- GOLD FINENESS IN HYDROTHERMAL ORES -

An Investigation into the Distribution

of

Gold and Silver in Southern Rhodesian Gold Ores,

by

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Abstract

This investigation is concerned with primary variations in the silver content of gold which occurs in hydrothermal deposits, particularly those of hypothermal character which are found in Basement rocks in Southern Rhodesia. The nature of the gold produced by a number of different mines has been studied by reference to production data, and microscope techniques as well as gold and silver assays have been used to determine and to explain the variations in gold fineness.

The literature does not contain a great deal of information which is relevant to this topic, but an attempt has been made here to summarize the more important contributions by different writers. From this it emerges that the interpretations given by different investigators are in conflict and that paradoxes may arise when efforts are made to explain observed variations in fineness in terms of certain generalizations which have become entrenched in the literature. In particular, it is shown that falling temperature alone cannot account for the occurrence of silver-rich gold in certain deposits.

The Gwanda district of Southern Rhodesia has been selected as a typical gold belt, and the variation in fineness in 150 producers is described. The deposits are hypothermal in character, and the average fineness of the gold is high but variable, but in a small proportion the fineness is low. It is shown that the nature of the host rock and the distance of a deposit from the granite contact appear to have no influence on the fineness of the gold and that there is no zonal arrangement of fineness values. There is a suggestion that diversity of mineral species in any particular area may be accompanied by rather wide fluctuations in the gold fineness.

The variations of fineness in eight typical Southern Rhodesian deposits are studied in detail, by analysis of production data, by assaying specimens of the ore and by the examination of polished specimens of gold-bearing ore. Briefer

reference is made to two other deposits in the territory, and to deposits in other countries which appear to bear out the conclusions reached in this section. It emerges that there are two factors which can commonly be correlated with variations in fineness. The first of these is the grade of the ore: high-grade ore generally contains purer gold than low-grade ore. Secondly, the textural evidence indicates that gold which separates relatively early in the paragenesis contains more silver than that which is deposited in the final stages of metallization.

A general survey which draws on the literature as well as on the writer's examinations of deposits in the territory indicates that, in general, gold which is associated with late-stage minerals such as tellurides, antimony, bismuth and bismuthinite is silver-poor. Gold associated with galena may be either silver-rich or silver-poor, whereas gold which is of the same age as chalcopyrite or sphalerite is very frequently rich in silver. The difficulty which is encountered in establishing the age of gold which is intimately associated with pyrite and arsenopyrite renders uncertain the correlation between fineness and age of gold in these latter cases. There are, however, indications that gold which is truly contemporaneous with either pyrite or arsenopyrite is silver-rich.

In the discussion, the objections to the common practice of singling out temperature as the most potent factor controlling gold fineness are listed. Chief amongst these objections is the fact that gold does not in all deposits increase in fineness with increasing depth: examples are quoted where fineness was found to decrease as deeper levels of the ore body were exploited. It is shown that there is no consistent relationship between the size of gold grains and their silver content. It is the writer's conclusion that in hydrothermal deposits in this territory the high fineness of the gold is due to increasing solubility of silver in the ore fluids in the late states, and that where hydrothermal deposits are characterized by gold with

low average fineness, an unusually large proportion of the gold has been deposited early in the paragenetic sequence. In the majority of hypothermal deposits, however, the bulk of the gold separates late in the sequence and the fineness is accordingly high. It is believed that the relationship which exists between fineness and tenor in many deposits is due to protracted crystallization of gold in those portions of the ore body which remained permeable to the latest stages. These portions of the ore body, which represent either valuable ore shoots or ore shoots in miniature, are likely to contain gold of variable character, but the average silver content will be low because a large proportion of the gold is 'late' gold. The factors which might cause epithermal gold to have a lower fineness than mesothermal or hypothermal gold are briefly discussed.

Some possible applications of this study are indicated in the final chapter. It is claimed that records of gold fineness might constitute a valuable addition to mill records. Tentative suggestions are made regarding a method whereby the approaching exhaustion of a deposit might in some cases be predicted. With regard to the origin of the gold in the Witwatersrand sediments, it is pointed out that the modified placer hypothesis is not fully equipped to explain certain of the variations in the composition of the gold.

CONTENTS.

Page

ACKNOWLEDGMENTS 1

CHAPTER I. METHODS OF INVESTIGATION 2

Definitions of Terms 2

Methods of Investigation 4
    Production Data 4
    Field Work 10
    Laboratory Work 11

CHAPTER II. NATURE AND SCOPE OF INVESTIGATION ... 13

Nature of Problems Studied 13

Previous Relevant Investigations ... 15

CHAPTER III. VARIATIONS OF GOLD FINENESS IN THE GWANDA GOLD BELT 25

Introduction 25

Brief Outline of the Geology of the Area 25

Statistical Data 27

Interpretation of Data 32

The Four Groups of Deposits 34

CHAPTER IV. VARIATIONS OF FINENESS IN SOME TYPICAL DEPOSITS 35

Introduction 35

A. The Olympus Mine 37
    Introduction 37
    Brief Outline of the Geology ... 37
    Analysis of Mine Records 39
    Experimental Sampling Data 43
    The Evidence of Polished Sections. 46

B. The Lone Hand Mine 59
    Introduction 59
    Brief Outline of the Geology ... 59
    Production Data 60
    Experimental Sampling Data 61
    The Evidence of Polished Sections 64

C. The Horn Mine 71
    Introduction and General Geology.. 71
    Experimental Sampling 72
    The Evidence of Polished Sections 74

D. The Jessie Mine 78
    Introduction and General Geology.. 78
    Production Data 79
    The Evidence of Polished Sections 79
    Experimental Sampling 88

E. The Turk Mine
    Introduction and General Geology.. 92
    Production and Fineness Data ... 92
    Experimental Sampling 94
    The Evidence of Polished Sections. 95

F. The Lonely Mine 97
Introduction and General Geology ... 97
Production and Fineness Data.. ... 98
Factors correlated with Variations in Fineness 101

G. The Blanket 'A' Mine 112
Introduction and Outline of Geology. 112
Fineness of Recovered Gold 114
The Evidence of Polished Sections... 115

H. The Makanga Mine 124
Introduction and General Geology ... 124
Production and Fineness Data ... 124
Mineralogy 126

I. The Antelope Mine 127

J. The Wanderer Mine 129

Other Relevant Investigations 130

CHAPTER V. GOLD FINENESS IN RELATION TO THE ASSOCIATED ORE MINERALS 133

Arsenopyrite 133

Pyrite 138

Pyrrhotite 141

Chalcopyrite 144

Sphalerite 147

Galena 148

Sulpho-salts 150

Late Minerals 150

CHAPTER VI. DISCUSSION: THE GEOLOGICAL FACTORS CORRELATED WITH VARIATIONS IN FINENESS .. 154

Grain Size 154

Depth and Temperature 157

Paragenesis and Availability of Silver... 159
Paragenesis of Gold 160
Silver-rich Gold and Other Silver Minerals in Hypothermal Deposits ... 163
The Causes of Silver Deficiency ... 166
Resolution of Some Paradoxes ... 167

Tenor of Metallization 169

The Depth Zones of Ore Deposition.. ... 172

CHAPTER VII. GENERAL SUMMARY OF CONCLUSIONS 175

CHAPTER VIII. APPLICATIONS OF INVESTIGATION 181
Mill Records 181
Mine Evaluation 181
The Occurrence of Gold in Ancient Sediments of the Transvaal 183

APPENDIX I. 187

LIST OF REFERENCES. 190

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CHAPTER I

METHODS OF INVESTIGATION

DEFINITIONS OF TERMS

Some of the terms which are used in the succeeding text have been employed by different writers in rather different senses. With a view to obviating confusion, the usage of each in this paper is now defined.

Fineness In its widest sense, the term gold fineness implies the proportion of pure gold in a gold alloy, usually expressed in parts per thousand. In the laboratory, gold can be made to alloy with a number of different elements (see Rose, 1909, pp.37-63), but in nature only rarely is any element other than silver of any importance. However, it is desirable to follow Fisher (1945, p.457) in using the qualifying term bullion fineness for crude bullion which may contain base metals, for this is an inexact value which may be influenced as much by the methods of mining and recovery as by primary variations within the orebody. To quote a commonplace example, copper detonators used in blasting are known to be recovered in the milling plants, in which case the variability of gold content in the bullion is produced artificially. Bullion fineness has thus not the same geological significance as true fineness, defined below, and is a term seldom used in this paper.

True Fineness The true fineness of gold may be defined as the proportion of pure gold in the pure gold-silver alloy, expressed in parts per thousand. The term true fineness of silver may be used in the same sense. The term expresses the composition of the alloy, and although it may in fact be a theoretical concept in many ores, being determined by calculation which excludes the base metal content, it is a more exact and consistent figure than bullion fineness, and is unaffected by artificially introduced base metal. True fineness is expressed by the value $1000\ Au/(Au + Ag)$ and throughout this paper the term true fineness, or simply fineness, is used in this sense. As mining returns in Southern Rhodesia always record the production of both gold and silver from each deposit, the true fineness of the bullion is nearly always readily available, whereas it may be impossible to collect data relating to bullion fineness, especially in the case of abandoned mines. Thus, in addition to the advantages of greater precision, the use of the true fineness value is recommended by the availability of the data. In order to determine the true fineness of gold particles in an ore, they should be separated by amalgamation with mercury, and the resulting amalgam assayed for gold and silver. It is thus possible to determine true fineness either from a study of production data, or by grinding specimens of ore with mercury in the laboratory.

Gold-Silver Ratio This term is used in this paper to express the ratio of the total gold in the ore to the total silver, irrespective of the mineralogical forms in which each may occur. This can properly be determined only by the assay of ore samples, but may, in the probably rare cases where gold and silver occur only in the form of an alloy of fixed composition, be determined from the true fineness of the constituent gold particles. In practice it is found more convenient, for purposes of comparison, to express the assay data in the form 1000 Au/(Au + Ag). The writer proposes to designate this the apparent gold fineness, or simply, apparent fineness. This is a useful procedure, for it is possible at a glance to compare the fineness of gold particles with the proportion of total gold to silver in the ore, and hence to estimate the amount of gold or silver occurring in the ore in some form other than that recoverable by amalgamation.

Amalgamation and Cyanidation Gold recovered by amalgamation or cyanidation is referred to in this paper as amalgam gold or cyanide gold respectively. The former includes all gold recovered by amalgamation with mercury, whether by amalgamation in the mortar-boxes of stamp mills, by plate amalgamation, or by barrel amalgamation of concentrates. The term is synonymous with 'mill gold'. Likewise, cyanide gold implies gold recovered by cyanidation of crushed or uncrushed ores, and cyanidation of sands, slimes or concentrates.

Grade or Tenor   Grade, or tenor of an ore body, is expressed in pennyweights per ton (dwt./ton) where 20 dwt. make 1 troy ounce, and where 1 ton equals 2,000 pounds. In these units, 1 dwt./ton is equivalent to .00017 per cent by weight, and 1 oz./ton is equivalent to .00343 per cent.

METHODS OF INVESTIGATION

Production Data

The study of production data is the most effective method of assessing gold fineness. However, care is required in the interpretation, for the fineness of gold produced may be greatly influenced by the metallurgical processes employed, and even where extraction methods are of the simplest, a knowledge of the mineralogy of the ore is essential. Some of the factors which influence the fineness of recovered gold are briefly discussed below.

Gold Fineness in Relation to the Methods of Recovery

(i) Recovery by Amalgamation

The fineness of gold recovered by amalgamation will generally reflect the average fineness of gold particles in an ore, while in smaller samples the fineness can be determined by grinding the sample with mercury by hand. Amalgamation reflects the fineness accurately only when gold and silver occur in the ore only as an alloy, for if any metallic silver be present, this will also readily amalgamate with the mercury, and the determined fineness will then lie somewhere between true fineness and apparent fineness.

The reliability of amalgamation data may also be rendered uncertain by the presence in the ore of certain sulphides of silver. Collins (1900, p.7) states that "mercury decomposes silver sulphide at ordinary temperatures when triturated with it, whether in the presence of water or not." Pyrargyrite, $3Ag_2S.Sb_2S_3$, and proustite, $3Ag_2S.As_2S_3$, are also said to be acted upon by mercury, but the reaction is much slower. The activity of mercury towards these sulphides is greatly increased by the presence in solution of ferrous sulphate or copper sulphate. Collins (ibid., p.7) quotes that under equivalent conditions the amount of silver extracted by amalgam from silver sulphide is nearly tripled in the presence of copper sulphate. This fact was known and turned to advantage as far back as the middle of the 16th century, as in the Patio process for treating ores containing native silver, argentite, stephanite, pyrargyrite, polybasite and proustite (Collins, 1900, p.44; Rickard, 1936). In this process, common salt and crude copper sulphate, termed 'magistral', were commonly used to facilitate amalgamation. It is important to note that argentiferous sulphides of other metals, such as argentiferous galena, sphalerite or fahlerz, are much less easily amalgamated than the previously mentioned sulphides. Some specimens are not acted upon at all. This variability in reactivity was attributed by Collins (p.7) to the fact that "silver exists in these minerals in two different conditions - sometimes as a true silver compound, mechanically interspersed through the base metal sulphide, and sometimes as a double sulphide chemically combined with it. In the former case, mercury can attack the silver sulphide, in the latter there is no action."

To summari~~s~~ze, the fineness of bullion recovered by amalgamation may be accurately representative of the fineness of gold particles in the ore when the mineralogy of the latter is simple, but when silver occurs also in the form of native silver or sulphides, the determined fineness may be less than the true fineness of gold particles.

Amalgamation processes, although falling into disuse in modern gold mills, are still in common use throughout Southern Rhodesia. The common methods used are copper-plate amalgamation at the mill discharge point, or barrel amalgamation of

James Table or strake concentrates.

(ii) Recovery by Cyanidation

The most important method of recovery used on established mines is that of cyanidation, in which either the ground ore, or heavy concentrates separated from it, are treated with a weak solution of alkali cyanide. The gold and silver, and perhaps other minerals as well, pass into solution, and are precipitated from solution using zinc dust or shavings, or sometimes activated charcoal or other reagents.

The reaction generally accepted for the dissolution of gold is that of Elsner (see American Cyanimid Company, 1950):

$$4Au + 8KCy + O_2 + 2H_2O = 4KAuCy + 4KOH$$

The presence of oxygen assists the reaction to proceed to the right, although MacArthur (see Rose, 1906, p.352) cited experiments to show that gold in ores could be dissolved in the absence of oxygen. Maclaurin (see Rose, p.352) found that gold dissolves most rapidly in potassium cyanide solutions containing between 0.005 per cent and 0.25 per cent potassium cyanide, dissolution being at a maximum in solutions of the latter strength. Solutions stronger or weaker than the latter dissolve gold more slowly. Christy (see Rose, p.353) found that for all practical purposes, potassium cyanide solution ceases to act when its strength falls below 0.001 per cent.

Many factors play a part in controlling the composition of cyanide solutions in contact with the gold-bearing ore. A discussion of these is beyond the ability of the present writer, but brief mention is made here of those which are perhaps most significant in determining the ratio of gold to silver in cyanide bullion.

Other minerals present in the ore besides gold and silver may pass into solution, and such fouled solutions may exhibit some degree of inhibited reactivity towards one or other of the precious minerals (Rose, 1906, pp. 350, 358; Julian and Smart, 1921, p.53).

Barsky (see Am. Cyanimid Co., 1950), investigating the relative rates of dissolution of gold, silver and their alloys, exposed surfaces of measured area of these metals to equal volumes of 0.10 per cent sodium cyanide solution, under conditions of constant aeration and agitation. He found that:

(i) silver dissolves at about half the rate that gold does (1.54 and 2.99 mg/cm^2/hour respectively);

(ii) the rates of dissolution of the alloys are roughly proportional to the composition of the alloys;

(iii) the proportions of the metals dissolved are practically in the same proportion as the metals in the alloys. Thus, cyanide solutions in contact with alloys assaying 79.8 per cent and 57.6 per cent gold, assayed 78.6 per cent and 56.5 per cent of gold respectively.

Julian and Smart (1921, p.63) showed that changes in the strength of cyanide solutions had little effect on the ratios of solubilities of gold and silver, where solubility is defined as the comparative weights of metal dissolved from surfaces of equal area in the same time and under the same conditions. Potassium cyanide solutions ranging in strength from 1 per cent to 0.05 per cent dissolved weights of gold and silver which bore a constant ratio of 1.81:1 to each other.

In the probably rare event in which gold and silver occur in a hydrothermal ore only as an alloy of constant composition, it is to be expected, from the experimental work of Barsky, described above, that cyanide bullion will reflect within tolerable limits of error the fineness of the gold in the ore. In this special case, the true fineness and apparent fineness would be the same, and it would be possible to place some reliance upon the composition of the cyanide bullion as a measure of true fineness. Prentice (1940, p.21) however, pointed out that the percentage extraction of precious metals falls as the value of pulp to be cyanided falls, and that the extraction of silver might be very incomplete, when it is present in only small amounts. The implication is that gold-silver ratios of bullion won from low-grade ores should be treated with circumspection.

Where particles of both relatively pure gold and native silver occur in an ore, the composition of the cyanide solutions should depend largely upon the relative solubilities of the metals. In practice this association is probably exceedingly rare in ores unaffected by supergene processes (Joralemon, 1951, p.296). The case does not appear to arise in Rhodesian deposits.

The effect of silver, as a sulphide, or in some other form, on the composition of cyanide solutions may be judged from the following statement (Rose, 1906, p.359): "It has been laid down as a general rule that oxides, hydrates, carbonates, sulphates and sulphides of those metals which are electropositive to gold in cyanide solutions are dissolved more rapidly than the last-named metal, whether it is present in the metallic form or contained in its commonly occurring salts." The experimental work of Christy (see Rose, 1906, p.360) showed gold to be electropositive to silver in 0.065 per cent KCN solution, and strongly electropositive to sulphides of silver such as ruby silver and argentite.

In conclusion, it should be noted that the assumption that the gold-silver ratio of the bullion produced will be the same as the gold-silver ratio in solution, is unjustified. Fouled solutions may not allow complete precipitation of either of the precious metals. Again, certain precipitants may be selective; carbon will selectively precipitate gold from cyanide solutions containing both gold and silver (Joralemon, 1951, p.304). Or, during smelting of the gold slimes, there may be gold in the slag, or in a base-metal slag which comes to rest on the gold matte in the crucible. This latter, known as the base bar, also contains a certain amount of gold and silver, but very often in proportions very different from those in the gold matte. The silver content is generally high.

To conclude, it may be said that, from various considerations concerning the chemistry of cyanidation, little reliance should be placed upon the fineness of cyanide bullion as a measure of either the fineness of gold particles, or the gold-silver ratio of the ore. In practice, it is found that the fineness of the cyanide bullion may often fall between these two values, and that this could be due to the incomplete dissolution of small amounts of silver-bearing sulphides in the ore, or to the dissolution of particles of gold relatively rich in silver, which are too small to be recovered by amalgamation. It is also found in practice that in some deposits the difference between the fineness of cyanide gold and the fineness of amalgam gold is exceedingly small, not exceeding a few per cent.

Interpretation of Production Data

In succeeding pages use has been made of production data to characterize the gold in different deposits. In the offices of the Mining Commissioners in Southern Rhodesia, the Gold Registers record the monthly outputs of both gold and silver for every gold mine in the territory. Returns for amalgam gold, cyanide gold, and gold recovered by the treatment of concentrates are kept separate, and little difficulty is encountered in determining the fineness of amalgam gold. Unfortunately, it is not uncommon for some mines to declare joint outputs from more than one source. In these cases, the information is valueless, and has to be discarded. In a few cases where data were sought, amalgam and cyanide gold were found to have been declared jointly, and such data are also of restricted value.

It has been found that in all of the deposits considered in succeeding pages, the number of outputs in which the amount of silver exceeds the amount of gold recovered, is quite negligible. This is true for both amalgam and cyanide gold. The conclusion seems inevitable that in the mines studied the amount of silver occurring in the ore, other than that alloyed with the gold, is exceedingly small, and hence the computed fineness values are generally reliable. It might be mentioned here that in the study of the mineralogy of the ores of a number of producers, it was found that silver minerals are exceedingly rare.

Production data have also been used for gaining some idea of the average grades of deposits. As Southern Rhodesian ores tend, in general, to be refractory, the average recoveries seldom reflect the average grades. While it is difficult to generalize, it is probably safe to estimate that most mines recover between 65 per cent and 85 per cent of their gold.

These two values, fineness and grade, have been found to be related in a number of deposits, and,in a later section, it will be shown that this relationship has its roots in the parageneses of the ores.

Field Work

The greater part of the field work for this investigation was carried out while the writer was in the employ of a mining company in the territory. Several of the mines, which are described in Chapters IV and V, were mapped and sampled both on surface and underground during this period. Others which are described were visited by the writer at a later date, when it was not possible to devote the same amount of time to detailed study, and sampling was the chief objective.

