentary deposits (figure 10) are of this type. In ore deposits that form from multiple stages of mineralization, such as hydrothermal related tin and porphyry deposits (figure 10), mineralization can be expected to differ in composition and habit from one stage to another, complicating concentration of the ore minerals.

Secondary processes such as weathering and metamorphism modify the properties of minerals, often greatly enhancing recovery. During metamorphism, fine mineral intergrowths, such as exsolution bodies in sulphide minerals and fine microintergrowths of ilmenite in magnetite, are reorganized to form intergranular films and grains. The exsolution bodies do not, therefore, pass with their host grains into the wrong concentrate. Likewise fine grained colloform textures are replaced by granular intergrowths which leads to better mineral separation during grinding (Reynolds, 1982; Evans, 1980).

Minerals in deposits such as porphyry copper, primary tin, and carbonatite deposits are rarely metamorphosed due to the geological environment in which they evolve. The viability of these deposits is however often affected by geomorphological processes, such as the weathering of a tin-greisen deposit facilitating recovery of resistate cassiterite, or the supergene enrichment of porphyry copper deposits. Metamorphism and deformation, on the other hand, are of particular importance in enhancing extractibility of minerals from the exhalative massive sulphide ores.

#### Preparation of mineral concentrates.

Concentration, the first step in extracting metals from ores, is often accomplished by natural ore forming processes so that little or no ore-dressing is required beyond crushing and occasional hand picking. Commonly ores of the abundant metals and chrome, that form from magmatic and syn-sedimentary processes (figure 10) in simple geological environments, do not require expensive concentration processes. Occasionally the process of extracting metals from minerals does not require pre-concentration beyond the natural mineral concentration, such as ores that are leached, including the secondary copper and uranium ores.

Concentration of the remainder of the ores is elaborate and essential to produce a suitable product from which metals can be extracted. The concentration processes become more expensive and elaborate as the content of metal being sought becomes lower in the ore, or if metal deposition occurred in multiple phases in complex geological environments so that the metals occur in minerals of different composition and habit. Referring to figure 10, it would appear that ease of concentration of minerals from ores decrease with the complexity of geological environment in which an ore deposit evolves. Deposits that formed from processes in which the environment played a minor role, or in a geologically simple environment such as the magmatic oxide, endomagmatic sulphide, endogranitic tin, large batholithic facies porphyry deposits, syn-sedimentary chemical deposits and probably also placers such as the thin, extensive Carbon Leader-types, are easier to concentrate than their counterparts that evolved in geologically complex environments. Deposits that form in geologically complex environments, or where ore deposition is controlled largely by the environment in which it occurs, are often difficult to concentrate due to factors such as multiple phases of mineralization resulting in a variable grade distribution, the presence of metals in more than one mineral phase, and characteristics of gangue minerals such as reactive carbonate minerals. Tin vein ores, for example, have complex mineralogy and are more difficult to concentrate than the greisen deposits.

Extraction of metals from minerals

The ease of extracting metals from mineral concentrates does not necessarily follow the pattern of ease of concentration of minerals from ores. Often the ease of extraction of metals from mineral concentrates is the inverse of the ease of concentrating the minerals from the ores. This is mainly because the relative ease of reduction of metals from their ores depends on the composition of the mineral containing the metal. In general the ease of reducing the compound of the metal as found in the ore to the metallic state, is reflected in the amount of energy required to affect this process (Gilchrist, 1980). It is, for example, far more expensive to obtain nickel-metal from a silicate nickel (laterite) ore than from a sulphide ore, therefore the average grade and ease of mining of silicate-nickel ores have to be better than those of sulphide nickel ores. Figure 61 shows requirements for the recovery of Fe, Al, Ti and Ca from various sources. The graph not only illustrates that metals can be won easier from certain ores, but also shows that a higher grade ore requires less energy to free

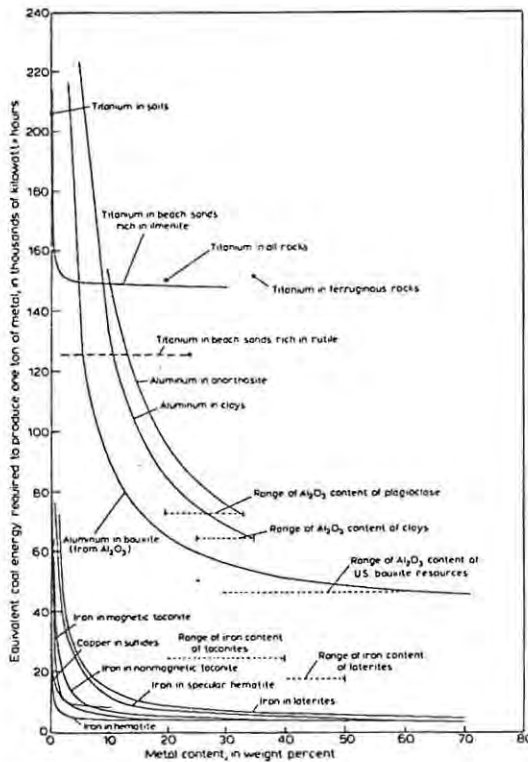


Figure 61: Energy requirements for recovery of iron, titanium and aluminium at different grades from various sources. (Wolf, 1981)

the same amount of metal. Because of the energy requirement most ore-minerals are usually native metals (precious metals, Au, Ag, PGE), oxides and oxysalts (spinel, cassiterite), sulphides, and arsenides (Sperrylite-Pt As<sub>2</sub>).

The end use of a metal also determines the amount of effort to be put into extraction of metals from ores and often it is not necessary to reduce an element to its metallic state. A proportion of nickel production, for example, is required as nickel salts for the plating industry. Likewise an alloy is sometimes produced, such as steel rather than a pure metal, and there would be no point in removing the copper impurity from nickel which was destined to go in the production of cupro-nickel (Gilchrist, 1980).

#### GRADE DISTRIBUTION IN MINERAL DEPOSITS

##### Some Implications for Geostatistical Studies

A knowledge of the configuration of the ore minerals inside an ore deposit is vital to the control of the efficient estimations of grade, size and the overall efficiency of a mining operation. If the geological controls of the grade distribution are understood then it is possible to interpret statistical and geostatistical studies in a meaningful manner and optimize selection of mining alternatives.

Some mineral deposits are almost solid economic mineral, whereas, at the other end of the scale, some deposits of the precious metals can be worked even though the metal content is as low as 100 mg/t (Dixon, 1979 a). Important from a mining point of view is not only the metal-content of a deposit but also the distribution of the minerals. A highly erratic carbonate hosted Pb-Zn deposit with a combined metal content of over 8% is, for example, far more difficult to mine than an evenly mineralized deposit such as the Merensky Reef containing 8 g/t platinoids. The spatial distribution of the minerals therefore has an effect on the ease with which reliable estimates of the recoverable grade can be made, which affects the design of the mining, and extraction processes. On the one end of the scale where distribution of metals is

uniform throughout the deposit, such as chromitite layers, reliable estimates based on small sample populations can be made, and geostatistics may not be required at all. At the other end of the scale the factors controlling grade distribution might be so complex as to render any geostatistical study meaningless, such as in tin- and gold- vein deposits. Grade distribution in tin-vein deposits is controlled by the interplay between a random component (pulses of hydrothermal fluids which are variably mineralized), a structural component, and often also a lithological component.