In the descriptions in Chapter IV, most attention has been devoted to the mineralogy of the ores, and only as much information on the character of the deposits in the field as is necessary for a background has been given. This procedure has been adopted because field details are generally irrelevant to the topic under discussion.

Where the deposit described has long since been worked out and abandoned, as, for example, in the case of the Lonely mine, it has not been possible to examine it in the field and the writer has been dependent on whatever literature is available, and the collections of ore specimens in the National Museum in Bulawayo and the Geological Survey in Salisbury.

Laboratory Work

Laboratory work has included the preparation of samples for assaying, and the preparation and study of polished ore specimens. Part of the work in the former category was carried out in the assay department of Connemara mine, at Hunter's Road. This work was directed towards establishing the variations in gold-silver ratio and gold fineness in different sections of several deposits, or in samples of different minerals. The actual assaying was not carried out by the writer. The writer is fully aware that in most of the ores studied, a greater number of assays would have lent stronger support to many of the conclusions which have been drawn. However, due to the lack of assaying apparatus of any form in the Geology Department of this University, where the bulk of the work was carried out, and very restricted funds for having assays carried out by professional chemists, the number of assays had to be very severely curtailed.

The polishing of ore specimens was carried out on a Cooke, Troughton and Simms Ore Polishing Machine, using a variety of polishing laps and diamond abrasives. Good surfaces can be prepared with this apparatus, rendering it possible to identify gold grains as small as 1-2 microns. A full account of the polishing technique used is given in Appendix I.

Microscopic examination was carried out with a Leitz S.M. Pol. microscope fitted with reflecting unit incorporating both plane-glass and prism reflectors. Photomicrographs were taken using a Leica camera fitted with the Makam adaptor and reflex housing.

For mineral identification, the writer was entirely dependent on the determinative tables of Short (1940). In view of the notoriously unreliable behaviour of etch reagents, efforts were made in all cases to confirm the identifications by microchemical tests. In many cases, however, this proved impossible, due to the tiny sizes of the grains studied. Useful confirmatory data, in the form of reflectivity values, were given by the use of a Cooke, Troughton and Simms Microphotometer (see Hallimond, 1953, p.131). This instrument has certain advantages over those of the photo-electric type, in that tolerably accurate determinations of reflectivity can be made on grains which fill only a small part of the microscopic field. The chief source of error in these determinations proved to be the concave surfaces produced during the polishing of tiny grains of soft minerals. Determinations on large grains can generally be made within an accuracy of 2 per cent. Tables of reflectivity are given by Folinsbee (1949).

The determinative tables of Davy and Farnham (1920) contain useful supplementary notes for the identification of ore minerals, while Stillwell (1931) has published useful data for the determination of telluride minerals. Both these references have been found valuable.

The writer had no access to X-ray or spectrographic apparatus, and accordingly no confirmatory tests could be made with these tools.

CHAPTER II

NATURE AND SCOPE OF INVESTIGATION.

NATURE OF PROBLEMS STUDIED.

The object of the present investigation is the examination of two main aspects of the problem concerning the variability of gold fineness. These two aspects are, firstly, the manner and degree of these variations, and secondly, the attempts to account for them. There is a dearth of precise information in the literature regarding the manner in which gold fineness and gold-silver ratios in ores vary. Although it is widely known that both of these values are subject to sharp fluctuations in different mining fields, as well as within individual deposits or even sections of workings on the same deposit, there do not appear to be many published accounts which describe in detail either the manner or the extent of these variations. It is seldom stated whether these variations follow any regular pattern, or are haphazard, or may perhaps be correlated with other geological features. Accordingly, an attempt is now being made to describe these variations in both gold-silver ratios and gold fineness in some Southern Rhodesian deposits which are typical of the hydrothermal veins and impregnations in the territory. The need for data of this nature is stressed in nearly all published investigations in this field, and it is hoped that this investigation will at least contribute towards the bridging of this gap.

The second aspect to which attention is devoted concerns several paradoxes which arise out of views which appear to enjoy current support. In what is perhaps the most comprehensive study of gold fineness in the literature, Fisher (1945) has drawn attention to the high silver content of gold characterizing epithermal deposits, and the progressively greater purity of the alloy in the mesothermal and hypothermal types of deposits. He concluded from this, as well as from a consideration of certain aspects of mineralogical zoning, that temperature and pressure were the chief factors influencing the composition of the alloy deposited during mineralization. Accordingly, he claimed (p.559) that, in ore channels "gold deposited nearer the source will be of higher fineness, and gold of lower fineness will be found with other silver minerals farther away, that is, usually at a higher horizon." While this is found in many cases to be true, such as in the Kolar gold field described by Pryor (1923), there are nevertheless many examples in which the reverse is true. For example, the work of Bruce (1943) pointed to an increase in the silver content of recovered gold with increasing depth in certain Ontario gold mines; A.B. Edwards (personal communication) states that some of the mines in Australia show a slight increase in silver content of the gold with depth; Threadgold (1958) showed that the gold fineness of the Morning Star mine, Victoria, decreases with depth, while several Southern Rhodesian mines show similar changes. In the Lonely mine, Bubi District, the fineness of the gold fell from over 950 fine in the upper levels to below 900 fine in depth.

From these facts it is clear that Fisher's conclusions cannot be accepted without some qualification, and that although temperature and pressure may well be the most important factors governing the fineness of gold, other factors must play an important part in bringing about these discrepancies. His general conclusions also appear to be incompatible with those arising out of Joralemon's study of the Getchell mine, Nevada (Joralemon, 1951). This deposit, described as a low-intensity epithermal deposit, contains native gold and native silver as separate minerals, whereas electrum is rare. Joralemon concluded (p.296) that, at very low temperatures, gold and silver do not form an alloy.

In the succeeding text, the mode of occurrence of gold grains containing varying proportions of alloyed silver is described in a number of deposits. It has emerged that grains, which differ markedly in composition, may occur in the same handspecimen and even in the same field under the microscope. It is inconceivable that temperature and pressure could vary so sharply over such small distances, bringing about marked differences in the composition of adjacent grains; this argument again emphasizes the need for modifying currently accepted hypotheses.

Many accounts dealing with variations in gold fineness are wholly concerned with post-depositional events, such as the effects of secondary enrichment and oxidation, and the refining of alluvial gold. Only brief mention has been made of work in this field in the present investigation, which is confined to primary or hypogene variations. Ore specimens showing the least traces of oxidation have been discarded, and, in the different mines studied, sampling was confined to the deeper levels.

To conclude, it could be said that the field of research is somewhat narrow, as it embraces only particular aspects of the greater problem of gold deposition. The work has not been assisted to any great extent by the copious literature dealing with gold, for there is generally little precise information regarding this particular problem, and the conclusions of different investigators are frequently in conflict. On the other hand, it is a field of great promise, in which there is still scope for studying fundamental principles of ore deposition.

PREVIOUS RELEVANT INVESTIGATIONS

The references to variations in gold fineness are scattered throughout the literature, and in only a few publications have there been systematic attempts to account for these variations. Few accounts even refer to the fineness of gold in the deposits under discussion, or, in a large proportion of those in which gold fineness is recorded, the nature of the gold, its associations and its manner of recovery are not stated. The following survey deals briefly with those investigations encountered by the present writer in which the features of gold fineness have been given special attention.

As has so often proved to be the case in other fields of study, Lindgren was amongst the first to make penetrating observations regarding the distribution of gold and silver in ores. The following statement is quoted in view of the significance it acquires in a later section of this paper. He wrote (Lindgren, 1896) that "there are, in general, two classes of gold-quartz veins, between which, however, no distinct line of demarcation exists. The first embraces those veins in which the gold is nearly exclusively connected with the sulphides and is not easily removed from them by simple amalgamation and in which free gold is found only in the upper decomposed zones; in these veins there is usually also much silver. The other class .... carry an ore of which the principal value lies in the free gold, the relative amount of which shows no diminution in depth once the surface zone of decomposition is traversed."

In his account of the ores of the Central City district of Colorado, Collins (1902) described the zonal distribution of gold and silver ores. Gold ores, located in a central position, are surrounded by a belt of silver-rich ores. The silver-gold ratios of the ores show great variation, and his work indicated that the silver-rich ores yield amalgam bullion richer in silver than that from silver-poor ores. This latter fact implies that the gold fineness decreases by small amounts where the total content of silver in the ore increases, but it is not stated whether other silver-bearing minerals perhaps yielded silver to the amalgam. His discussion of the influence of milling techniques upon the reliability of data which might be used for assessing the characters of the original ore, contains valuable information. His tables in which the gold fineness is compared with the silver-gold ratio in the ore bring out the interesting fact that,although the silver content of the ore may exceed by many times the gold content, the gold fineness is nevertheless moderately high, being 730 to 870. Silver does not, as might be expected, dominate over gold in the natural alloy.

Emmons (1904, pp. 63-64) raised the question whether there was any uniform change with depth in the proportions of gold and silver in the bullion from the Homestake mine, South Dakota. His figures indicated a steady decline in gold-silver ratio from 4.90, prior to 1880, to 3.88 in 1899-1900. He considered that this trend was shown even in ore below the zone where leaching of silver might have been expected. A detailed investigation by Sharwood (1911) was directed to determining the causes of this variation, and although his conclusions nullified Emmons' suggestions, his other findings remain of general interest. He showed that the decline in gold fineness in the bullion could be accounted for by changes in the milling procedure, and that the variations in gold fineness were more marked in the different ore bodies than in different horizons in the same ore body. Tests carried out on gold particles proved that in the Homestake mine the smaller gold particles contain more silver than those which are larger; this conclusion was substantiated by the fact that after the removal of gold particles in the ore by amalgamation, the still finer particles which were dissolved by cyanide solutions were found to contain even more silver.

Bastin (1917) incorporated Collins' work (loc. cit.) in his account of the economic geology of Gilpin County and adjacent areas, without extending the latter's researches in this field. However, he contributed mineralogical data, to which reference is made in a succeeding section in this paper. In the most recent account of the geology of the Front Range, Lovering and Goddard (1950) qualify certain of Bastin's observations, but do not add further to Collins' work.

In his description of the ~~Walhalla~~-Wood's Point auriferous belt, Junner (1920) suggested a correlation between gold fineness and the ore minerals with which the gold is intimately associated. Here the gold fineness was said to vary from about 800 to 970, and he stated that "apparently the nature of the vein-sulphides has influenced the fineness of the gold". Where stibnite was the predominant mineral, he found that the gold was invariably of good quality, and where the ore minerals were chiefly sulphantimonites and sulpharsenites such as bournonite, tetrahedrite, jamesonite and arsenopyrite, the gold was usually of good quality. However, where galena and sphalerite predominated in the veins the gold was rarely of good quality.

Pryor (1923) described the variations in gold fineness in the Kolar gold field of Mysore, India. From a study of production data over a period during which some ten million ounces of gold were produced, and during which methods of recovery remained constant, he showed that the average fineness of the mill gold increased steadily from 890 in the upper levels to about 930 in the deepest workings more than 6,000 feet from surface. This trend was shown by each of the different sections along a strike-length of some 10,000 feet. By determining the average depths of the sources of ore from mine records, he was able to show that, in longitudinal section, the contours representing equal fineness values are concave towards the surface. He concluded that temperature was the chief factor in controlling gold fineness, and wrote: "it may be assumed that each 'contour line' represents a line of equal conditions for the deposition of gold. The wall rocks have not been found to have any particular precipitating action on the gold ...... The 'contour' lines may therefore be regarded as indicating the general shape of the iso-therms." Pryor's contribution might thus be considered to be one of the first in which an emphatic correlation is made between temperature of deposition and gold fineness.

H.G. Ferguson (1924, p.106) noted that the Tertiary arsenical ores of the Manhattan District, Nevada, yield gold with a very small proportion of silver, in contrast to other Tertiary ores in the district in which pyrite is the only sulphide of importance and in which silver is relatively abundant.

In the former ores, containing arsenopyrite, realgar and orpiment, the ratio of gold to silver is about 17:1, whereas it is 2:1 or 2.5:1 in the latter. Free gold is not seen in the arsenical ore, but samples treated with nitric acid yielded minute specks of gold (p.99). Ferguson suggested that the low silver content of the gold was due to the selective precipitation of gold from solution by arsenical minerals, and concluded that "it is at least a tenable hypothesis that hypogene solutions that are rich in arsenic and free from lead, zinc and copper, tend to precipitate gold without any important mixture of silver."

Van der Veen (1925) noted briefly the occurrence of gold grains with zonal structure in deposits of Transylvania and Banat Province, Hungary. (It is of interest to note that such grains show a silver-rich core which is surrounded by zones successively poorer in silver, suggesting that gold of low fineness is earlier in the paragenesis than gold of high fineness).

Macgregor's study of the Lonely mine, Southern Rhodesia (Macgregor, 1928) established that here the gold fineness decreased from 958 in the upper levels to less than 900 below the 23rd level. Macgregor offered no explanation of these facts, but noted that this trend was the reverse of that characterizing the Kolar gold field.

Knopf's findings in the Mother Lode system of California (Knopf, 1929), recall to mind those of Junner in Victoria and Ferguson in the Manhattan District of Nevada. While, from available evidence, there is no indication of a change in gold fineness with increasing depth, he indicated that there does appear to be a connection with the associated sulphides and tellurides. Gold associated with arsenopyrite was found to be 839 fine, and that with pyrite was 825 fine. Gold associated with the later minerals galena and petzite was of higher fineness, respectively 870 and 899 fine. Knopf remarked that these results "suggest that the fineness of the gold is influenced by the nature of the sulphides or tellurides with which it is associated."

Many passing references to the fineness of native gold are to be found in Lindgren's 'Mineral Deposits' (1933). In particular, the differences in gold characteristic of the epithermal, mesothermal and hypothermal deposits are noted. Of gold in the epithermal deposits, he wrote (p.445): "It contains silver, as a rule, and is of pale yellow colour; a proportion sometimes occurring is ounce for ounce when the mineral is of very pale grayish-yellow colour (electrum). Deep yellow gold is not unknown, however." With reference to mesothermal deposits of the California and Victoria type, he stated (p.545) that "the free gold always contains a little silver, the average fineness being 800; the sulphides are likely to carry more silver in proportion than the native gold." The gold in the examples of hypothermal deposits quoted by him carry, in general, a relatively small proportion of silver.

J.C. Ferguson (1934, p.87) suggested a correlation between gold fineness and the nature of the accompanying sulphides in the pre-Cambrian deposits of the area surrounding Filabusi, Insiza District, Southern Rhodesia. He concluded that "the pyrrhotite-bearing ore bodies have yielded gold of good quality, and that those which are heavily mineralized by chalcopyrite and galena have given poorer gold. The relations between the quality of the gold and the nature of the mineralization are, however, rather vague; and the fineness seems to depend as much on the geographical position of an orebody as on its mineral assemblage. This suggests that the fundamental point to be determined is the identity of the granite magma to which the orebody is related."

M.S. Fisher's account of the structure and composition of gold (Fisher, 1935) contains valuable data relating to its temperatures of deposition and recrystallization. He showed that gold grains containing appreciable amounts of silver, deposited from hypogene solutions, may have a zonal structure, and that this structure may be revealed by the etching of polished specimens with aqua regia. He concluded that the variable fineness exhibited by successive zones in gold grains arises out of variations in temperature and the character of the gold-bearing solutions which deposit the metal, and that this zonal structure could be destroyed by diffusion where temperatures are high enough. He showed, further, that the secondary purification of gold in placer deposits may be due to the solution of both gold and silver from the surface of particles, followed by the deposition of almost pure gold on the surface so attacked.

Bruce (1943) investigated the gold-silver ratios in bullion produced by mines in the Porcupine and Kirkland Lake areas of Ontario. He found the data to be somewhat conflicting, and was unable to arrive at any definite conclusions, in view of the fragmentary nature of the evidence. However, he indicated that "the gold-silver ratio for some deposits seems to decrease with depth." He also found that the gold-silver ratio was different for different kinds of wall rocks, and that the silver content of the ore varied less than the gold content.

Mackay (1944) described the differences in silver content of gold bullion produced by amalgamation and by cyanidation in shallow mines in the Lupa gold field of Tanganyika, and established that, as a general rule, the fineness of gold particles declined rapidly with increasing depth. This feature, and the fact that the differences in gold-silver ratio in amalgam bullion and cyanide bullion, respectively, became less marked with increasing depth, he attributed to secondary enrichment and supergene removal of silver. While the present writer does not deny that this is probably the case, it will be shown later that some of Mackay's initial assumptions were not justified, and that some of the features described by him are also characteristic of deposits unaffected by secondary enrichment.

Probably the most comprehensive study of the variations in gold fineness is that of N.H. Fisher (1945). While the bulk of this paper is devoted to alluvial gold and the effects of secondary enrichment, variations arising out of hypogene effects are also considered in some detail. The conclusions he drew from this study are of wide application and those which are most significant are summarized here. From an extensive study of available data, Fisher concluded (p.484) that although gold and silver will alloy, in the molten state, in any proportions, in ore deposits the lower limit of fineness is about 450. Bullion recoveries indicating a higher silver content than this are suspect, and probably represent incorporation of silver from other minerals. The content of silver in ores was shown to have little effect upon the fineness of gold, except in the case where insufficient silver was originally available, when the gold fineness would inevitably be high. In support of this contention, several instances are quoted where the silver content of the ore is greatly in excess of the gold content, but where the gold fineness is not particularly low. A statistical examination of gold fineness in epithermal, mesothermal and hypothermal deposits showed that gold in the first is typically 500 to 800 fine, whereas in the last the lower limit is 800 fine. Mesothermal deposits typically carry gold which is intermediate in quality between the other two classes. Fisher found no evidence to support a correlation between gold fineness and the nature of the wall rocks or the composition of the associated intrusions from which the ore fluids had been derived. Following on his contention that "the increase in fineness with depth strongly indicates that temperature and/or pressure, and not the nature of the wall rock, was the dominating factor in determining the amount of silver alloyed with the gold", he concluded that "gold deposited nearer the source will be of higher fineness, and gold of lower fineness will be found with other silver minerals farther away, that is, usually at a higher horizon." He also concluded that under any given set of conditions, gold fineness tends to be constant, particularly in deposits connected with the same intrusive batholith, whereas wide variations may occur in ores connected with the same intrusion, but formed under different physical conditions.

Bichan's investigation of the Kolar gold field (Bichan, 1947) led him to postulate that variations in pressure could best explain the downward increase in gold fineness, established by Pryor (1923). He proposed that the differences between the prevailing pressure, and the critical pressures for the separation from the mineralizing fluids of gold and silver respectively, would cause relatively more silver to be precipitated at lower pressures, and relatively more gold at higher pressures. As a result of this, gold precipitated in the upper levels would contain more silver than that in deeper levels.

A downward increase in the fineness of gold recovered by amalgamation has been established at the O'Brien mine, Quebec, by Mills (1954). This change takes place between the depths of 700 feet and 2,100 feet, and the increase in fineness is from about 860 to about 930. From a comparison of the nature of the bullion recovered respectively by amalgamation and by cyanidation, Mills concluded that the average size of gold particles decreases with depth, and that the smaller particles are purer than those which are larger. (In this latter respect the O'Brien mine ore may be contrasted with that of the Homestake mine, where Sharwood (loc. cit.) found that the larger gold particles tend to be purer.) It is worthy of comment that, in the O'Brien mine, the bullion recovered by cyanidation has less silver than that produced by amalgamation; this is unusual and the reverse is usually the case.

Threadgold (1958) stated that the fineness of gold shows a slight decline with depth in the Morning Star Gold Mine, Victoria. Down to the 4th level the average fineness was about 805. Between the 5th and 7th levels this value dropped to 790, and below the 14th level this value dropped still further to 785. It was also stated that the fineness of the gold varies locally by as much as 25 degrees.

The variations in fineness of the Maude and Yellow Girl gold have been described in some detail by Edwards (1958). In this ore the gold-silver ratio varies from 10/1 to 1/100, whereas the gold fineness varies from place to place between 685 and 950. The finer gold occurs in small pockets or short sections of the veins; some mill products and occasional underground samples indicate that it may reach close on 1000 fine. The abundant silver in the ore varies independently of the gold, iron and arsenic, but appears to be associated with the elements copper and antimony. Pyrargyrite is a constituent of the ore. About 10 per cent of the gold is intimately associated with pyrite and arsenopyrite, as sub-microscopic particles or in solid solution, and Edwards stated (p.124) that "from the paragenesis of the ore it could be expected that very little silver would be associated with this early deposited gold". This study led to the conclusion (p.131) that "the fineness of the gold depends on two independent factors:

(i) the availability of silver, i.e. the concentration of silver in the mineralizing solutions, in conjunction with the concentration of other elements with which the silver could combine (partition factor);

(ii) temperature of deposition (assuming more or less constant pressure during mineralization). Provided sufficient or excess silver is available, some factor such as the temperature must control how much silver can alloy with the gold. Otherwise the composition of the gold should vary more or less with the silver content of the ore at any given place in the vein, which apparently it does not."

CHAPTER III

VARIATIONS OF GOLD FINENESS IN THE GWANDA GOLD BELT

Introduction

The work of Lindgren (1932), Fisher (1945) and others has clearly shown that fineness varies from one mining field to another, but that, in the broadest sense, gold of high fineness is characteristic of hypothermal deposits, and gold of low fineness is typical of most epithermal deposits. It is also well known that fineness varies from one deposit to another in any particular group of deposits, and may even fluctuate widely within a single deposit. It was considered that the present investigation would benefit from a statistical determination of the average fineness values, and the degree of variation in values, in one of the typical gold-producing areas in Southern Rhodesia. The Gwanda area, lying some 60 miles south-east of Bulawayo, was selected for this purpose. Several factors influenced this choice. It is, firstly, a fairly small area, but it contains a large number of deposits in which the gold fineness varies from low to very high. Secondly, the geological structure is not as complex as in some areas. Lastly, production data for this area were readily available to the writer whilst he was stationed in Bulawayo. Accordingly, the records of production for a period of 16 years were systematically examined and the fineness values of all mines which were in operation during this period calculated from the data extracted.

Brief Outline of the Geology of the Area

The area has been geologically mapped and described by Tyndale-Biscoe (1940). The following outline has been drawn from his description.

The area is underlain by Archaean rocks including a wide variety of altered intermediate and basic lavas, metamorphosed sediments and banded ironstones, as well as intrusive rocks which are now represented by serpentinites and talc-schists. The assemblage is thus similar to that of many other occurrences of Primitive System inliers in the Old Granite in Southern Africa. These rocks dip steeply and are probably synclinal in general attitude, but tightly folded in complex fashion, forming a belt about 45 miles long and 10 miles wide. The schist belt is wholly surrounded by intrusive granitic rocks which show considerable variation in character. The rock immediately ringing the schist belt is chiefly gneissic granite, which also crops out at several localities within the confines of the inlier. In addition, there are smaller stocks of adamellite and monzonite which intrude the metamorphics.

Tyndale-Biscoe distinguishes between what he terms primary structures, such as the boundaries between formations and foliation in the gneissic granite, and secondary structures such as cleavage, fracturing and faulting. The former include movements that are believed to have taken place before complete consolidation of the granitic rocks, while the latter are much younger. There is a decided relationship between the distribution of gold deposits and the primary structures, which suggests the utilization of planes of bedding by mineralizing fluids during their ascent.

The relative abundance of gold deposits in the different rock types appears to have been largely controlled by their competency. Accordingly, serpentinites are devoid of gold deposits, whereas 75 per cent of the gold has been produced from deposits within greenstone and epidiorite. Banded ironstones and granitic rocks account for 11.5 per cent and 6 per cent respectively, and quartz-schist and greywackes for 7.5 per cent.

The intrusive stocks are not particularly favourable areas as regards mineralization. Tyndale-Biscoe explains that this is due to the prolonged erosion which the area has suffered, so that the stocks do not represent the uppermost projections of batholiths so much as deep-seated 'trough cupolas'. In general, broad folds are not favourable sites for mineralization: the best zones of mineralization occur where the rocks dip very steeply. The steeply inclined stratification apparently provided channels for the passage of ore fluids expelled from the deep-seated granite.

The gold deposits may be referred to four main groups, according to their geographical location, and, to a lesser extent, to a community of geological characteristics:

<u>Sabiwa Group</u> This group lies along a highly mineralized zone extending north-west from Gwanda township. The deposits are chiefly arsenical impregnations, and the strike and dip of the ore bodies conform with those of the country rock.

<u>Tuli Group</u> These deposits are in the southern limb of the synclinal structure, and dip northwards. These are again chiefly arsenical impregnations and arsenical quartz reefs.

<u>Central Group</u> Deposits of this group extend eastwards from Gwanda township, and are mostly quartz veins, impregnations being uncommon. The reefs may either cut across the strike of the country, or run parallel to it.

<u>Eastern Group</u> Here the deposits are variable in strike, dip and composition, and include quartz reefs and some impregnation deposits. Tyndale-Biscoe states that "they have no dominating characteristic." The sulphides include many species.

Statistical Data

The production data for all mines which produced gold in the Gwanda area during the years 1933-1948 were studied, and the tons milled and the ounces of both gold and silver recovered by the several methods of treatment recorded for each deposit. Using only the figures for production by amalgamation, the

1000Au/(Au + Ag) values were then calculated in order to gain an indication of the fineness of the gold in each deposit. In the case of the larger producers which made outputs over periods of several years, the total amounts of gold and silver produced annually by amalgamation were used. Where, however, production was small or intermittent, it was in some cases better to break the annual outputs down further into monthly outputs in order to have sufficient separate lots on which to assess the fineness values. Where possible, preference was given to the use of the yearly figures.

Tyndale-Biscoe (p.76) gives the total number of mines which have produced more than 1 ounce of gold as 268. This is 53 less than the number of deposits actually listed by him. The later records show that an additional 44 deposits were brought into production subsequent to the date of his writing. The actual number of ore bodies discovered and tested is thus of the order of 365. Of these, 154 have produced less than 100 ounces of gold in all, and have accordingly been excluded from consideration in the present survey, on the grounds that this amount is not sufficiently representative. Data are presented in Table 1 relating to 150 producers, representing 71 per cent of those deposits whose production has exceeded 100 ounces of gold. For several reasons, fineness values for the remaining 29 per cent could not be determined. Joint declaration of amalgam gold and cyanide gold has in many cases rendered the returns valueless for present purposes, while in others ore from several adjacent deposits was milled at one central plant. Again, many deposits had been exhausted before 1933, which date marks the start of the period covered by the present survey.

The fineness values are given in Table 1, in descending order from highest to lowest. The highest and lowest values obtained for each deposit are given, together with the total number of yearly outputs, or in some cases, monthly outputs, taken into consideration.

Table 1.

Fineness Values of 150 Producers in the Gwanda District.

Name of Producer	Highest Fineness	Lowest Fineness	Number of Outputs
Le Touquet	988	943	10
Mali	985	917	12
March	984	910	11
Emerald Isle	982	861	12
Daisy	977	933	10
Gum	977	969	5
Horseshoe	977	915	25
Lady Anna	977	913	9
Svithoid	977	913	9
Yiv	974	953	9
Zingela	974	954	4
Victor 2	972	927	7
Abe	972	930	7
Cork	971	930	5
Good Hope	971	948	10
Ali	970	919	7
Sinti	970	931	6
Cheque	969	879	4
West	969	960	9
Geduld	968	943	9
Rattle	968	886	12
Annie	967	926	7
Scallywag	967	906	4
Yukon	967	944	4
Minx	966	880	10
Coronet	965	938	8
Gorge	965	861	4
Namara	965	894	6
Only	965	922	15
Borrow	964	952	10
Zonda	964	865	18
Peregrine	963	931	6
Black Snake	962	812	5
Annette	960	896	12
Bunnyruth	960	918	10
Ponkwana	960	938	13
Barts	959	946	3
Betty Watson	959	936	3
Double Crown	959	825	12
Dyke	958	915	5
Chance	957	929	5
Joy 3	957	888	13
Xanthic	957	944	7
K.K.	955	907	14
Ore	955	918	13
Champion	954	904	6
Lady	954	899	3
Wallaby	954	899	5
Mazeppa	952	893	17
Mdala	952	904	13
Bucks Reef	948	879	15
Bikkers Luck	947	938	5
Primus	947	927	5
Doper 2	946	921	5

Name of Producer	Highest Fineness	Lowest Fineness	Number of Outputs
B.E.F.	945	894	5
Baltimore	944	905	10
Tiger	944	922	3
Princess Betty	943	867	5
Riverside	943	908	13
Banshee	942	848	10
Lima	942	877	20
"T"	942	924	4
Mabel IN	941	905	15
Freda	940	936	8
G.G.	940	919	14
None-go-bye	939	836	5
Mary and Alice	938	894	9
Port	937	899	6
Cheerio	936	871	9
Minnies Luck	936	884	23
Rosy Morn	936	906	4
Unreliance	936	903	11
Monaco West	933	906	6
Granite	932	892	8
Horn	932	866	21
Tide	932	886	4
Zephyr	932	894	14
Sabiwa	931	887	17
Bye-and-Bye 2	930	898	8
Chaka	930	891	4
Venus	930	914	9
Big Ben	929	921	5
Geelong D	929	868	3
King John 2	929	921	3
Boulder	928	856	7
Cobra	928	862	3
Farvic	927	883	13
Kameel	927	864	14
Kohler	927	914	3
Dans Luck	926	891	15
Rolls Royce	925	901	14
Act	924	897	10
Jonnie	924	879	17
Maluti	924	883	11
Prince Olaf	923	900	31
Winjon	923	865	4
Sphere	922	913	4
Drift	921	881	5
Jethro	921	909	13
Long John	920	882	25
Joy	919	888	7
Smiler	919	815	6
Geelong	918	899	7
Assam	917	876	4
Bushy Park	917	895	12
Msasa	916	872	3
Longhurst	915	902	9
Redwick	915	899	3
Lady Lina	913	850	17
Faith	912	876	7
Blanket A	911	901	10

Name of Producer	Highest Fineness	Lowest Fineness	Number of Outputs
Prince	909	863	11
Val	909	872	11
I.D.T.	908	862	9
Scraam Boom	908	828	4
Abercorn	905	892	7
Great Abercorn	904	847	8
Ettrick	903	879	5
Blanket	901	896	4
Cleveland	901	876	8
Imani	901	876	3
Jean C	899	868	11
Riverbank	899	878	6
Golduck	898	794	14
Lone Hand	897	882	6
Sally	897	841	19
Scaynes Hill	897	826	3
Standard	892	864	19
Tuli	891	775	10
Bena	883	840	14
Gift	880	858	6
Penzance	880	873	9
Bunny's Luck	879	829	8
Galatea	878	846	8
Yadkin	874	843	7
Caberfeidh	864	820	6
Coatbridge	863	800	4
Black Mamba	862	770	9
Auric	860	809	3
Bassick	859	838	7
Nicholson	859	802	27
Mogul	840	699	13
Queen of Sheba A	839	607	3
Jessie	819	600	7
Pats	818	814	3
New Jess	813	463	6
Valley	797	685	20
Thorleen	765	717	9
L. and J.	755	503	7
London Wall	638	244	5

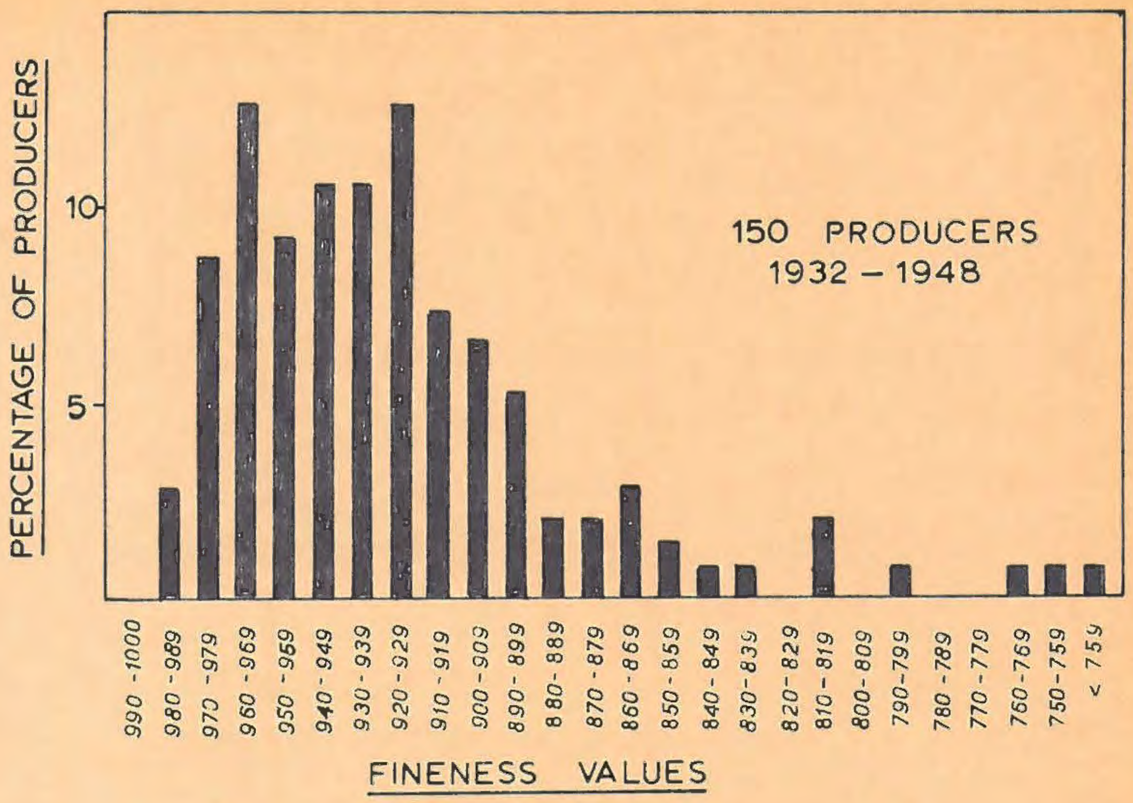


Fig. 1-A

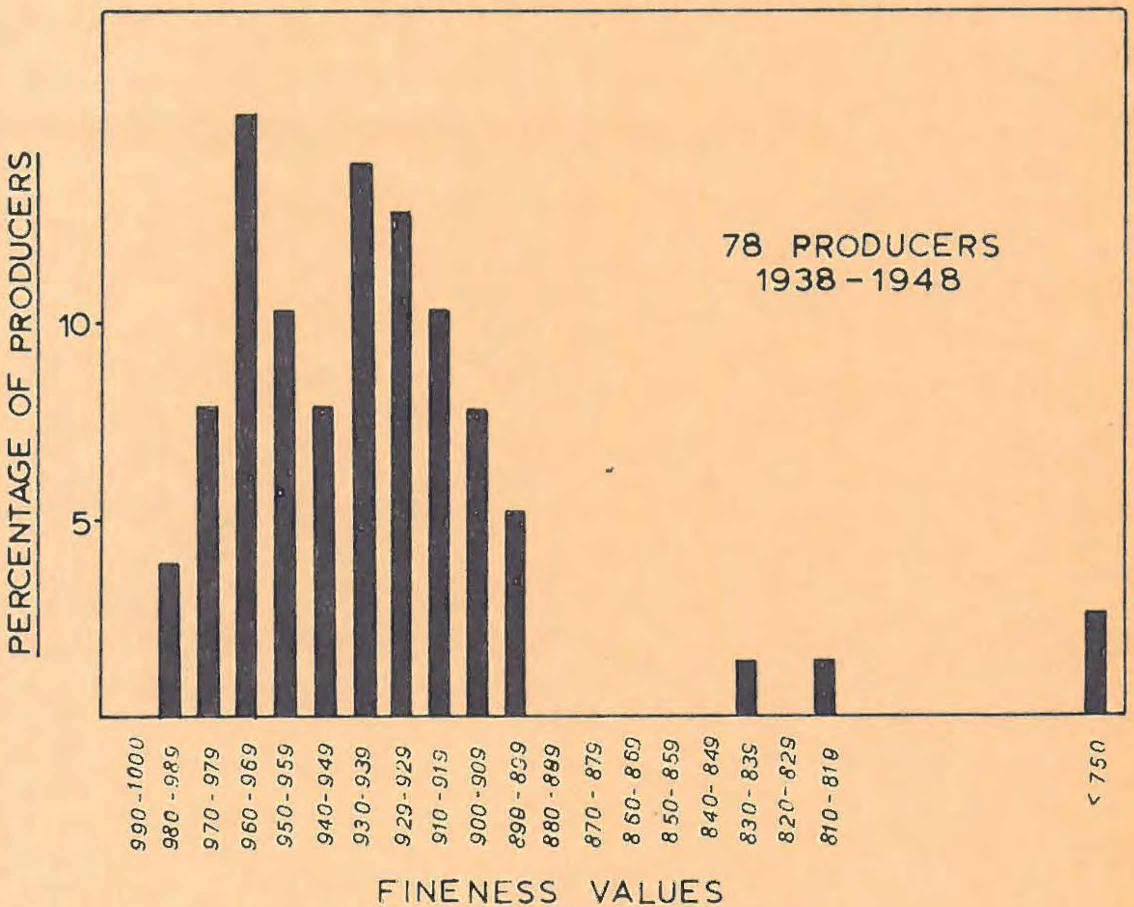


Fig. 1-B

FREQUENCY OF OCCURRENCE OF FINENESS VALUES FOR DEPOSITS IN THE GWANDA GOLD BELT.

Fig. 1-A is based on the data of Table 1, and shows in graphical form the frequency of occurrence of different fineness values. The significant figure for each deposit has been taken as the highest fineness value recorded in each case. This procedure is fully justified in a later section, where it is shown that, for many deposits, there is a characteristic maximum fineness value. An added advantage is that this also guards against the accidental incorporation of additional silver due to decomposition of silver sulphides. The chief source of inaccuracy in the data is likely to be the effect of supergene refining of gold, a factor whose potency it is impossible to estimate.

For purposes of comparison, the range in fineness values shown by the smaller number of producers in operation during the shorter period 1938-1948 is illustrated in Fig. 1-B. The differences between Fig. 1-A and Fig. 1-B are slight, even although the first represents nearly twice the number of producers. This suggests that the data are in fact truly characteristic of the area, and not unduly influenced by extraneous factors which have not been taken into account.

Interpretation of Data

From Table 1 it is clear that the average fineness of gold produced in the Gwanda area is high. 81 per cent of the deposits yield gold above 900 fine, while in 95 per cent this value is above 850. Only a very small proportion, 2.6 per cent of the total number of producers, yield gold of exceptional purity, which is above 980 fine. As a first conclusion, it can be said that the Gwanda area is in line with other areas yielding gold of deep-seated origin, in that the gold is of high fineness (see Fisher, 1945).

It is significant that in Table 1, which is based on close upon 1,400 separate calculations of fineness values, there are only two outputs in which the amount of silver in the amalgam bullion exceeds the amount of gold. These two outputs stem from two deposits in which fineness is in any event low. These facts suggest that silver, either native, or as sulphides, is not present in more than small amounts in the Gwanda deposits. If silver were more widespread in occurrence, it would be expected that more than an insignificant proportion of outputs would show fineness values below 500. Fisher (1945) has stated that fineness values below 450 indicate that additional silver has been incorporated with the bullion, for in nature a fineness of 450 appears to be the lower possible limit. By this criterion, silver might be present in only one or two deposits in the area.

It is further brought out in Table 1 that fineness in any particular deposit is seldom a rigidly characteristic figure, and that variations of 100 parts per thousand are by no means uncommon. These variations appear in both annual and monthly outputs, and are seldom regular or predictable.

In Fig. 2 (at end) the producers in the Gwanda area have been located on a simplified geological map adapted from that of Tyndale-Biscoe (loc. cit.). A colour code enables the range in fineness values within each group to be read without difficulty. Several conclusions may be drawn from a study of the figure. It is clear that there is no zonal arrangement of deposits showing different degrees of fineness, although there is a general increase in the number of deposits with low fineness values, in an easterly direction. There is no relationship between the fineness and the distance of deposits from the granite contacts. For example, the deposits of the Tuli group, which lie close to the granite contact, are mostly characterized by gold of high fineness, whereas those of the Eastern group, which may lie equally close to granite, are generally of lower fineness. Finally, it is clear that the nature of the host rock has not influenced the fineness of the gold. Gold of high or low quality may occur in each of the several rock types.

These conclusions, although negative in character, are nevertheless of considerable value, in that certain factors can apparently be excluded from consideration in this study. The fundamental causes of the variations must be sought elsewhere.

The Four Groups of Deposits

The frequency of occurrence of different fineness values in the four groups of deposits is represented in Fig. 3. Each group shows different characteristics, but in the Sabiwa and Tuli groups the gold fineness varies less widely than in the other two. The greatest range is found in the Eastern group. There is a suggestion that the Central group contains deposits of two distinct types, one of which may be identified with the mineralization more characteristic of the Eastern group. It is not inconceivable that two slightly different phases of mineralization are represented here.

It is significant that a tentative correlation may be drawn between the degree of variation in fineness, and the diversity of mineral species in each group. It was quoted earlier that the Sabiwa and Tuli groups are characterized by arsenical impregnations, whereas the Central group shows greater variety. The Eastern group is a heterogeneous assemblage in which the quartz reefs display a variety of minerals. It may be concluded from these broad considerations that a search for a relationship between fineness and the type of mineralization offers the most promising field for further study.