Geostatistics is commonly applied to solve problems concerned with estimation of reserves in ore deposits. Errors of reserve estimation are inevitable and can result in either underestimation or, more dangerously, overestimation of reserves. An individual block of ore may have a grade much different from the sample prediction, or a change in a mining cutoff grade may not result in the predicted working grade. Geostatistics provides a means of both quantifying and minimizing such errors, but what is often overlooked is that the problems have fundamental geological causes. For geostatistics to create a better picture of reality and to assist the solving of practical problems, a knowledge of geological characteristics such as the continuity of the ore, zone of influence of a sample, the homogeneity of the mineralization, and the effects of scale on mineral distribution must be quantified. Grade distribution is intimately related to the ore forming process from which an orebody evolved, and therefore, certain types of orebody are characterized by more regular and predictable features than others, which may be irregular and unpredictable.

#### Primary ore forming processes and their control on grade distribution

From the discussion on the individual ore forming systems, and as shown in figure 10, it is clear that those deposits that form from an interaction with, or are closely influenced by, the environment in which the ore forming mechanism operates, have more complex grade relationships than ore deposits that form in a relatively closed system, or in a system in which the environment is simple or does not influence the ore forming process significantly. Larger rich deposits also tend to have

simpler distributions as the ore forming processes operated more efficiently, resulting in more pervasive mineralization, which is less prone to be influenced by local environmental features.

Ore deposits with simple grade distributions are therefore formed in simple geological environments, or in a closed system, where the ore forming mechanism dominated the process of generating ore. Included in this group are the magmatic oxide deposits (Cr, Ti-V-Fe), the Merensky Reef, and the syn-sedimentary chemical deposits of Fe and Mn. Epigenetic deposits illustrate the influence of the geological environment on grade distribution well. Of the low temperature epigenetic sedimentary (or statiform) deposits, sedimentary copper deposits commonly have relatively uniform mineralization in contrast to the sedimentary uranium deposits, which are characterised by highly erratic mineralization. This is because the mineralization is largely controlled by the host environment. Lacustrine, or shallow restricted marginal marine environments, with uniform hydrology and reductant content control deposition of sedimentary copper mineralization, while fluvial, multiply sealed porous sand bodies, with complex hydrology and erratically distributed reductants control uranium deposition.

Paramagmatic hydrothermal primary tin and porphyry deposits also show and increase in complexity of grade relationships as the environment becomes more complex, for example, greisen-tin versus vein-tin, or 'batholithic-facies' porphyries versus 'subvolcanic-facies' porphyries. Another point well illustrated by the hydrothermal paramagmatic deposits, which is also important for the low temperature epigenetic sedimentary deposits, is the effect of multiple, or successive, pulses of mineralizing fluid on the grade distribution. Even though the environment of deposition may be well conditioned for precipitation of metals from the brines, each successive pulse of brine may have variable amounts of metal, or may be barren of metals. During the period between the pulses of fluid, conditions at the site of deposition may change, and in porphyry- and tin-vein-deposits a new pulse of mineralization may have a completely new grade distribution and different mineralogy to the previous pulse.

The influence of the environment on grade distribution is also illustrated by the Witwatersrand placers, where the Carbon Leader-type placers, which were deposited onto even, unrestricted surfaces, show less variability than the Venterspost Conglomerate Formation placers, deposited on an irregular and restricted depository.

Secondary ore forming processes and their control on grade distribution.

Secondary processes could alter the grade distribution of an ore deposit significantly. Supergene alteration, commonly present in orebodies such as porphyry copper deposits and unconformity uranium deposits, may not only enrich or deplete certain portions of an orebody but will also result in mineralization with a different character (mineralogy) and distribution to the unaltered portions. At the Mamatwan mine in the Kalahari Manganese Field, for example, where the ore bed (braunite, hausmanite, jacobsonite) was chemically precipitated, the primary lateral variation in grade is negligible. Grade variations due to secondary processes do however affect mine planning significantly and are related to two sets of fissures. Supergene enrichment accompanies one set of fissures cutting through the orebody, and ferruginization, diluting the ore, is present in the immediate vicinity of the second set of fissures.