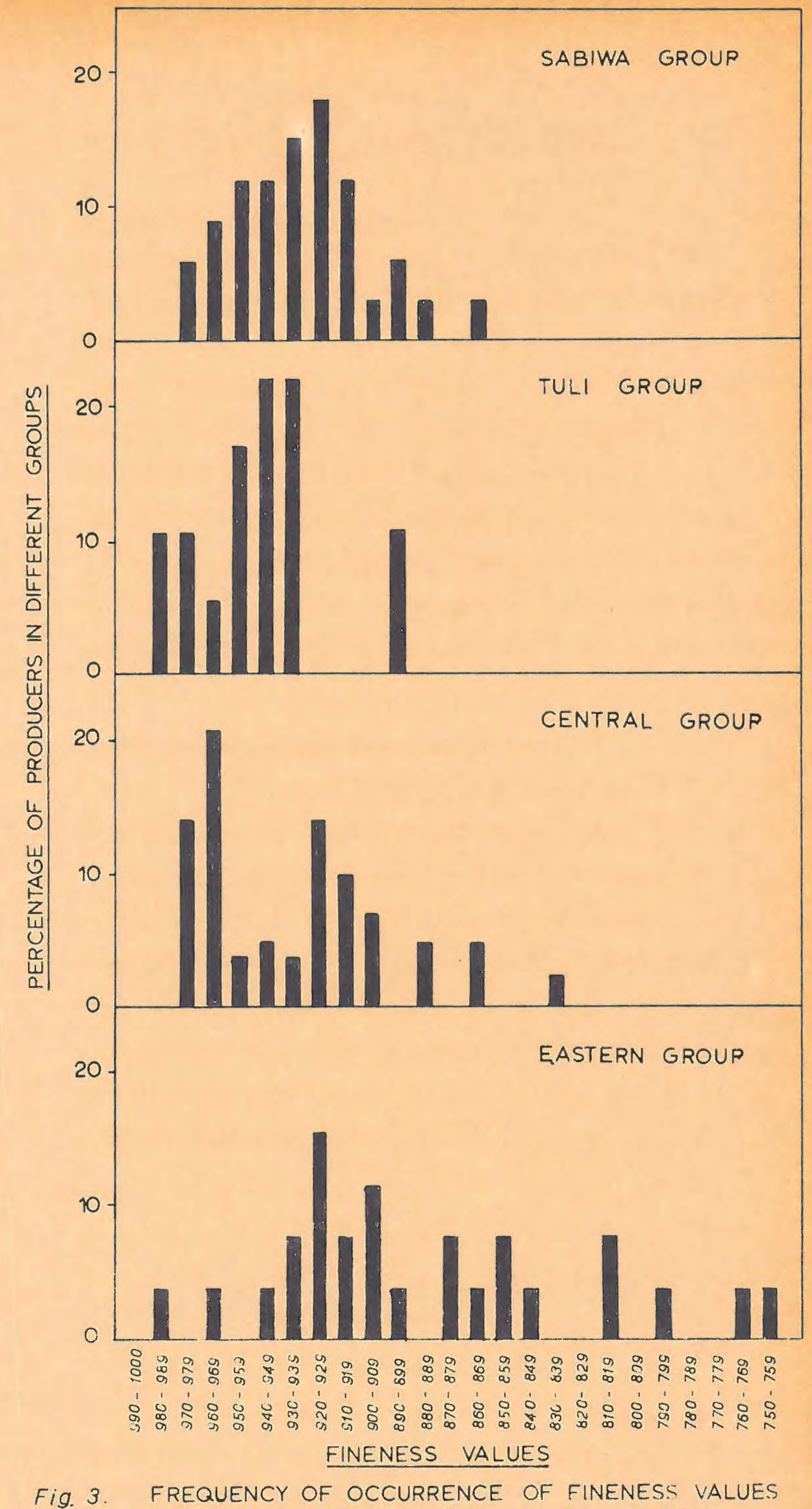


Fig. 3. FREQUENCY OF OCCURRENCE OF FINENESS VALUES FOR DEPOSITS IN THE MAIN GROUPS, GWANDA GOLD BELT.

CHAPTER IV.

VARIATIONS OF FINENESS IN SOME TYPICAL DEPOSITS

Introduction

In this section the variations of fineness and apparent fineness in some typical Southern Rhodesian deposits are described. Special emphasis is laid on those features, such as the fluctuations in the grade of the ore bodies, and the association of gold with different ore minerals, which appear to be related to the changes in the silver content of the gold particles.

In some of the deposits the mineralogy of the associated ore minerals has been investigated more fully than in others, but, throughout, the occurrence of the gold itself has received most attention. In particular, the textural relationships between gold and the other ore minerals have provoked close study. Details regarding the structure of the ore bodies have been summarily dealt with, as there are no indications that these are of importance in the present study, except in an indirect way.

The deposits which are described were not singled out for special study in the hope that they would lend support to any preconceived ideas. They represent, rather, deposits with which the author happened to become familiar during the course of field work, or which showed promise of yielding interesting information. The Lonely mine, which the writer has not examined underground, as it was closed many years ago, was included because sufficient statistical data were available to make the study worthwhile, and because earlier referances had specifically called attention to the changes in gold fineness. The mines discussed here represent, then, a random sample.

At the end of the section which deals with the case histories of local deposits, brief reference is made to other investigations carried out in other mining fields, in which the findings are of special interest.

The work described here constitutes the 'backbone' of this research project, and the disproportionate length of this chapter may perhaps be condoned on these grounds. Abstracts which outline the salient features of each deposit are given for the convenience of the reader who does not wish to follow the course of each separate examination.

A. THE OLYMPUS MINE

Abstract.

The variations in the fineness of the gold are studied in some detail. From the production data it is clear that the fineness of the gold in the two main ore shoots is different, and also that an increase in fineness in each shoot can be correlated with an increase in the average grade of the ore. Experimental sampling carried out underground confirms this conclusion. The study of polished sections reveals that even in small specimens of ore the silver content of gold grains varies widely, and that the gold which precipitated at an early stage contains more silver than that which precipitated late. This late gold, which may be intergrown with tellurides, or which occurs as discrete particles, may contain very little silver. The variations in grain size of gold grains are described.

Introduction

The Olympus Mine is located 25 miles from Mtoko in the north-east corner of Southern Rhodesia. The deposit was first explored and developed in modern times at the beginning of this century, but extensive shallow workings show that it had been discovered and worked at some much earlier date by the unknown people usually referred to as the 'ancients'.

A brief description of the mine appears in Macgregor's account of the geology of the district (Macgregor, 1935), and its location is shown on the geological map accompanying the report. In 1956 the writer spent one week mapping and sampling the underground workings, and the account which follows is based on this work. Shortly after the examination of the mine had been completed, the mine was closed down.

Brief Outline of the Geology

Two ore shoots, termed respectively the Olympus and Old Umbrella Shoots, are located about 700 feet apart in a long zone of shearing and mineralization extending in the Basement rocks for several thousands of feet north-west of the Siram claims. The average strike-lengths of these shoots are, however, only 350 feet and 500 feet respectively. In detail, bifurcation of the zone of shearing is common, the main mineralized zone sending off tongues into the country rock, while in the Umbrella section the strike swings to northerly for a distance of 200 feet where the mineralization follows a well-defined shear trending obliquely to the general strike. Dips vary between 50 and 70 degrees to the south-west, the average being close to 65 degrees. The country rock is a Primitive lava showing excellent pillow structures. In the Olympus section a medium-grained, acid dike trends parallel to the shear zone and locally constitutes the country rock, while in the Umbrella section an intrusion of quartz porphyry, older than the ore, is found on all levels. Several basic dikes are also found in the workings. The minor intrusions appear to have been intruded at some stage between the initiation and cessation of shearing, but appear to be older than the ore, and it is worth noting that the better-mineralized sections of the shear zone are contained within or lie close to the acid intrusions, suggesting some form of control of ore deposition.

The shear zone pinches and swells from a few inches to several feet in width, and within it mineralization takes the form of coarse-grained chalcopyrite, pyrrhotite and less abundant pyrite in a very hard, brittle and generally fine-grained vein quartz. Macgregor noted that mispickel was found in the unoxidized ore within 100 feet of the surface, but this mineral has not been observed in depth by the writer. The richest sections of the reef show a core, two to three feet in width, of coarse sulphides and quartz, within the zone of shearing. Away from the ore shoots, the core shrinks to a thin, discontinuous quartz stringer with a very erratic gold content. In a few sections of the workings sulphides occur disseminated throughout the shear zone and extend into the weakly sheared walls, giving abnormal widths of ore in excess of eight feet.

The gold occurs chiefly in the quartz-sulphide core.

Assay values are erratic, ranging from less than a pennyweight to nine ounces per ton. Values in the sheared rock enclosing the quartz core seldom exceed 2 dwt. gold per ton.

The two shoots have yielded slightly less than 100,000 tons of ore from which an average of 3.9 dwt. gold per ton of ore has been recovered. The average value of the mill residues is close to 1.2 dwt./ton, indicating that the average tenor of the ore is 5.1 dwt./ton. Copper has also been produced as a by-product.

At the time of the writer's visit development had reached the 6th level. The samples on which the laboratory work was conducted were taken from the 5th level at approximately 320 feet, on the incline, from surface. At this level the ore is hard and unoxidized, and supergene effects are not seen.

Analysis of Mine Records

Detailed records are available only for the period January 1954 - July 1956. Prior to this, no detailed records were kept, and the mine closed down in the latter half of 1956.

The gold was recovered by amalgamation and flotation. Approximately 50 per cent was recovered by barrel amalgamation of a first-cut strake concentrate, and the remainder in a flotation concentrate rich in chalcopyrite. The latter concentrate was sold without further treatment on the property. The total recovery was on the average rather less than 80 per cent of the total gold in the ore.

The relevant statistics abstracted from the detailed mine records are shown in Table 2. In this, Column 1 gives the value 1000Au/(Au + Ag) (i.e. true fineness of gold) calculated from the analyses of the gold recovered from both shoots by amalgamation. Column 2 gives the estimated monthly grade of ore milled, in dwt./ton; this is based on the sum of the total recovery from both shoots plus the content of gold in the mill residues. In Column 3 is given the percentage of gold contributed by the Olympus shoot, and in Column 4 the estimate of the average grade of ore from that shoot, a value based on sampling. Columns 5 and 6 give similar data for the Umbrella shoot. These latter figures were obtained by calculation based on the detailed underground records, which show for each month the tonnage and estimated grade of ore yielded by each section of the workings.

TABLE 2

Olympus Mine Production Data

Column:-	1.	2.	3.	4.	5.	6.
Period	Average		Olympus Shoot		Umbrella Shoot	
	Fineness	Grade dwt./ton	Per cent of gold	Grade dwt./ton	Per cent of gold	Grade dwt./ton
1954 Jan	861	5.3	97	5.2	3	n.d.
Feb.	875	3.9	96	4.8	4	n.d.
Mar.	872	5.9	96	5.1	4	n.d.
Apr.	874	5.5	100	5.5	0	n.d.
May	868	5.2	88	5.9	12	n.d.
Jun.	860	6.1	92	5.4	8	n.d.
Jul.	860	4.5	89	5.2	11	n.d.
Aug.	856	4.9	91	5.2	9	n.d.
Sep.	863	5.2	96	5.1	4	n.d.
Oct.	855	4.9	77	5.0	23	n.d.
Nov.	839	5.0	79	4.9	21	n.d.
Dec.	843	4.8	70	5.0	30	n.d.
1955 Jan.	850	4.7	77	4.8	23	n.d.
Feb.	837	4.8	65	5.4	35	4.8
Mar.	837	5.4	33	n.d.	67	5.7
Apr.	809	6.4	7	n.d.	93	5.7
May	821	5.9	12	n.d.	88	6.1
Jun.	816	6.2	11	n.d.	89	7.0
Jul.	826	6.2	12	n.d.	88	7.3
Aug.	784	6.9	17	n.d.	83	4.9
Sep.	787	6.1	6	n.d.	94	5.2
Oct.	801	5.3	6	n.d.	94	5.1
Nov.	810	3.7	4	n.d.	96	5.0
Dec.	818	4.0	33	n.d.	67	5.5
1956 Jan.	827	3.7	25	n.d.	75	6.0
Feb.	832	5.3	n.d	n.d.	n.d	n.d.
Mar.	841	5.3	18	n.d.	82	5.8
Apr.	823	5.5	9	n.d.	91	5.7
May	789	4.0	20	n.d.	80	4.8
Jun.	787	5.3	10	n.d.	90	4.9

The data in Table 2 have been used in the construction of Fig. 4, where the fineness of the amalgam bullion has been plotted against the proportion of gold contributed by the Olympus shoot in successive months. This proportion ranges

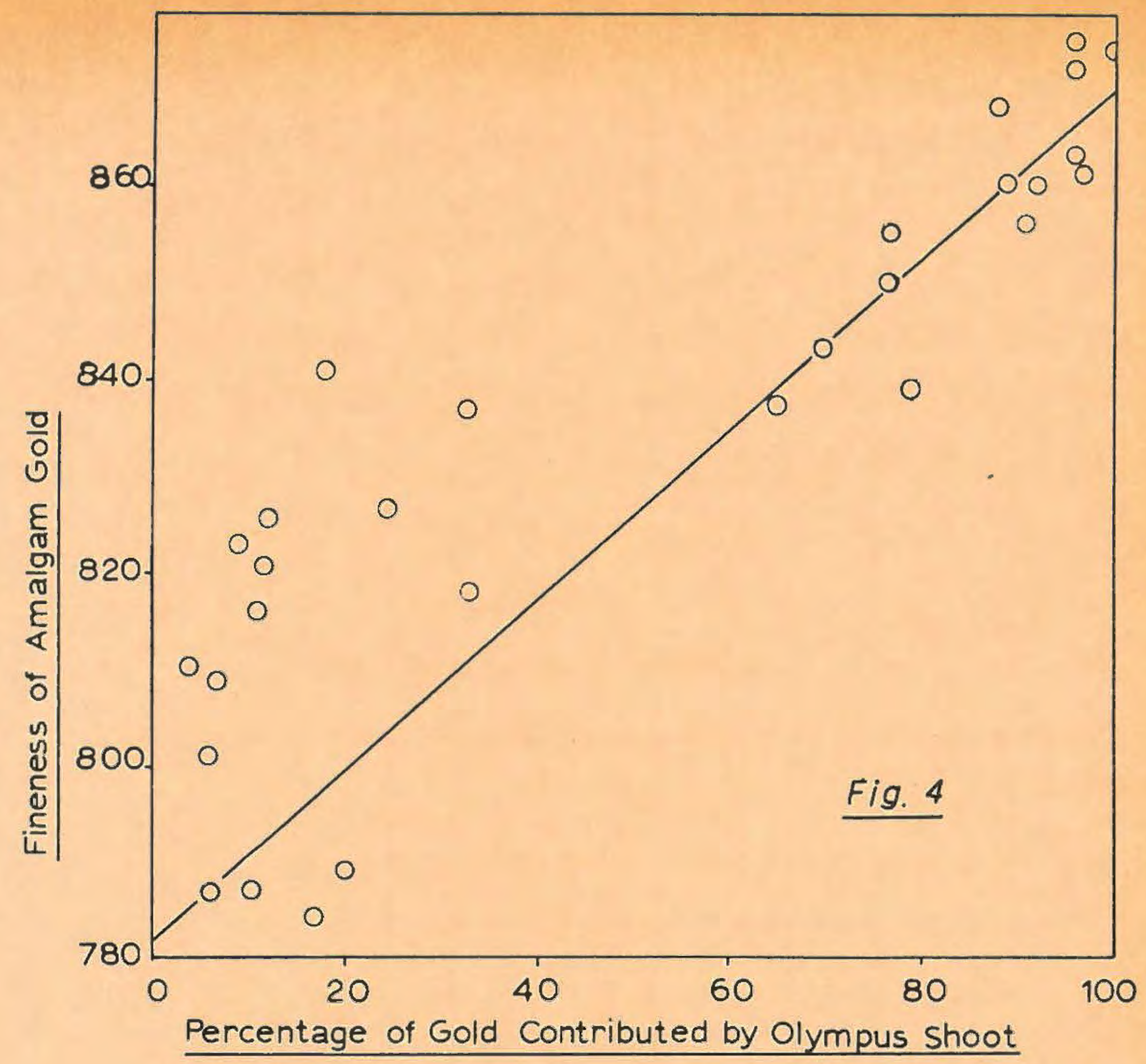

Fineness of Amalgam Gold
860
840
820
800
780
0
20
40
60
80
100
Percentage of Gold Contributed by Olympus Shoot

Fig. 4

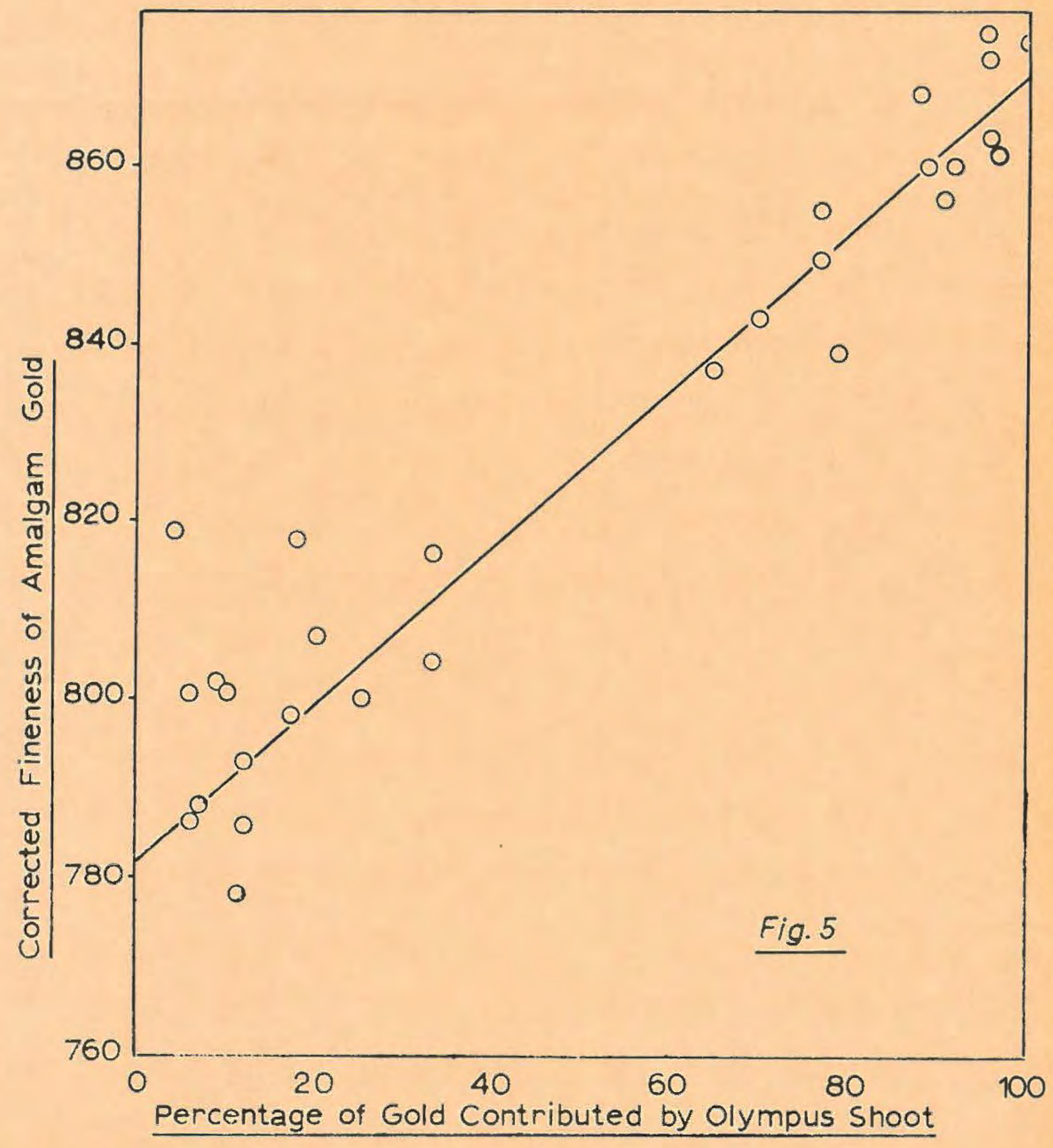

Corrected Fineness of Amalgam Gold
860
840
820
800
780
760
0
20
40
60
80
100
Percentage of Gold Contributed by Olympus Shoot

Fig. 5

from 4 to 100 per cent, and the fineness varies from 784 to 877. It is clear from the figure that as the proportion of gold contributed by the Olympus shoot increases, the average fineness increases. This rule is most closely adhered to when the proportion of gold contributed by the Umbrella shoot is small: when the proportion of Umbrella shoot gold exceeds 50 per cent the plotted points are more scattered.

Closer examination of Fig. 4 reveals further interesting data. Where more than 60 per cent of the gold is yielded by the Olympus shoot (upper-right sector of diagram) the plotted points lie, within acceptable limits of error, close to the mean straight line. Considering the difficulties encountered in compiling accurate underground records, closer correspondence than this is not to be expected. The average tenor of ore in this shoot was 5.2 dwt./ton, and the maximum variation from 4.8 to 5.9 dwt./ton. In the Umbrella shoot, however, the average grade of ore varied more widely, from 4.8 to 7.3 dwt./ton, and inspection reveals (lower-left sector of diagram) that where the average grade of ore from that shoot was in any month particularly high, the average fineness of the gold recovered was also high, and the corresponding plotted points lie well above the projected straight line. Similarly, points which lie close to the projected straight line represent months during which the average grade of ore from the Umbrella shoot was close to 5.2 dwt./ton. The average grade of Umbrella shoot ore for the nine monthly outputs which, when plotted as above, lie furthest from the projected mean straight line, is 6.1 dwt./ton. The remaining six, which lie closest to the straight line, average close on 5.2 dwt./ton. There are, however, two months during which the average fineness was particularly high, although the average grade was not correspondingly high; these do not conform to the general rule, and other factors might have been responsible for the discrepancy.

Making use of these facts, it is possible to apply an empirical correction to those points lying in the lower-left sector of Fig. 4, so that nearly all come to lie, within reasonable limits of error, along a straight line. Inspection shows that an increase of 1 dwt./ton over the average grade of 5.2 dwt./ton is marked by an increase in the gold fineness by about 30 - 35 parts per thousand. Allowance can then be made for this factor by either adding or subtracting from the average fineness, as the case demands, the value $30 + (\log \overline{5.2 \backsim X}).30$, where 'X' is the grade of the Umbrella shoot ore for any particular month, and provided that $5.2 \backsim X$ is not less than 0.1. Corrected values are given in Table 3. Replotting of the data, as in Fig. 5, shows that all points, excepting those two previously mentioned, now lie approximately along a straight line. No particular significance is attached to the formula suggested above, except that it illustrates that variations in gold fineness can be correlated with variations in grade.

Table 3.

Fineness Values Corrected for Variations in Grade.

Period	Average Fineness	Grade of Umbrella Shoot ore dwt./ton	Correction	Corrected Fineness	Per cent of Total Gold
1955 Mar.	837	5.7	-21	816	67
Apr.	809	5.7	-21	788	93
May	821	6.1	-28	793	88
Jun.	816	7.0	-38	778	89
Jul.	826	7.3	-40	786	88
Aug.	784	4.9	14	798	83
Sep.	787	5.2	0	787	94
Oct.	801	5.1	0	801	94
Nov.	810	5.0	9	819	96
Dec.	818	5.5	-14	804	67
1956 Jan.	827	6.0	-27	800	75
Feb.	832	n.d.			
Mar.	841	5.8	-23	818	82
Apr.	823	5.7	-21	802	91
May	789	4.8	18	807	80
Jun.	787	4.9	14	801	90

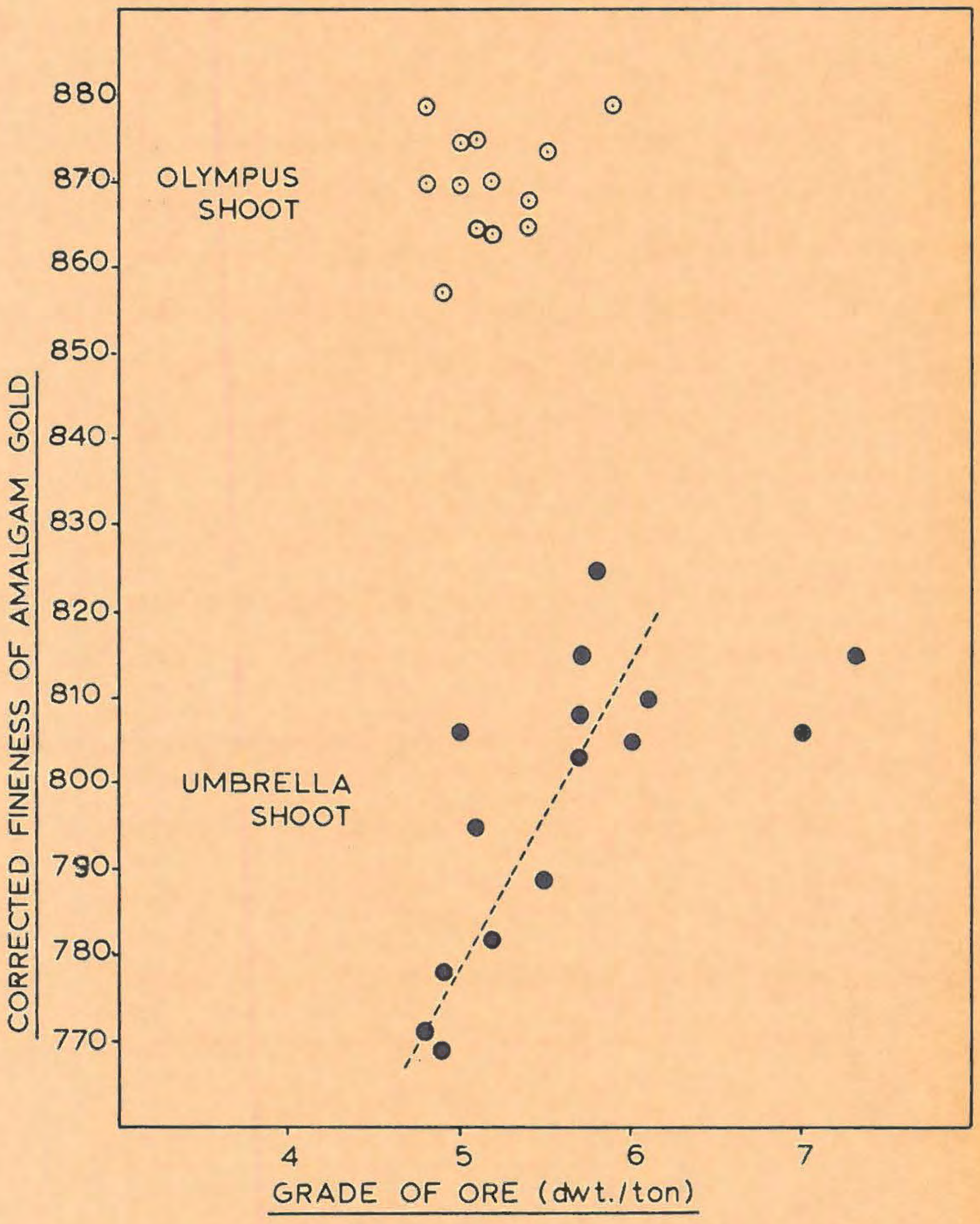


Fig. 6 Relationship between fineness of gold and grade of ore in Olympus and Umbrella Shoots.

The data of Table 2 may be used, as in Fig. 6, to demonstrate in another way that there is a relationship between fineness and tenor, although it is by no means exact. In order to minimi~~s~~ze the effect, on the composition of the gold, of mixing ore from the two shoots during milling, each plotted point in Fig. 4 was projected parallel to the mean straight line to the ordinates representing either pure Olympus shoot or pure Umbrella shoot ore, and its corrected fineness read off. These corrected fineness values were then plotted against the grade of the ore yielded by that shoot for each month, as in Fig. 6. It is seen that there is a tendency for points representing Umbrella shoot ore to be aligned along a curve, but in the case of the Olympus shoot, where the average grade varied by only small amounts, the relationship is more obscure. The slope of the curve for the Umbrella shoot indicates that, for an increase of 1 dwt./ton, the average fineness increases by about 35 parts per thousand. In the study of several other deposits a similar tendency has been observed: where the grade varies widely the relationship between it and the fineness is clearest, but where the variations are small other factors assume greater importance.

Experimental Sampling Data

The examination of the results of assay determinations carried out on samples collected at the mine by the writer leads to the same conclusions as analysis of the mine records.

Channel samples taken across the ore body on the 5th level of the Olympus and Umbrella sections were assayed for gold in the normal way. Each sample, several pounds in weight, was then passed through a mechanical pulveri~~s~~zer and carefully panned to a smaller bulk. This heavy concentrate was then assayed for both gold and silver, and finally the value 1000 Au/(Au + Ag) calculated. This latter figure is the 'apparent fineness' as earlier defined, and is not necessarily the same as true fineness, unless gold and silver occur in the ore in no form other than that of the natural alloy. The data are summarized in Table 4, and in Figs. 7 and 8 the assay values of the samples before panning have been plotted against the apparent fineness values.

The data are admittedly scanty, but sufficient to indicate quite clearly that apparent fineness varies sympathetically with tenor. In common with diagrams of this type for other deposits, most of the plotted points lie close to a curve with a positive slope, while those remaining lie scattered above it. None, within tolerable limits of error, lie below it. So characteristic is this disposition of plotted points in this type of diagram, as will be shown in the succeeding text, that, apart from indicating the general correlation between fineness and tenor, it also shows that high fineness may not uncommonly be associated with low-intensity metallization, while richer metallization is seldom characterized by gold of low fineness.

Special attention is directed to a further aspect brought to light in Table 4. Samples taken at intervals of only a few feet show apparent fineness variations as great as those between samples 50 feet apart. There is no serial change along strike, and the exact location of the sample is of little assistance in the determination of which factors influence variations in fineness.

Table 4

Assays and Apparent Fineness Values of Samples from Olympus and Umbrella Shoots.

Olympus Shoot

Sample Location	Sample Assay (dwt./ton)	Conc. Assay (dwt./ton)		Value $\frac{1000\ Au}{(Au + Ag)}$
		Gold	Silver	
P + 0 ft.	23.6	984.6	200.9	830.5
5 "	20.6	150.0	21.8	854.6
20 "	17.8	525.6	178.1	746.9
25 "	24.2	269.5	60.0	817.9
40 "	24.2	181.5	36.5	832.5
60 "	44.6	9061.7	710.6	927.2
75 "	31.0	413.5	69.6	855.9
90 "	4.3	105.1	46.7	692.3
100 "	5.4	476.0	110.9	811.0
115 "	3.4	70.8	34.3	673.6
125 "	3.0	104.0	30.3	774.3
135 "	9.2	343.4	60.7	849.7
145 "	9.6	470.8	35.1	930.6

Umbrella Shoot

S + 0 ft.	10.7	76.4	28.2	730.4
5 "	6.1	98.3	26.4	787.0
10 "	4.8	50.6	38.0	571.1
20 "	2.8	33.9	22.2	604.2
25 "	5.7	172.9	121.4	587.4
30 "	19.6	258.6	58.4	815.7
30 "	10.7	189.5	80.2	702.6
50 "	4.9	168.7	180.3	483.3
55 "	5.2	28.6	10.3	735.2
T + 3 ft.	1.8	15.4	13.4	534.7
13 "	1.7	93.4	50.7	648.1
18 "	5.4	48.7	38.9	555.9
28 "	5.7	49.4	43.0	534.6
38 "	7.0	122.6	52.6	699.7
43 "	11.2	86.6	36.0	706.3

While Figs. 7 and 8 are essentially similar in general features, the details in which they differ are of interest. The mine records show that the true fineness of the Olympus shoot gold is higher than that of Umbrella gold; experimental sampling shows that the same is true for apparent fineness, although the differences are exaggerated. It will

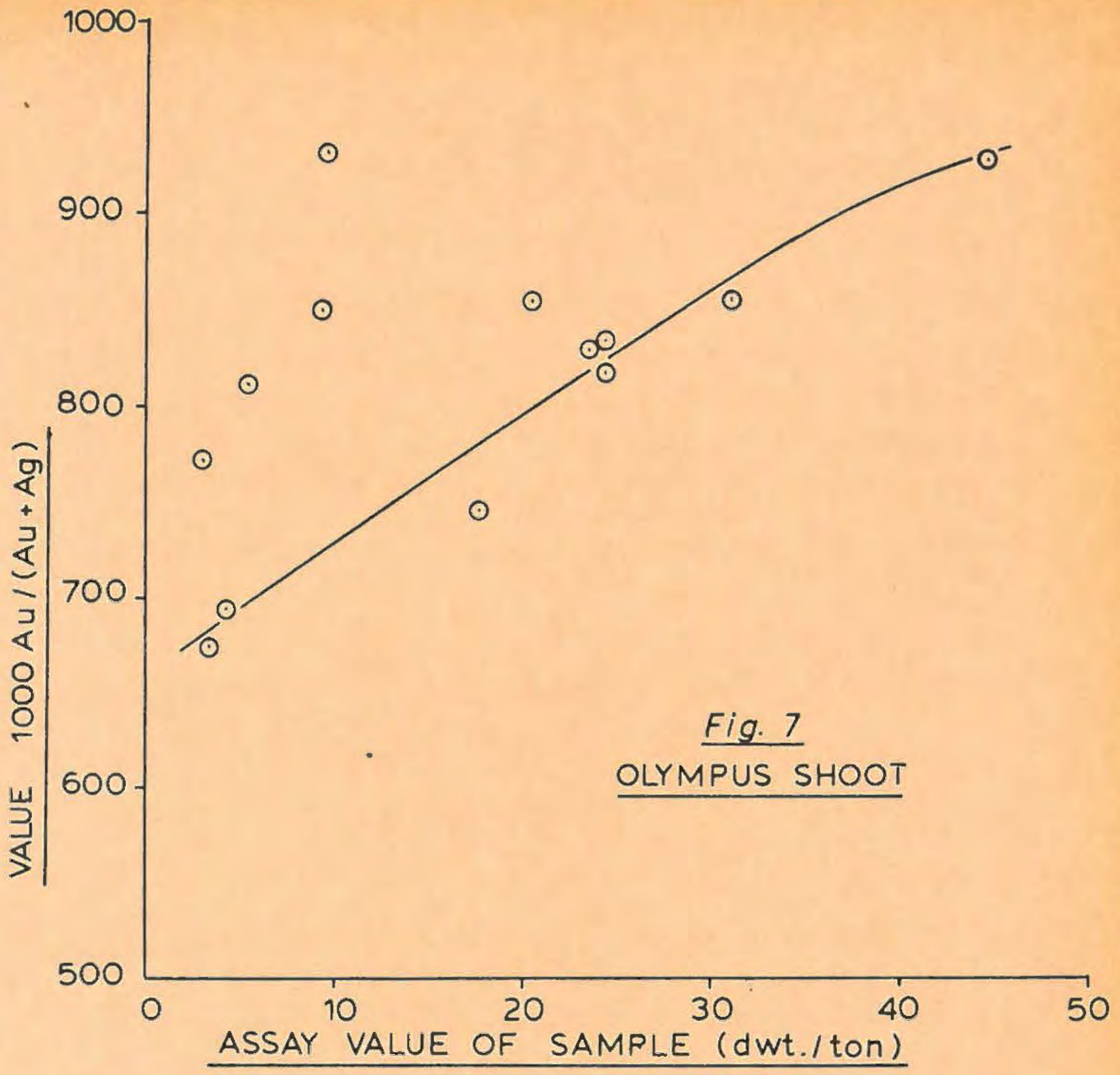


Fig. 7
OLYMPUS SHOOT

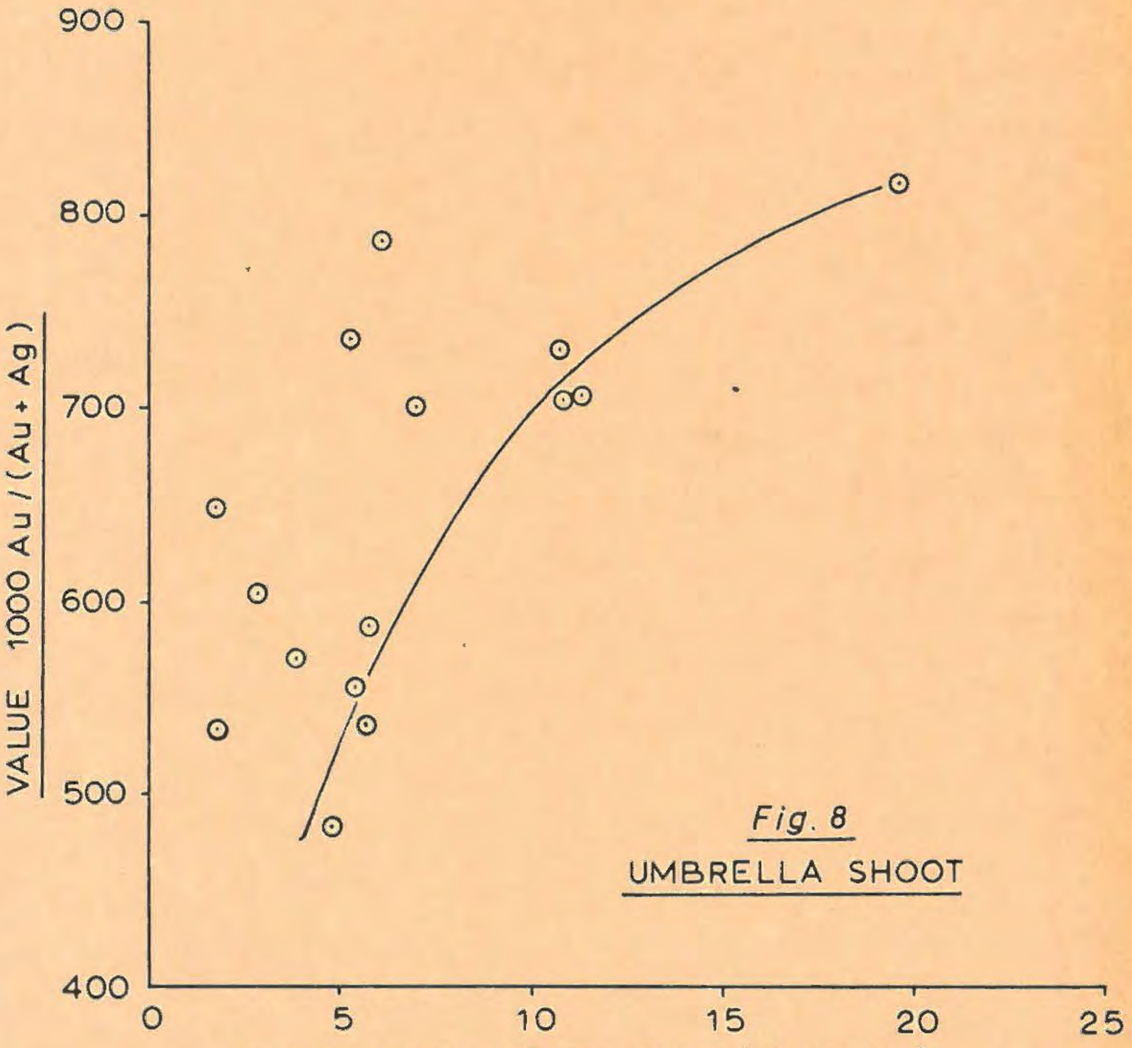


Fig. 8
UMBRELLA SHOOT

also be noted that the slope of the curve for the Olympus shoot is less steep than that for the Umbrella shoot. That is, as the average fineness decreases, the change in fineness concomitant with change in grade becomes very much more marked, and the curve tends towards vertical as it approaches the origin. This feature is again common to diagrams of this type depicting numerous other deposits. It may be concluded that where the fineness is low, the fineness-tenor relationship is more obvious than when it is high.

Finally, it will be noted that the variations in apparent fineness for each shoot are very much greater than the monthly outputs would indicate. For example, the variation in apparent fineness in the Olympus shoot is 250 parts per thousand, whereas it is only 40 parts per thousand in terms of true fineness. This can partly be explained by an inevitable 'averaging-out' which takes place during the recovery of a monthly output; small samples are understandably more likely to show the maximum variation. Justification for this conclusion appears in the succeeding section devoted to the mineralogy of the ore, where it is proved that the purity of the gold may be different in grains even less than 1 mm apart.

The Evidence of Polished Sections

Although the mineralogy of the ore is relatively simple, a number of interesting aspects emerge. In particular, the microscope has been an indispensable tool in studying the variations in the character and occurrence of the gold. The degree of oxidation of the specimens is seen to be negligible, and supergene processes have left no imprint on them. This latter fact is of importance in that the correlation between tenor and fineness is shown to be of hypogene origin.

(a) Mineralogy and Mineragraphy

Pyrite appears to have been the first sulphide to crystallize, and is found as rounded or irregular grains largely replaced by younger pyrrhotite and chalcopyrite. *Pyrrhotite* is abundant, being the most common sulphide in the ore, and ranges in size from microscopic grains to masses several centimetres across, which are seen, between crossed nicols, to be a mosaic of smaller grains. The anisotropism, reaction with etch reagents and colour appear to be normal.