Important in particular the exhalative massive sulphide deposits is the effect of deformation on the grade distribution. Apart from creating new grade relationships by folding, faulting and shearing of ore zones, grade distribution may also be affected on a smaller scale. Commonly massive sulphide portions of orebodies such as those of komatiite-nickel deposits and the exhalative massive sulphides show significant heterogeneity in their grade distribution. This is due to the relative ductility of the ore minerals during deformation so that massive sulphide ore commonly shows greater variability of grade than the accompanying disseminated ore.

## Grade distribution and ore reserve estimation

The uncertainty of ore reserve estimations is controlled by the amount of sampling and by the relationship between the geometry of the sampling scheme and the geometrical aspects of the grade distribution (fabric). An unfavourable interaction between the geometry of the sampling scheme and that of the mineral distribution can cause bias which will not be detected by geostatistical methods. Many deposits show grade variation patterns caused by phenomena such as oriented fracture systems and bedded mineralization, that could cause bias if not sampled correctly. For example, a set of vertical boreholes sampled at 2 m intervals in a porphyry copper deposit will give a great deal of information about the vertical variation but little about the horizontal variation (Dixon, 1979 b). It therefore follows that bias is more likely to occur in heterogenous deposits, showing anisotropy of mineralization due to the complexity of the environment in which they evolved. In the more homogenous orebodies, such as the Merensky Reef, where no 'pay-shoots' or trends are present, the chances of sampling bias and the resultant geostatistical error are minimized.

A fundamental knowledge of the geological controls on grade distribution will minimize the error caused by bias in sampling. Understanding grade distribution of a deposit will also allow a competent classification of the orebody into geologically homogenous ore types. For ore reserve estimation and for mine planning, different ore types need to be treated separately such as massive and disseminated, or primary and supergene enriched ore. Patterns of grade variation are relatively constant and simple in ground that is similar in mineralization, texture, fabric, host rock etc. If the ore types are treated separately, then the problems of describing the grade variation, and scale effects, become much simpler.

With any geostatistical application the role played by scale in sampling and grade estimates must be appreciated. Often different geological phenomena affect the grade of an orebody at different scales, which must be understood in order to specify mining alternatives such as the optimum grade control block size (or smallest mining unit), equipment specifications and design of mining method. Variability of

grade is function of the scale at which observations are made and it is useful to try and analyse the causes of different types of variation in terms of the geological phenomena responsible for the variation. Understanding the control of scale on the variability of grade will also lead to better understanding of problems related to estimation variance, which is the measure of error inherent in forecasting the grade of, for example, a block of ore, on the basis of average sampling.

As an example, the grade variation in a molybdenum porphyry deposit (David, 1977) illustrates the importance of the scale at which grade observations are made. Figure 62 A shows a semivariogram of  $\text{MoS}_2$  grade of 10 ft lengths of split core samples taken from 96 holes drilled in fan patterns. At this scale the semivariogram shows almost a pure