Chalcopyrite, although less abundant than pyrrhotite, is found in all specimens, and favours the interstices between pyrrhotite crystals, or occurs abundantly as discrete crystals wholly surrounded by quartz. It has replaced the pyrrhotite in places, particularly along grain contacts, and may then show the convex surfaces typical of caries texture. Intergrown with the chalcopyrite is *cubanite* ($CuFe_2S_3$) which is rather more pink in colour, moderately anisotropic, and unreactive towards the standard etch reagents. The cubanite is easily distinguished from pyrrhotite in that it shows hardly any relief against chalcopyrite, whereas pyrrhotite is perceptibly harder. Cubanite is also more brittle than chalcopyrite, and requires more prolonged polishing to remove all pits. The cubanite characteristically occurs as thin plates or lamellae which reach a maximum thickness of perhaps 200 microns, but are more commonly close to 10 microns thick. The lamellae are perfectly straight, and their length may be up to 200 times greater than their width. These occur in great profusion in the chalcopyrite, lying exactly parallel in any one host grain, in which they may extend from margin to margin with unchanging width, or taper towards the edges (Plate I). The proportion of chalcopyrite to cubanite varies greatly, and either may locally be dominant, although the latter is usually quite subordinate. Rare instances show areas of cubanite, without chalcopyrite lamellae, moulded on pyrrhotite, and grading through a zone of alternating lamellae to chalcopyrite without cubanite lamellae. Apart from a possible slight preference for the cores of

Plate I.

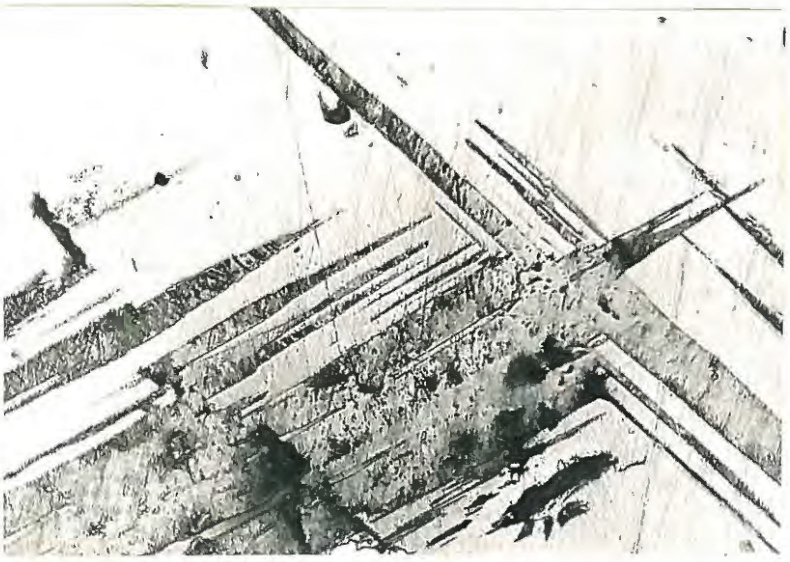


Fig.1. Intersecting exsolution lamellae of cubanite (dark) in chalcopyrite (lighter). Etched with dilute HCl/CrO_3. x 360.

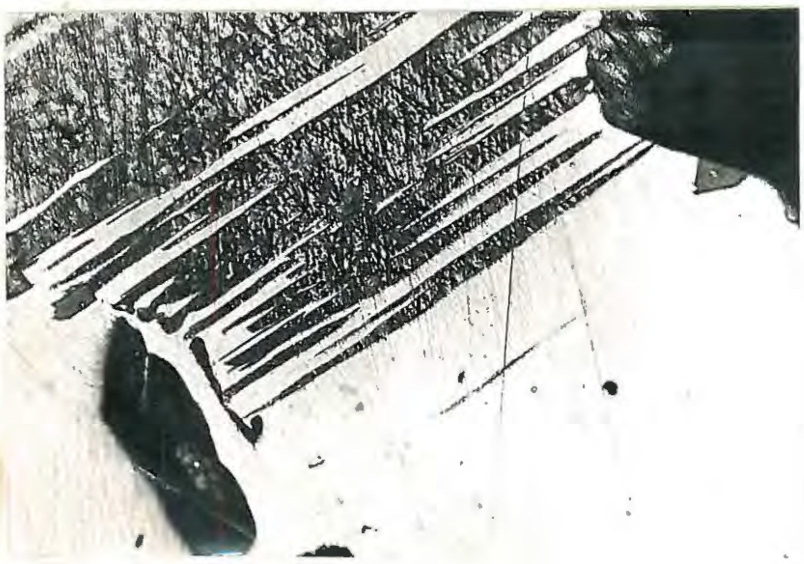


Fig.2. Transition from cubanite (dark) to chalcopyrite (light) with intermediate zone in which the two minerals occur as alternating lamellae. Note tapering of exsolution lamellae towards margins of crystal. Etched with dilute HCl/CrO_3. x 360.

chalcopyrite crystals, isolated cubanite lamellae may occur in any part of the host crystal. There is no tendency for it to migrate along crystal boundaries, and the cubanite is clearly an example of exsolution. No minerals having the properties of valleriite or chalcopyrrhotite were found.

A younger generation of <u>pyrrhotite</u> is present, and it is believed that **this** is due to exsolution. This occurs only in intimate association with chalcopyrite, as spindle-shaped inclusions which do not appear to exceed 10 microns in width (Plate II, Fig. 1). Although at best it is an exceedingly rare constituent of the ore, it is most likely to be found where exsolved cubanite lamellae are abundant: here the pyrrhotite spindles lie parallel to the cubanite lamellae, although they do not show perfectly straight margins as the latter do. In such areas there is also a tendency for this younger pyrrhotite to segregate around any chance inclusions of older pyrrhotite in the intergrowth. In general the tendency to segregate along crystal margins is strong, and the younger pyrrhotite may not uncommonly be found along quartz-chalcopyrite contacts, as lenticular patches a few microns across (Plate II, Fig. 2). Although it is believed that this younger pyrrhotite is due to exsolution, the possibility that it is due to replacement at a later stage cannot be ignored. The distinction between the two varieties is readily drawn according to the properties listed below.

Property	Older Pyrrhotite	Younger Pyrrhotite
Pleochroism	Not perceptible	Distinct, pale rose to grey-brown
Anisotropism	Moderate	Intense
Polarization Colours	Blue-grey and Orange-brown	Blue-white and Orange-white
KOH reaction	Positive, strong	Positive, weak

Plate II.

Fig.1. Chalcopyrite and cubanite (medium-grey and dark-grey bands) with younger pyrrhotite (white and black) blebs and plates in regular orientation. Texture probably due to exsolution of younger pyrrhotite from chalcopyrrhotite during transformation to cubanite. Older, weakly anisotropic pyrrhotite (light-grey with high relief) fills remainder of field. Nicols slightly uncrossed. x 360.

Fig.2. Younger pyrrhotite (white, centre of field) along contact between quartz (black) and chalcopyrite - cubanite intergrowth. Probably due to exsolution and segregation towards margins. Crossed nicols. x 360.

Sphalerite is present in minor amount, always associated with chalcopyrite, and showing 'mutual boundaries' against it, or replacing it. In rare cases, a very fine-grained exsolution of chalcopyrite from sphalerite occurs.

Tellurides occur sparsely in the ore, always as minute grains which are found in the quartz, moulded on sulphides, or in fractures in the sulphides. Due to the small sizes of grains and their softness, identification may be tedious, but where sufficient quantity can be gouged from the polished surface for microchemical tests, the reaction with CsCl and KI is positive. Several species appear to be present, of which the most common is tetradymite, $Bi_2(Te,S)_3$. This effervesces with 1:1 HNO_3, and reacts positively with HCl and $FeCl_3$ but is unaffected by KCN,KOH or $HgCl_2$. The reflectivity was determined as 53.5 per cent on several grains with imperfect polish. This value is within reasonably close correspondence with the values given by Moses (56.9%) and Folinsbee (49.1%) (Folinsbee, 1949). The tetradymite can be distinguished from the other tellurides present by its silver-white colour and strong anisotropism. A mineral of identical appearance and reactivity towards etch reagents is tentatively identified as altaite, PbTe, but this is of very rare occurrence and may in fact be tetradymite oriented so that anisotropism is very weak. Creamy-yellow calaverite (Au,Ag)Te, and grey hessite, Ag_2Te, were identified by the etch tests and physical properties, but full confirmation of their presence is attended by the difficulty of finding sufficient material with which to carry out the microchemical tests. In any event, tetradymite is the only telluride to occur with any frequency in the ore.

Chief attention was paid to the gold, which occurs relatively abundantly in many specimens studied. Its distribution is, however, erratic, and some polished surfaces show none at all. From the variations in its colour it is seen that within even small specimens the fineness is variable. The characteristics of the gold are more fully described in a succeeding section.

(b) Paragenesis

Pyrite was the first mineral to crystallize, followed by pyrrhotite and then chalcopyrite. Sphalerite and chalcopyrite crystallized at the same time, although the former appeared first. On cooling, sphalerite exsolved chalcopyrite, at some temperature in the region of 350°-400° (Edwards, 1954, p.98). Cubanite lamellae are explained by Borchert (Edwards, 1954, p.106) by the transformation to cubanite of chalcopyrrhotite which exsolves from chalcopyrite between 450° and 255°, chalcopyrrhotite being unstable below the latter temperature. The excess FeS in chalcopyrrhotite usually combines with chalcopyrite to form more cubanite, but in the case of this ore it seems that a younger generation of pyrrhotite has been formed which now occurs as oriented lamellae in chalcopyrite-cubanite intergrowths, or as segregations at grain margins.

The tellurides were the last of the ore minerals to crystallizd, whereas the relationship of gold to other minerals suggests a fairly wide variation in its age. It is considered that some of the gold started to crystallize soon after chalcopyrite had started to form, as it is now found as euhedral crystals included in chalcopyrite; it continued to crystallize to a late stage, when it became intergrown with the tellurides.

(c) Characteristics of the Gold

In order to study the gold, a number of selected specimens were polished with particular care, using lead and solid nylon laps for prolonged periods in order to produce a minimum of relief between gold and tellurides and the harder minerals. These specimens were examined by traversing at intervals of 300 microns with high-power objectives, and full notes were made on each gold grain as encountered. In addition, the dimensions were measured with a micrometer eyepiece. The following description is based on these observations, but, as the specimens examined were not outstandingly rich, the total number of grains amounted to less than 300.

(i) Crystal Size and Shape of Gold

Much of the gold which is considered to have crystallized at a relatively early stage shows crystal faces, these grains being platy or octahedral (Plate III). That gold which crystallized later, as a rim to sulphides or in association with tellurides, does not commonly show crystal faces. Veinlets in quartz or in fractured sulphides are exceedingly rare, and the shape of most grains tends roughly towards equidimensional. Of 200 gold grains, ranging in size from the smallest to the largest encountered in the polished specimens, the length to breadth ratios were determined as follows:

Length/breadth Ratio	Proportion of Total
1.0 - 1.5	51 per cent
1.6 - 2.0	27 " "
2.1 - 3.0	13 " "
3.1 - 4.9	5 " "
over 5.0	4 " "

In order to determine the range in grain size, the square root of the product of length and breadth was used to define the average dimension of each grain. As the majority of grains have a low length to breadth ratio, the error introduced is probably not serious. In the table below, the percentages of the total number of grains of different grain sizes are shown. The percentages are recorded as cumulative values, and the total

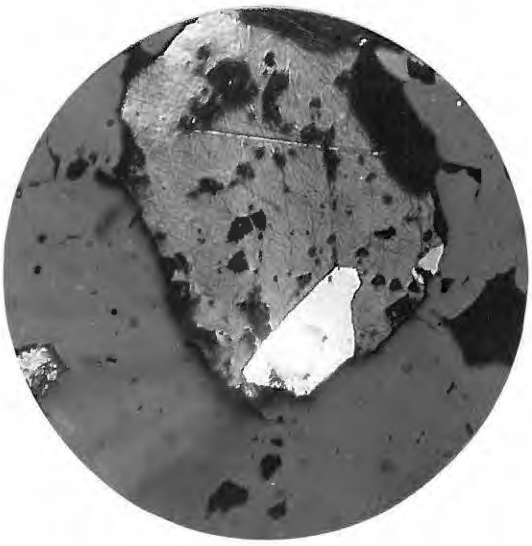


Fig.1 Gold with crystal faces partly enclosed by chalcopyrite at margin with quartz. x 360.

Fig.2 Euhedral grain of gold wholly enclosed by chalcopyrite. x 360.

number of grains measured is 282.

Sizes of Grains in microns	Cumulative Percentage
below 3	16.7
5	40.8
7	57.5
10	74.9
15	88.0
20	93.2
25	94.3
30	95.7
35	97.5
40	98.2
50	98.2
60	98.6

Although the conclusion is based on admittedly scanty data, it is clear that the majority of grains are small in size, with 75 per cent of the total number falling below 10 microns. Grains of larger size become increasingly more rare.

(ii) Variations in Gold Fineness

The colour of gold in polished section is an index of its fineness, for pure gold is golden with a distinctive ruddy tint; with increasing proportion of alloyed silver the colour changes to yellow and ultimately to a pale silvery-yellow as in electrum. Wide variation in colour is characteristic of the Olympus mine gold, which ranges from a reddish gold (over 950 fine) to a pale yellow (approximately 600 fine). Every gradation between these two limits can be seen in even the small area encompassed by a single polished specimen, and extremes of difference exist in grains but a few hundreds of microns apart. The spacial distribution of grains of different degrees of fineness appears quite haphazard, and if any direct correlation exists between fineness and grain size, it is ill-defined and unreliable.

A preliminary search for a possible relationship between the fineness of individual grains and the particular ore minerals with which they are associated proved sufficiently promising to encourage a more detailed investigation along these lines. Accordingly, the following procedure was adopted.

In the absence of any colorimetric apparatus, four shades of colour were defined for the gold, as follows:

Pale Yellow : distinctly paler and more silvery than chalcopyrite;
Medium Yellow : close to the colour of chalcopyrite, allowing for the rather more greenish tinge of the latter;
Golden : richer and more golden than chalcopyrite;
Reddish Gold : golden, with a distinct ruddy tint.

The scale above proved to be admirable for this ore, as the chalcopyrite is so abundant as to be rarely absent from the microscopic field of view.

While examining each gold grain encountered while traversing the surface, the field of view should be reduced in size by means of the iris diaphragm and the light source adjusted on the ammeter to constant intensity. High power objectives only should be used. The surface of the specimen should be swabbed and wiped at least a half-dozen times with clean linen squares soaked in carbon tetrachloride, as the slightest trace of oil film on the surface results in colour fringes on the grains. The colour of the grain is recorded, and also its exact textural relationship towards the associated minerals. Thus, the position of the gold grain determines whether it is classified as "discrete" or "enclosed by" or merely "associated with" other ore minerals. Gold grains placed in the third category occur in visible microscopic fractures in the host, partially rim it along its margins or merely touch it, while in the second category grains are deeply set in their host and no grain boundaries or fractures appear to intersect the gold grains. Development of crystal faces is taken as evidence in support of enclosure rather than possible replacement or filling of fractures not visible under the microscope.

While the shortcomings of this rigid partition of grains into a limited number of groups are obvious, it is considered that the errors introduced by this procedure are less serious than those resulting from inflexible acceptance of the oft-quoted rule that gold is invariably the last of the ore minerals to crystallize in hydrothermal ores. As stated earlier, it is accepted by the writer that gold has here had a relatively long period of crystallization, and has grown side-by-side with each of several ore minerals.

The results of this examination are shown in Table 5. In the case of tellurides no distinction has been made between "enclosure" and "association", as these are in any event undoubtedly late minerals. Those gold grains classified as discrete grains occur in quartz and are not in contact with any of the other ore minerals. The upper figure in each pigeon-hole of the table gives the total number of grains, in all specimens examined, falling into that category, and the lower figure the calculated percentage of the total volume of gold which those grains represent. This latter value was obtained by assuming that each grain is a cube of side equal to the average dimension as previously determined, and then calculating the total volume of gold in each category. In order to eliminate undue weighting of certain categories due to the occurrence in them of a few very large grains, all grains larger than 30 microns, constituting 4.3 per cent of the total number encountered, have been ignored.

TABLE 5. Relationship between fineness (colour) of gold grains and textural relationships with associated minerals.

Upper figure in each pigeonhole is the number of grains placed in that category while the lower figure is the volume percentage of tho whole.

Colour	Enclosed in Pyrrhotite	Enclosed in Chalcopyrite or Sphalerite	Associated with Pyrrhotite	Associated with Chalcopyrite or Sphalerite	Associated with Tellurides	Discrete	Totals
Pale Yellow	0 0	0 0	1 0.	16 12.0	6 3.0	25 4.5	48 19.5
Medium Yellow	0 0	6 1.5	5 1.0	20 28.5	20 12.5	32 2.0	83 45.5
Golden	0 0	1 0.5	8 3.0	5 1.5	43 17.0	64 6.5	121 28.5
Reddish Gold	0 0	1 0.5	0 0	0 0	9 0.5	20 5.5	30 6.5
Totals	0 0	8 2.5	14 4.0	41 42.0	78 33.0	141 18.5	282 100.0

The data of Table 5 are interpreted as follows. The greatest amount of the pale-yellow gold is associated with the chalcopyrite, and smaller amounts occur discrete or with tellurides. Medium-yellow gold is the most abundant type, and by far the greatest proportion of it is associated with chalcopyrite, while a small amount is found with tellurides. Golden-coloured gold is abundant, but less so than medium-yellow gold, and the greatest proportion occurs with tellurides, a smaller amount occurs discrete, while only minor amounts occur in contact with either pyrrhotite or chalcopyrite. Gold with a reddish tint is distinctly rare, but the greatest amount of it occurs discrete. It is of particular importance to note that no gold is enclosed by pyrrhotite, and that very little even occurs associated with it. This is to be expected, pyrrhotite being a high-temperature mineral of early crystallization, and gold a lower-temperature mineral of somewhat later age. It also indicates that replacement of early sulphides by gold has probably been insignificant.

If the ratio of the number of grains to the percentage volume in each pigeonhole in the table is studied, it is clear that the coarsest gold is generally associated with chalcopyrite, and that the most finely divided gold occurs as discrete grains. The arithmetical averages of actual sizes based on measurements show that the gold associated with chalcopyrite averages 18 microns, whereas that wholly enclosed by chalcopyrite averages 12 microns. The gold in contact with tellurides averages 9 microns, and the most finely divided gold, occurring discrete, averages 6 microns.

These two characteristics of the ore - the tendency of the purer gold to occur discrete or with the younger tellurides rather than with chalcopyrite, and the tendency for the grain size of the gold to be greatest where it is associated with chalcopyrite - are considered to point to a relationship between gold fineness and the stage at which the gold was deposited. The following sequence is postulated. Early crystallization of pyrrhotite at high temperature was not accompanied by the precipitation of gold. When chalcopyrite started to form, a small amount of gold started to separate with it, and these crystals were relatively rich in silver, and small in size. These are now found as rather rare inclusions in chalcopyrite, some of them being euhedral. Towards the closing stages of deposition of chalcopyrite, conditions were most favourable for the rapid precipitation of gold, and hence relatively large grains are partially intergrown with chalcopyrite (Plate IV, Fig. 1) or occur indenting the outer margins of it. This gold was purer than that deposited earlier. The purest gold was deposited late, and is hence intergrown with tellurides (Plate IV, Fig. 2) or occurs as discrete granules. The temperature was lowest in the closing stages, and grains formed at this stage were small.

In brief, then, it appears that gold which separated at a relatively early stage in the paragenesis has a high content of silver, and that progressively purer gold was deposited in the later stages. This conclusion can be supported by a further relationship which emerges from consideration of the production data. If the ratio between the amount of gold recovered by amalgamation and the amount recovered in the concentrates is plotted against the fineness of amalgam gold as in Fig. 9, it is found that plotted points are aligned, within experimental error, along a straight line. This means that gold which is easily amalgamated is purer than that which cannot easily be recovered by amalgamation. This in turn implies that the gold which is relatively easily liberated from enclosing minerals during stamp milling is purer than that which remains entrapped within or coated by sulphides, and it is thus reasonable to argue that this again points to the greater purity of late gold in contrast with the silver-rich quality of early-separated gold deeply entrapped in sulphides.

Plate IV

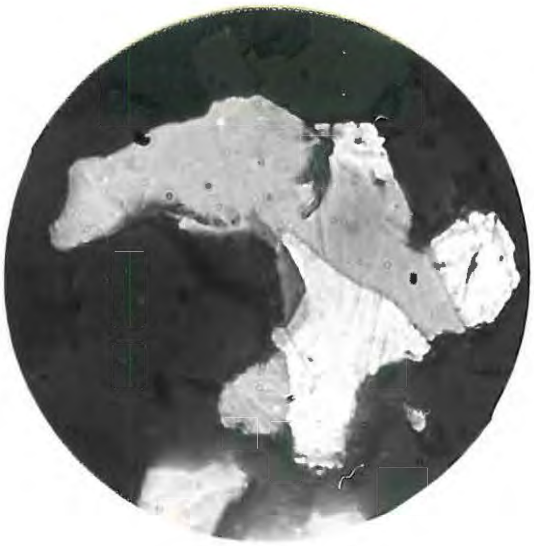


Fig.1 Typical intimate intergrowth of chalcopyrite (grey) and gold (white) in the form of tiny patches in quartz (black). x 750.