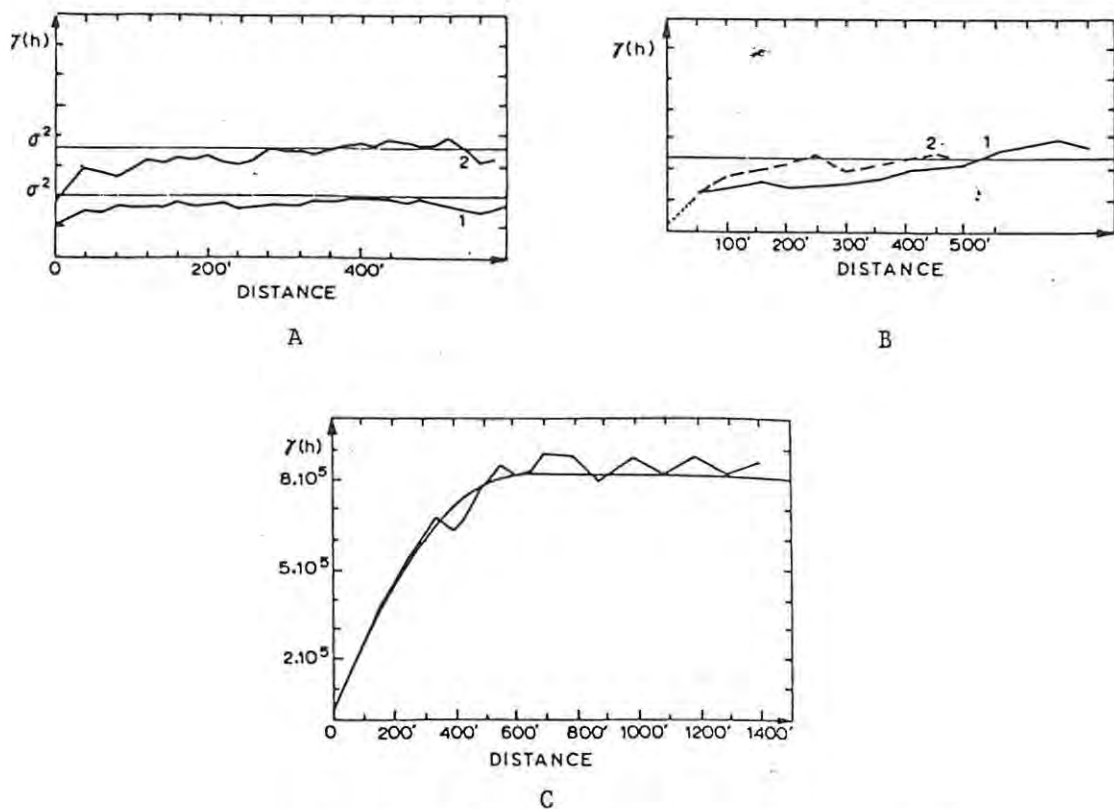


Figure 62 A: Average semivariogram of  $\text{MoS}_2$  grade of 10 ft samples from vertical (1) and 45° dipping (2) holes in a molybdenum porphyry deposit.  
 B: Average semivariogram of  $\text{MoS}_2$  grade of 50 ft composite samples from vertical (1) and 45° dipping (2) holes.  
 C: Average semivariogram of  $\text{MoS}_2$  grade of cluster samples in 200 ft blocks showing a very good structure.  
 (David, 1977)

nugget (or random) effect. Composing samples over 50 ft intervals gave a fairly similar picture (figure 62 B) although the nugget effect had been reduced. The samples were then combined into groups of five and their average values assigned to 200 ft blocks in which the samples occurred. The computed semivariogram for these blocks is shown in figure 62 C and shows a very low nugget effect and well defined sill. At a small scale, in this example, there is an aparent random change between high and low values, and at the larger scale, a more systematic change between grade values. This relationship only holds within an homogenous area and the same relationship may not hold for different porphyry deposits. The more heterogeneous El Abra deposit (page 59), with smaller homogeneous areas, may not have the same continuity at the larger scale.

Depending on the ore forming process, different ore deposits obviously have different variabilities at different scales. The variability can be related to the scales at which ore forming processes operate, identification of which can assist in developing a sound model for ore reserve estimation. Ore deposits such as the magmatic oxide and Fe-Mn syn-sedimentary chemical deposits (figure 10) with uniform mineralization will, due to their mode of formation, show great continuity and predicability of grade at all scales. Deposits such as the porphyry copper example cited above, large tin-greisen deposits, and some gold placers of the Witwatersrand such as the thin, extensive, Carbon Leader-type placers discussed earlier, will show great variability at a small scale but greater continuity at a large scale involving larger samples. At the smaller scale, distribution of copper mineralization in porphyry deposits, for example, is controlled by random veinlet swarms and stockworks, but at the larger scale distribution is related to the alteration halo surrounding a porphyry intrusive. distribution, in this case, unconfined braided stream flow on a relatively smooth surface.

The opposite to the porphyry example is probably true for many exhalative massive sulphide and komatiite nickel deposits. In these deposits the primary ore forming process is responsible for relatively even, continuous, lateral mineralization, e.g. the settling out of

immiscible sulphide droplets, or the precipitation of minerals close to an exhalative vent. This primary continuity is still present on a small to intermediate scale (tens of meters) after deformation, but due to the deformation great variability can be expected on the large scale, and geostatistics (or any ore reserve calculation) can strictly only be applied to smaller homogenous areas. Likewise the grade distribution for many ore deposits can be anticipated by identifying the ore forming processes and the scales at which they operate.

#### Flexibility of Working Grade

Changing mining and economic constraints often determine that different grades of ore have to be mined at certain times during the exploitation of an ore deposit. In response to a drop in metal prices, the working grade of a mine may have to be increased to maintain the same level of profitability. To do this, either an increase in ratios of production rates from high grade to low grade blocks is undertaken, or a higher cutoff grade is applied (Dixon, 1979 b). On the other hand mining conditions may change, for example, in an open-pit, as ore is mined down to deeper levels, mining costs and the stripping ratio increase, and the required cutoff grade is raised to meet the increased cost (McKenzie, 1982). High-grading is sometimes practised during extraction of metalliferous orebodies with non-uniform grade distribution, when for economic reasons during the first half of the life of the mine ore is mined at above average grade, and during the latter half at below average grade, the grade decrease being in progressive relatively small steps from start to finish (Thomas, 1976).

As a corollary to the previous section, in which grade distribution was discussed, heterogeneous orebodies that form in the more complex geological environments will be able to respond to changes in target working grade easier than deposits that formed in the more simple geological environments. Mining of homogeneous mineral deposits such as the orthomagmatic oxide deposits, sedimentary Fe-Mn deposits and the Merensky Reef, that are exploited at their natural grades, cannot respond

to changes in economic conditions. Because of natural geological boundaries to mining, or because of the scale of mining, many heterogeneous orebodies also cannot be mined selectively. Undeformed volcanic-associated massive sulphide orebodies are characterized by sharp hangingwall contacts (fixed- cutoff) and diffuse footwall contacts (flexible). Undeformed volcanic-associated massive sulphide orebodies are, however, rare and they are commonly folded. The Otjihase massive sulphide copper deposit, in South West Africa, is preserved in a flattened fold closure resulting in a plunging sheetlike orebody of about 3 to 6 m thick, with sharp foot- and hangingwall contacts. Although the mineralization is not homogenous, the deformation has resulted in a flat orebody with the best mineralization occurring against the top and bottom contacts. This, together with the adapted contour stoping method used to mine the orebody, does not permit high grading.

Raising or lowering of cutoff grades to meet new grade requirements in heterogenous orebodies is usually not straightforward, and a knowledge of the ore forming processes and their controls on grade distribution is necessary. The raising of cutoff grades often not only raises the grade of the ore but increases the proportions of waste that is misclassified, and the two changes may be self-compensatory. The mining of higher grade ore may also result in an increase ratio of impurities. What must be elucidated during the evaluation of a deposit is therefore not only the overall ratio of co-products and the expected amount of bi-products and impurities, but also their differential distribution in the deposit (Dixon, 1979 b).

Porphyry deposits seldom show precise boundaries of mineralization and mining limits are determined by assay. The cutoff may vary within a deposit, being dependant on such factors such as the metal recoveries in different ore types and different waste to ore ratios (Empsall, 1981). In some porphyry copper deposits, lowering of the copper-cutoff will increase the Mo:Cu ratio, while raising it may have the reverse effect. Tight grade control is therefore necessary in multiple constituent deposits or those deposits containing important impurities, and changing the working grade is more complicated. In deposits such as the exhalative massive sulphide deposits and komatiite-nickel deposits it is common to find distinct zones of massive and disseminated mineralization, the

former being of higher grade. The normal way of changing working grade is to alter the ratio of production rates from the two kinds of ore, resulting in a change in the ratio of the products and the impurity contents of the concentrates. The increased proportion of massive ore mined will increase the amount of iron-sulphides. Not only are impurities such as arsenic and antimony frequently associated with the iron sulphides, but also the increase in sulphur content in the resulting concentrate can affect the energy balance in smelting. There are even some instances of working grade changes in komatiite-nickel deposits, where an increase in the ratio of massive to disseminated ore has had such a marked affect on mill recovery that an attempt to respond to falling nickel prices has been self-defeating (Dixon, 1979 b).