Fig.2 Gold (light grey) partly enclosed by tetradymite (dark grey), both being set in quartz (black). x 750.

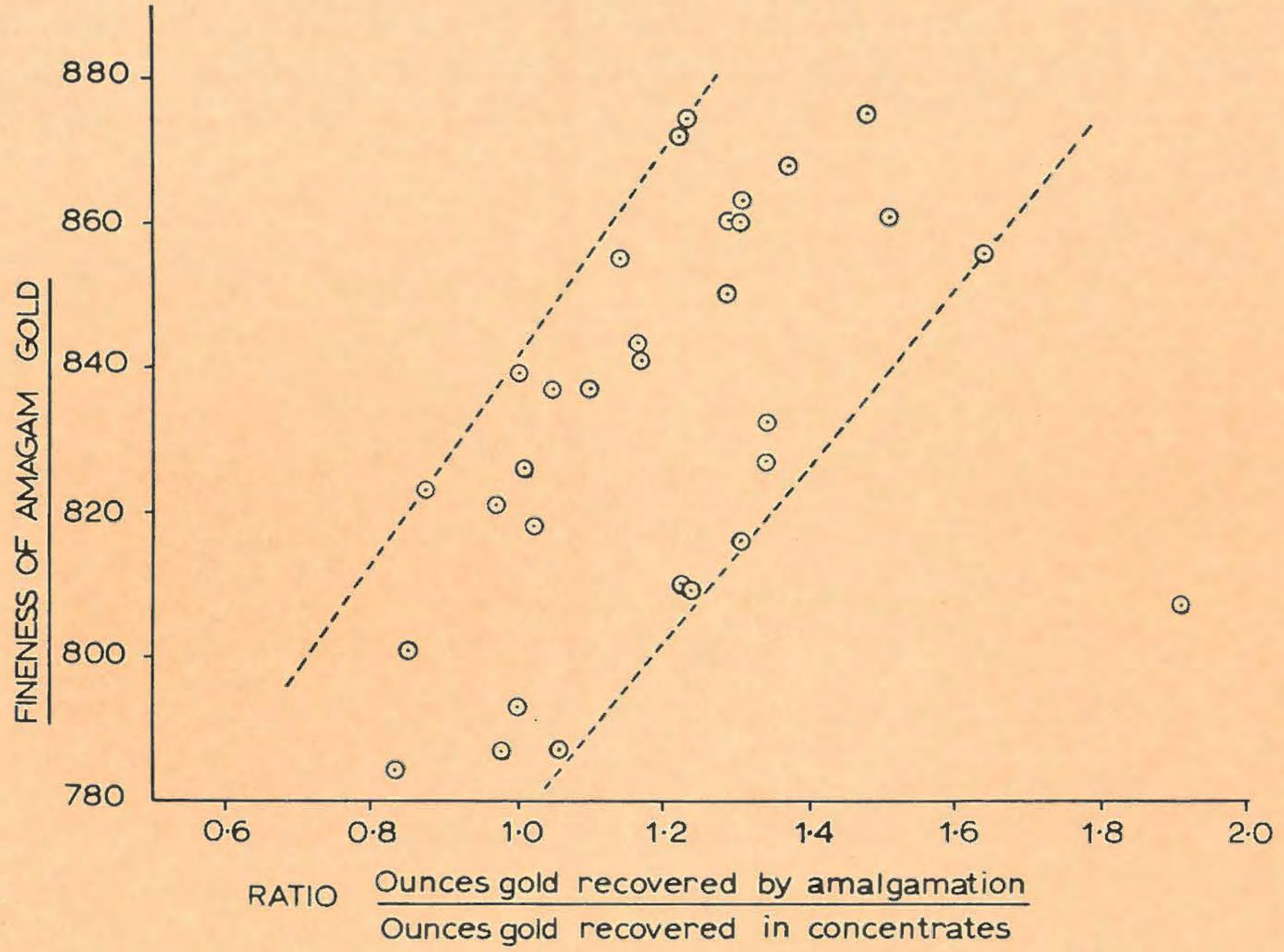


Fig. 9 *RELATIONSHIP BETWEEN FINENESS OF AMALGAM GOLD AND PROPORTION OF 'FREE GOLD' IN THE ORE.*

(iii) Structure of Gold Grains

A variety of reagents, including aqua regia, KCN and HCl/CrO_3 of different degrees of dilution, were used to determine whether any zoning exists within gold grains in this deposit. A large number of grains were etched, but little clear evidence of zoning was found. In a number of cases, the cores of crystals tended to darken more rapidly, with HCl/CrO_3, than the outer zones, suggesting a silver-rich core, but this evidence is not accepted without reservation, for on repeating the etching after re-polishing, the identical pattern was not reproduced in most cases.

Etching does reveal twinning in some grains (Plate V), which, by the criteria of Fisher (1935) can be attributed to recrystallization rather than growth-twinning. This implies that the metal has either been deposited at a temperature above 230°, or has, subsequent to its deposition, been strained and heated to that temperature (Fisher, loc. cit., p. 416).

The absence of zoning in the gold grains is not surprising. The diffusion of gold into silver takes place at even moderate temperatures, and Fisher (loc. cit.) states that diffusion is appreciable at 300° within some months.

Plate V

Twinning in gold revealed by etching with dilute HCl/CrO_3. Gold grain is enclosed in chalcopyrite (grey) and quartz (black). x 360.

B. THE LONE HAND MINE

Abstract

While production data suggest that the silver content of gold recovered from this deposit remains constant from year to year, detailed examination by the assay of samples, by simple amalgamation tests and by microscope techniques shows that the silver content varies widely. The data suggest very strongly that gold deposited at high temperatures early in the sequence, now occurring deeply entrapped in hard sulphides, contains very much more silver than that which grew side-by-side with low-temperature minerals. The probable occurrence of the rare mineral aurostibite, $AuSb_2$, is recorded.

Introduction

The Lone Hand mine is on Tuli River Farm, 17 miles west of the township of Gwanda. From available records, production appears to have been started in 1912, and has been maintained, with several breaks, until the present time.

The mine was examined by the writer in August 1955, and at the time of a further visit in 1958, development was being extended below the 10th level. Accordingly, all samples taken were perfectly fresh and free from the effects of supergene processes.

Brief Outline of the Geology

The gold-bearing reef is not a true quartz vein. Tyndale-Biscoe, who makes brief reference to the deposit (ibid. 1940, p.149) describes it as a zone of silicification, carbonation, and sulphide mineralization in quartz-schist. He notes that pyrite, which is the chief sulphide, occurs in massive bands parallel to the walls of the ore channel, and comments on the apparent absence of arsenopyrite.

The dip of the reef is steep, averaging 70-80 degrees, and the pitch of the ore shoots coincides with the dip. Three ore shoots occur within a strike-length of less than 500 feet of reef, and although mineralization extends for considerable distances to either side of these, the great bulk of production has been won from these shoots. The width of the reef is variable, and has improved with depth, but usually falls within the limits of 3.5 and 10 feet.

Production Data

Unfortunately, the production data are for long periods not of great assistance in assessing the variations in gold fineness, the production having been declared jointly with that of the neighbouring Orby mine. For the period 1940-1948, the fineness of the recovered gold shows little variation, ranging from 876 to 898. As far as can be determined, little or no Orby mine ore was mixed with Lone Hand ore during this period.

It is clear, however, that the recovered gold is of moderately high average fineness, and that there is little fluctuation in the average silver content from year to year. The bullion fineness is very much lower due to a content of base metal, and varies from 737 to 798 during the same period. This content of base metal is introduced chiefly as a result of cyanidation, for a recent analysis of 65.7 troy ounces of mill gold gave the following results:

Fine gold	-	90.30 per cent
Fine silver	-	9.06 " "
Copper	-	0.50 " "
Lead	-	tr.
Iron	-	tr.

The fineness of this bar, calculated from these figures, is thus 908.8

Up to 1953 the total tonnage milled had risen to close on 130,000 tons for an average recovery of 6.5 dwt./ton. The fact that less than 10 per cent of the gold has been recovered by cyanidation indicates that the bulk of the gold is 'free' gold amenable to amalgamation. The deposit may thus be described as a small, relatively high-grade producer.

Experimental Sampling Data

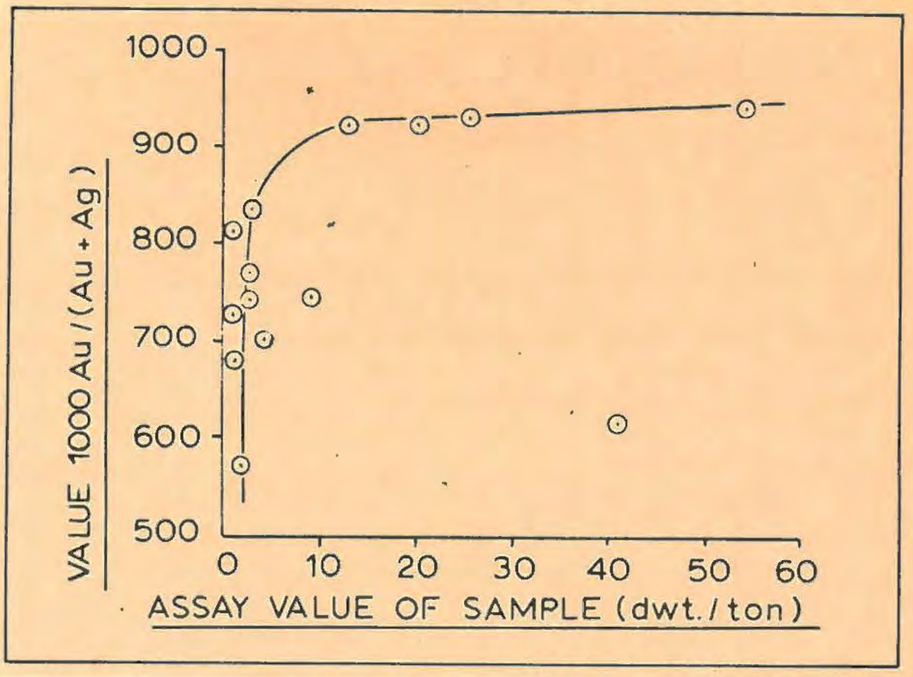
A visit was paid to the mine in January, 1958, for the specific purpose of making a collection of specimens for gold-silver assay and for study. With the assistance of the owner of the property it was possible to make such a collection which, although small, covered the range from very low-grade to very high-grade material. Normal channel sampling was rejected in favour of chipping a sample from the selected portion of reef, from an area no larger than could be covered with the open hand. This procedure was prompted by the suspicion that the fineness is subject to sharp variations over very short distances and the conviction that sampling by this method would be most likely to show best such variations. Fifteen samples were taken at intervals of five feet along strike, from the hangingwall, footwall and central sections of the lode. In the laboratory the samples were crushed and then repeatedly quartered until a small representative sample had been extracted. This was assayed for gold. The balance of each sample was then carefully panned to a smaller bulk and assayed for both gold and silver, giving in this way a more reliable estimate of the apparent fineness than would otherwise have been possible without prior concentration. The results of the determinations are shown in Table 6, and graphically in Fig. 10. The variation in apparent fineness is from 573 to 942, a range of 369 parts per thousand, in samples of ore containing from 0.9 to 363 dwt./ton. As in the case of other deposits tested in this manner, it is clear that there is a correlation between apparent fineness and tenor, with rich samples characteristically carrying purer gold than lean samples. Fig.10 indicates a sharp distinction between those samples averaging less than 5 dwt./ton in which the fineness is less than 820, and those exceeding 10 dwt./ton, in which the fineness is in six cases out of seven above 900.

Table 6

Assays of Lone Hand Mine Samples

Sample No.	Sample Assay (dwt./ton)	Conc. Assay (dwt./ton)		Value $\frac{1000\ Au}{(Au + Ag)}$
		Gold	Silver	
3858	1.0	2.4	1.1	685.7
3859	2.4	2.0	0.7	740.7
3860	4.0	8.9	3.8	700.7
3861	1.0	2.2	0.8	733.3
3862	25.6	149.6	10.8	932.6
3863	363.1	3741.4	366.6	910.7
3864	2.2	4.4	1.3	771.9
3865	20.1	232.0	22.7	910.8
3866	53.8	487.6	29.9	942.2
3867	9.1	33.6	11.6	743.3
3868	2.7	25.4	5.6	819.3
3869	1.8	5.5	4.1	572.9
3870	12.7	179.8	15.5	920.6
3871	0.9	2.1	0.5	807.6
3872	41.2	125.5	80.0	610.7

Fig.10. Apparent Fineness of Samples Plotted Against Grade, Lone Hand Mine



Two features of Table 6 call for special comment. Even although the samples represent portions of the reef taken at regular intervals along strike, there is no regular arrangement of fineness values. Their arrangement is haphazard, such that very high and very low values may characterize adjacent samples. Secondly, it should be noted that the range in apparent fineness values is far greater than would be suspected from the production data, which suggest only very little variation in the silver content of the gold. As in the case of the Olympus mine, the explanation appears to be the 'averaging-out' of extremes which results from extracting gold from many tons of ore rather than from samples weighing but a few pounds.

In order to assist the investigation, a simple test was carried out to determine whether any significant differences exist between gold which is easily amalgamated, and which is thus presumably easily freed from the ore during crushing, and that which is not recovered by amalgamation. A composite sample was made by mixing together some of the richer concentrate samples from the previous experiment. This was then broken down into +100, 100-200 and -200 mesh fractions by sieving. Each sample was then ground by hand in a mortar for about 20 minutes, with mercury and water made weakly acid with H_2SO_4. The mercury and amalgam were then separated from the samples and assayed, and the residual concentrate assayed separately. The results of the test are given in Table 7.

Table 7.

Sample	Assay (dwt./ton) Gold	Silver	Value $\frac{1000\ Au}{(Au + Ag)}$
Amalgam from +100 mesh	455.8	14.4	969
Amalgam from 100-200 mesh	497.3	9.0	982
Amalgam from -200 mesh	925.2	14.2	985
Residual concentrate	210.7	47.7	815

While the results are not necessarily representative of the ore as a whole, as they are based on analysis of particularly rich samples, it is clear that apparent fineness as determined by assay of the whole ore sample is a value intermediate between the fineness of relatively pure gold which is readily amalgamated, and the value 1000 Au/(Au + Ag) in the residual concentrate, from which the gold is not readily extracted by amalgamation. The lower apparent fineness of gold in the residual concentrate could be due to either, or both, of the following factors. Firstly, gold which is entrapped in hard sulphides and which would not be liberated without excessively fine grinding, may be an alloy of lower fineness than that which occurs as 'free' gold, or, secondly, there may exist in the sulphides other silver-bearing minerals which do not amalgamate with mercury, but which contribute to the total content of silver as determined by assay. The evidence of the microscope, which is fully described in the succeeding section, points unequivocally to the first of the two alternatives suggested above. While the presence of small amounts of silver-bearing minerals cannot be refuted on microscope evidence alone, the distinctly more silvery colour of much of the gold intimately associated with early pyrite in the ore makes it unnecessary to invoke their presence. The high silver content of this gold, judged by its silvery colour, is by itself capable of explaining low apparent fineness values.

The Evidence of Polished Sections

The productive reef embraces varieties of ore varying from a coarse intergrowth of sulphides with very little quartz to a schistose quartz-sericite rock in which sulphides occur very sparingly and are generally so fine in grain as to be barely visible to the unaided eye. The former usually contains little gold, whereas the latter is an excellent carrier, individual samples of which were found to contain up to 18 ounces of gold per ton.

(a) Minerals Present

The early sulphides in the ore are arsenopyrite and pyrite. The former is not abundant, and has been extensively replaced by pyrite so that it is visible only under the microscope. The pyrite, in the massive sulphide ore, occurs as grains as large as 5 mm. across, which rarely show the development of crystal faces. In the fine-grained ore, crystal faces are better developed. Pyrrhotite is very abundant, forming a coarse mosaic in which the earlier sulphides are enclosed. Traces of chalcopyrite fill interstices in massive sulphide ore, but it is only in the quartz-sericite type of ore that it becomes an abundant constituent. In this, patches may be as large as 4 mm. across, when thin lamellae of exsolved cubanite lie within it. Sphalerite, with deep red internal reflection and innumerable minute blebs of exsolved chalcopyrite, occurs only as tiny grains intergrown with chalcopyrite or surrounding it. Tetrahedrite, while it has not been found in the massive type of sulphide ore, is relatively abundant in the fine-grained quartz-sericite ore, where it occurs as patches up to a maximum size of 150 microns. Chalcopyrite and arsenopyrite have suffered vigorous attack by replacement by the tetrahedrite. Gold has been found in all specimens of ore, but it is very rare and fine-grained in habit in the massive sulphide ore. It is abundant in the quartz-sericite ore where it occurs in association with the younger sulphides. A fuller description of the gold is given later. Closely associated with the gold is a mineral whose properties do not correspond with any of those listed by Short (1940). Although this mineral occurs only in minute quantities in the ore, its properties and manner of occurrence are distinctive, so that it is quickly detected under the microscope. It most closely resembles the rare mineral aurostibite, $AuSb_2$, which occurs in the Giant Yellowknife mine, N.W.T., and the Chesterville mine in Ontario, as described by Graham and Kaiman (1952, pp. 461-469). The properties of the Lone Hand material are compared, in Table 8, with those of aurostibite as described by these authors.

Table 8

Properties of Aurostibite

Property	Aurostibite	Lone Hand Material
Colour	galena-white	galena-white
Hardness	C- (slightly harder than gold)	about the same as gold
Anisotropism	not stated	isotropic
Cleavage	no cleavage	no cleavage detected
HNO_3(1:1)	rapidly acquires iridescent coating	rapidly turns iridescent red-brown
HCl (1:1)	dark brown stain	dark brown stain
HCl fumes	sweat halo forms	sweat halo forms
$FeCl_3$ (20%)	immediately acquires iridescent coating	instantly becomes deeply iridescent
KOH (40%)	slowly acquires light brown coating and polishing scratches are accentuated	stains brown fairly rapidly
KCN (20%)	no reaction	negative - faint stain after long standing
$HgCl_2$ (5%)	no reaction	negative - faint stain after long standing.

A peculiarity of this Lone Hand material, which at first led to confusion, is the extraordinarily rapid rate of tarnish. Immediately after polishing and swabbing with carbon tetrachloride, the colour is a bright silver- or galena-white. Within a few minutes the colour changes to light pink, then bornite-pink and ultimately a pinkish brown, rather like a tarnished penny. Graham and Kaiman note that aurostibite from the Giant Yellowknife mine shows a bornite-like tarnish, whereas that from the Chesterville mine does not.

A specimen of ore containing this mineral was sent to the Department of Mines and Technical Surveys, Ottawa. The writer is indebted to Dr. M.H. Haycock and Mr. Kaiman for having made an examination of the material, and for reporting as follows:

"We attempted to remove the larger grains for X-ray diffraction analysis .... The X-ray diffraction pattern of this minute sample, after sixteen hours exposure, shows distinct lines of quartz and chalcopyrite. One very definite line, however, cannot be attributed to either of these minerals, but it does correspond to the strongest line of aurostibite."

They conclude that the mineral in question may be either aurostibite or a closely related, undiscovered species.

The largest grain seen in any of the polished specimens measures 50 x 30 microns, thus it is quite impossible to gouge out uncontaminated material for microchemical tests. Crushed pellets of ore rich in gold, however, give a positive reaction for antimony with KI and CsCl, although tetrahedrite may be responsible for this. In the Lone Hand ore the presumed aurostibite also occurs as vermicular bodies about 20 x 5 microns replacing pyrrhotite and chalcopyrite (Plate VI, Fig. 2), replacing arsenopyrite (Plate VII, Fig. 2) or in intimate association with gold. It is undoubtedly a very late mineral, as it either partly rims gold (Plate VII, Fig. 1) or replaces it. Some occurs as discrete crystals. Graham and Kaiman figure aurostibite enclosing or partly armouring gold grains and arsenopyrite exactly as described here.

Plate VI.

Fig.1 Intergrowth of gold (light grey) aurostibite (?) (medium grey) and tetrahedrite (stippled). The intergrowth is moulded to the faces of quartz crystals (dark grey). x 750.