For an ore deposit to have some form of working grade flexibility, the grade distribution must be known in advance. It therefore follows that high grading of some extremely erratic deposits with unpredictable grade distributions, such as tin and gold vein deposits, would be difficult.

### GRADE OF A MINERAL DEPOSIT

The grade of a mineral deposit is determined by the effectiveness of an ore forming process, which is the interaction between an ore forming mechanism and the environment in which it operates. Secondary geological phenomena such as deformation and metamorphism may have a constructive or destructive modifying effect on the grade of a mineral deposit. The primary and secondary geological factors determine properties such as the distribution and nature of gangue and ore-minerals, and the metal contents and impurities of the minerals. Mining and economic constraints determine factors such as which portion of a mineral deposit is to be extracted, or how much waste material is to be included with the ore during mining. Geological phenomena totally determine the grade of a mineral deposit and it is only once a body of rock has been artificially delineated in the ground, or extracted from the mineral deposit, that non-geological factors will influence the average grade of the body of rock.

A high grade mineral deposit will ideally have characteristics such as a high metal content, simple grade distribution, simple mineralogy and ease of mining and extraction of the metal from the orebody. Due to the abundance and geochemical behaviour of metals, and the ore forming processes in which the metals become concentrated into mineral deposits this is rarely achieved. Better or higher grade deposits tend to develop in the larger ore forming systems, a point which is well illustrated by the volcanic-associated massive sulphide deposits and the stratabound copper deposits. Processes that operate with little direct influence from their geological environment, in a relatively closed system, result in deposits with a uniform and simple grade distribution. These deposits often contain large tonnages, and their ores, if not already sufficiently concentrated, relatively easily yield a mineral concentrate. The deposits are relatively homogenous (unless significantly modified by secondary processes) and tend to be mined at, or close to, their natural grades, and it is therefore not possible in these cases to respond to economic fluctuations by high-grading. Examples of such deposits would include

those that form in closed magmatic environments (Cr, V-Ti-Fe oxide and PGE-Ni-Cu sulphides), and sedimentary iron and manganese deposits.

As soon as the geological environment becomes directly involved with the ore forming process, the complexity of the mineral deposits tend to be controlled by the complexity of the environment in which they evolve. Superimposed onto the complexity imparted by the environment are often multiple influxes of mineralizing fluids, particularly in paramagmatic (porphyry-copper; primary-tin) and low temperature epigenetic stratabound deposits (sedimentary-copper and uranium; carbonate hosted lead-zinc). A great number of variables influence the grade characteristics in these deposits, resulting in difficulties in obtaining reliable estimates of the recoverable grade. The deposits tend to be characterized by complex mineralogy so that it is more difficult to obtain a mineral concentrate. Because of their heterogenous nature the deposits can often be high-graded in response to economic fluctuations (if mining methods permit it).

Extractibility of metals, or metal compounds, from the mineral concentrates is largely independant of the environment in which an ore deposit evolved. The ease of extracting metals from the mineral concentrates is instead dependant on the ore forming mechanisms such as magmatic segregation, leading to finely intergrown minerals. Secondary geological phenomena, such as deformation and metamorphism, often enhance the extractibility.

The interaction between an ore forming mechanism and the geological environment in which an ore deposit is generated determines the grade of a mineral deposit. Knowledge of the factors controlling the grade of a mineral deposit will lead to efficient delineation, evaluation and development of an ore deposit.

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