Fig.2 Aurostibite (?) (deeper grey) and tiny grains of gold (white) replacing pyrrhotite (lighter grey) in the centre of the field. Chalcopyrite is moulded on pyrrhotite on the right, and an exceptionally large grain of gold occurs on the left. Slightly etched with KOH. x 360.

Fig.1 Gold grain partly rimmed by younger aurostibite(?) (tarnished). x 360.

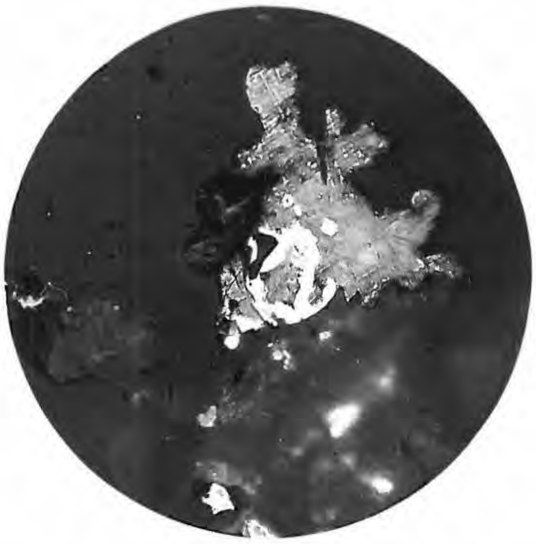


Fig.2 Arsenopyrite (white) partly replaced by aurostibite (?) (grey) giving rise to a form of atoll texture. x 360.

Plate VIII

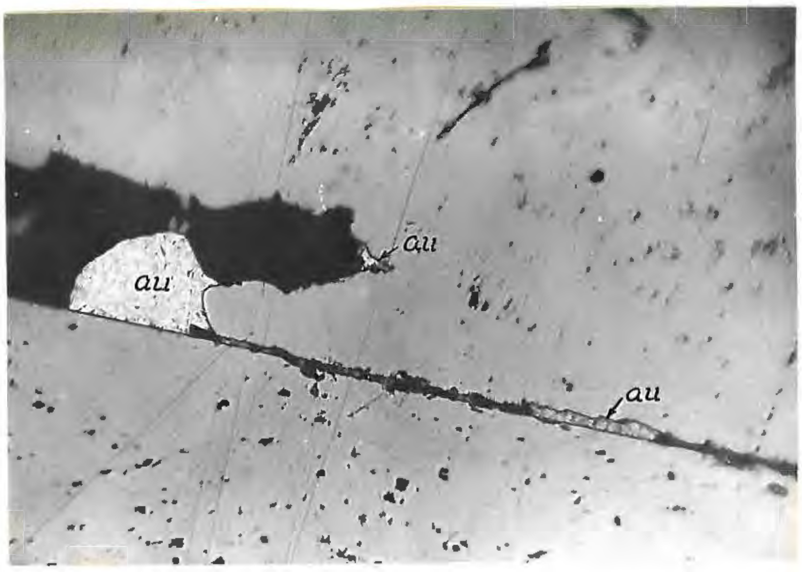


Fig.1 Pale-yellow gold filling fractures in pyrite, and locally replacing it. Quartz (black) accompanies gold. x 360.

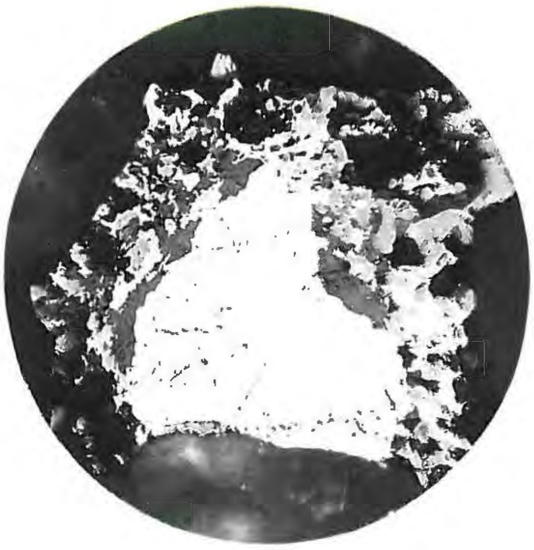
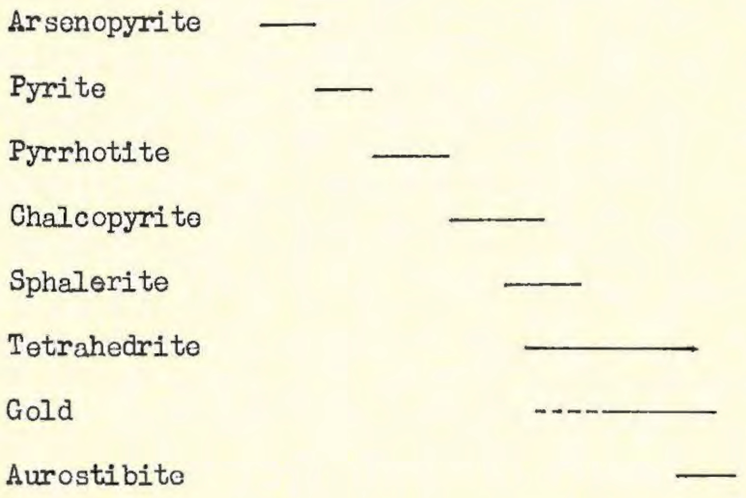


Fig.2 Gold (white) and pyrrhotite (light grey) replaced by aurostibite (?) (dark grey). x 360.

The paragenesis of the ore minerals may be illustrated diagrammatically as follows:



(b) Characteristics of the Gold

Attention was earlier directed to the lower apparent fineness of the gold in sulphides or sulphide-rich ore, compared with that in quartz-sericite ore with sparse, fine-grained sulphides. It has also been noted that the tenor in the former is low compared with that of the latter. A set of polished specimens was accordingly prepared with particular care in order to determine whether the low apparent fineness of gold intimately associated with early sulphides is due to a high silver content of the gold itself, or to the presence of other silver-bearing minerals.

Specimens of coarse-grained sulphide ore show an abundance of high-temperature minerals such as arsenopyrite, pyrite and pyrrhotite, very minor amounts of chalcopyrite, and no sphalerite, tetrahedrite or aurostibite (?). Protracted search eventually established the presence of minute gold grains enclosed in pyrite and filling fractures in it (Plate VIII, Fig. 1). None was found greater than 50 microns in diameter, and most grains are less than 10 microns. These gold grains are not accompanied by any of the low-temperature ore minerals previously listed. Their most striking feature, however, is their pale-yellow colour, suggestive almost of electrum. The fragment of ore, from which this particular specimen was cut was then assayed and found to contain 15.2 dwt. of gold per ton, and 6.4 dwt. of silver. The apparent fineness is thus 704. The occurrence of gold in fractures in these high-temperature minerals, unaccompanied by any of the low-temperature minerals, suggests very strongly that this gold was precipitated in an environment chemically, and perhaps physically, different from that in which it was precipitated in the quartz-sericite ore.

All of the polished specimens of quartz-sericite ore show some gold, and in some it is remarkably abundant. In its mode of occurrence it contrasts strongly with that described above, in that it is associated with tetrahedrite and particularly with the late-stage aurostibite (?). The high-temperature sulphides are also sparsely disseminated as tiny crystals in the ore, but no gold has thus far been found showing any preference for them. This gold is of rich golden colour. There is some variation in the amount of alloyed silver: this can be detected by slight variations in the colour, but is best brought out by the varying reactivity of different grains towards CrO_3/HCl. No distinct zoning has been observed in spite of efforts to reveal it with different reagents. One of these polished specimens was split and assayed, and found to contain 301 dwt. gold per ton and 20.2 dwt. silver per ton, giving an apparent fineness value of 937. A second specimen, identical in appearance to the first, assayed 357.4 dwt. gold per ton, and gave an apparent fineness value of 979.

These data leave little doubt that the massive sulphide ore, composed of high-temperature sulphides, is relatively poor in gold, and that that gold which is present in it has a high silver content. The failure to detect other silver-bearing minerals or any other low-temperature sulphides in this type of ore strengthens the view that the low apparent fineness is due to a high silver content of the gold and not to other factors. Conversely, the occurrence of deep-yellow gold with relatively large amounts of those minerals deposited at moderate temperatures, such as chalcopyrite and sphalerite, but more particularly with late tetrahedrite and aurostibite, points to an increasing inability of gold to alloy with silver in the later stages of vein formation.

The concentrates from the underground samples collected at the 10th level were mounted in a plastic cement and polished for microscopic examination. The rich samples, characterized by high apparent fineness values, showed abundant golden-yellow gold, some of it intergrown with aurostibite. The low-grade samples, with low apparent fineness values, showed, unfortunately, either no gold or perhaps a single grain only. Microscopic examination of the concentrates has thus provided no further information.

C. THE HORN MINE

Abstract

Experimental sampling shows that low-grade gold ore contains relatively more silver than high-grade ore. An amalgamation test indicates that free gold which is readily recovered by amalgamation is relatively purer than that which is not so readily recovered. Other considerations suggest that sparse silver-rich gold associated with early-formed sulphides causes low apparent fineness of low-grade ore specimens. The general conclusions are the same as those reached in the case of the Lone Hand deposit.

Introduction and General Geology

This property falls within the Tuli group of deposits in the Gwanda area, and lies very close to the Lone Hand reef. A brief visit was made to it while the latter deposit was being studied, chiefly for the purpose of sampling a section of reef in order to gain some idea of the variations in fineness in this rather unusual type of deposit. Accordingly, the following account is concerned primarily with the nature of the gold itself, while the details of structure and mineralogy have been kept to a minimum.

Tyndale-Biscoe (1940, p.133) gives a short account of the deposit. The strike-length is quoted as 2,400 feet, and the rather unusual features may be inferred from the following extract:

"The country rock is granitic gneiss rich in biotite and carrying inclusions of greenstone schist, the contact with the schist belt being a few hundred feet to the east. The northern section of the reef channel dips vertically or steeply east, while the southern section dips north-west at 45 degrees. As far as can be seen the two sections are continuous and connected by an even curve. There is no evidence of a break. The oreshoots have a uniform northerly pitch, and consist of subparallel lenses and stringers of quartz in a broad, strongly sheared zone in the gneiss."

Experimental Sampling

A short section of a drive along good average grade of reef on the 3rd level was sampled by the writer at three-foot intervals along the strike, and the samples treated and assayed in the same way as those taken at the Lone Hand property. The results of this experimental work are shown in Table 9, while in Figure 11 the apparent fineness values of the concentrates have been plotted against the grade of the concentrates. The grade of the concentrates, rather than the grade of the original samples, has been used as abscissae, as the presence of coarse gold particles, easily detected under the microscope, has caused the latter assays to be somewhat erratic.

From Table 9, it is clear that the apparent fineness varies sharply from point to point along the strike of the reef, and that there is quite definitely no serial variation. This is in accord with the findings for other deposits examined. The apparent fineness varies from 743 to a maximum of 962, this variation being much greater than that in the fineness of gold recovered in the mill by amalgamation. The average fineness of this amalgam gold, calculated from 21 separate outputs, appears to vary only from 866 to 932. Fig. 11 is very similar to Fig. 10 depicting the Lone Hand deposit. In spite of the scattering of plotted points to either side of the mean curve it is again apparent that low-grade ore has usually a relatively greater silver content than high-grade ore. It becomes important to establish whether this variation is caused by fluctuation in the silver content of the alloy, or by the presence of other silver-bearing minerals.

Table 9.

Assays of Horn Mine Samples

Sample No.	Sample Assay (dwt./ton)	Conc. Assay (dwt./ton)		Value $\frac{1000\ Au}{(Au + Ag)}$
		Gold	Silver	
3840	2.5	56.3	9.0	862.1
3841	2.6	10.7	2.4	816.7
3842	2.8	4.7	0.5	903.8
3843	3.1	5.8	2.0	743.5
3844	0.9	4.0	0.6	869.5
3845	1.0	4.5	0.5	900.0
3846	23.3	134.5	7.7	945.8
3847	3.8	31.8	4.9	866.4
3848	2.6	13.0	1.0	928.5
3849	1.0	5.1	1.2	809.5
3850	24.2	136.3	13.3	911.0
3851	0.9	2.1	0.7	750.0
3852	2.5	35.6	1.4	962.1
3853	2.6	46.5	3.8	924.4
3854	7.2	63.9	2.8	958.0

Notwithstanding the fact that four of the samples described above contain only 1 dwt. gold per ton or less, equivalent to 0.00017 per cent or less of gold by weight, the total amount of silver present in any of these samples does not exceed even one third of this amount. If silver minerals other than gold do in fact occur in these specimens of ore, they can be present in only exceedingly small amounts and their contribution to the total silver in the ore must be negligible. On the other hand, the fact that some of the low-grade samples yield moderately high apparent fineness values shows that these variations cannot be attributed to analytical errors such as silver being introduced into the samples in the litharge used in assaying. There is little to support

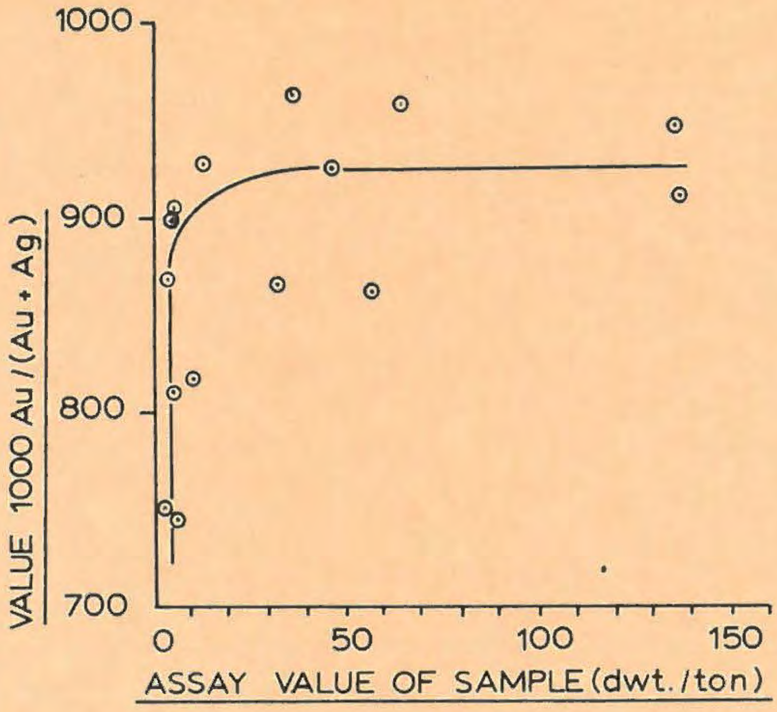


Fig. 11 ROUGH RELATIONSHIP BETWEEN APPARENT FINENESS AND TOTAL GOLD CONTENT OF HORN MINE CONCENTRATE SAMPLES.

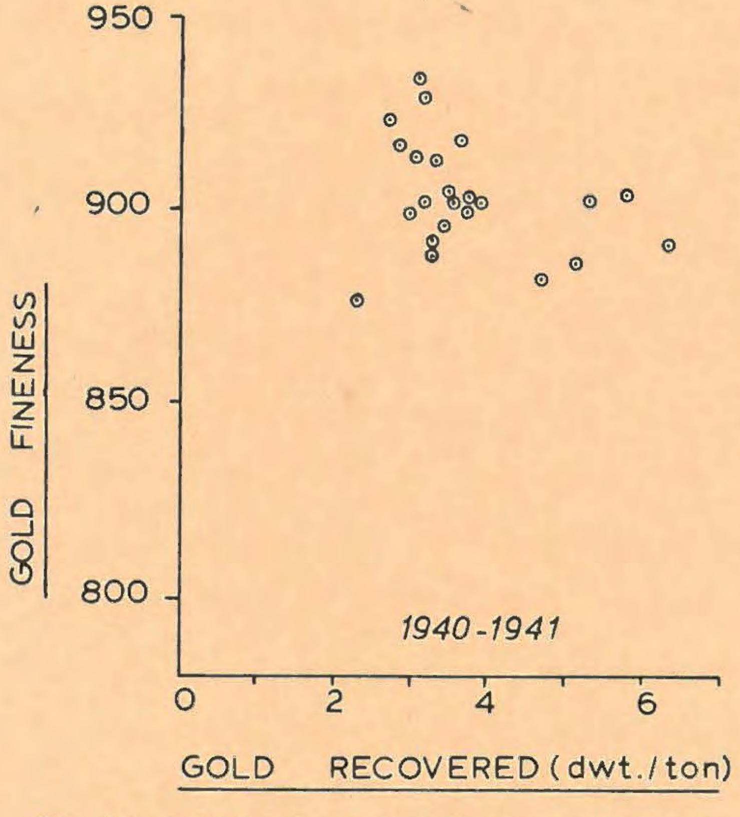


Fig. 12 DIAGRAM ILLUSTRATING RELATIVELY SMALL VARIATION IN AVERAGE GOLD FINENESS, HORN MINE. CONTRAST WITH Fig. 11.

any contention that the drop in apparent fineness in low-grade specimens is due to any cause other than a drop in the fineness of the gold particles themselves.

In Fig. 12 the fineness of gold recovered by amalgamation has been plotted against the recovered grade for the period 1938-1941. It is of interest to note that there is no suggestion of a relationship between tenor of the ore and fineness of the gold recovered. This is due to the "averaging-out" which takes place during milling, which has here caused the variation in fineness to be subdued to such an extent that the range between maximum and minimum values has become too small to endorse the conclusions reached by experimental sampling. This feature is no doubt common and must overshadow a correlation between fineness and tenor of ore in many similar cases.

The Evidence of Polished Sections

The mineral assemblage is indicative of deposition at high temperatures. In the specimens polished for microscopic study, and which come from the same section of reef as sampled, the early-deposited sulphides include molybdenite, pyrite and pyrrhotite and the later sulphides chalcopyrite and sphalerite containing exsolved chalcopyrite blebs. Arsenopyrite also occurs in the ore, but was not encountered in any of the polished sections. Goldberg (1960) states that galena is encountered in some instances. A second generation of pyrite is also present in the ore, rimming and replacing these sulphides, but its exact position in the paragenesis is not clear. The specimens show no trace of oxidation, and it is unlikely that this pyrite is supergene. Careful examination of both high-grade and poorer specimens failed to show any gold intimately intergrown with the sulphides, although gold does occur moulded on them. The gold also occurs as isolated grains in the quartz gangue, but most typically it is intergrown with either of two soft minerals deposited late in the sequence. From their respective reactions with the standard etch reagents, and other properties, these minerals were identified as native bismuth and native antimony. Unfortunately, these occur in all specimen~~t~~s as grains too minute to be gouged out for confirmatory microchemical tests. A small specimen of light-grey quartz containing a nugget of gold measuring 5 x 2 mm , lent to the writer by the owner of the mine, showed tiny grains of soft, grey material intimately intergrown with the gold. This material, consisting presumably of more than one mineral, gave strong reactions for antimony and bismuth. This seems to confirm the identification by etch tests.

The following extract from a report by the Government Mining Geologist (Goldberg, loc. cit.) is relevant:

"A feature of the mine is the occurrence of bismuth in some of the orebodies; the bismuth combines with the mercury used for amalgamation to form a gold-bismuth amalgam. In the retort much of the bismuth-rich liquid can be decanted to produce a white metal, relatively rich in gold, and sold as a base gold bar."

In this account it is stated that the mineralogical form of the bismuth in the ore had not been determined.

Spectrographic analyses (Goldberg, personal communication) of concentrates of the ore confirmed the occurrence of bismuth, but the occurrence of antimony was not noted (Table 10.)

Table 10. Spectrographic Analyses of Two Samples of Concentrates

Element	Sample A	Sample B
Molybdenum	-	tr.
Bismuth	tr.	tr.
Arsenic	-	5 - 10%
Zinc	tr.	below 0.5%
Copper	0.1%	0.1%

The preference shown by gold for ore containing low-temperature minerals is summed up in the following Table 11, which indicates the progressive change in four representative samples ranging from low to high grade. In each, pyrite and pyrrhotite are abundant, and no special comment has been made regarding their presence.

Table 11

Association of Gold with Low-Temperature Minerals

Sample Number	Gold Assay	Apparent Fineness	Minerals in Polished Specimens
3849	1.0 dwt.	810	chalcopyrite (rare) sphalerite (rare)
3848	2.6 "	929	chalcopyrite (rare) sphalerite (rare)
3854	7.2 "	958	chalcopyrite (small amounts) sphalerite (small amounts) antimony (trace) bismuth (trace) gold (trace)
3846	23.3 "	946	chalcopyrite (common) sphalerite (small amounts) antimony (relatively abundant) bismuth (relatively abundant) gold (relatively abundant)

The increase from low to high apparent fineness with the appearance of lower-temperature minerals is striking.

In order to determine whether variations in apparent fineness of the concentrates are due to variations in the composition of the gold itself, polished specimens were prepared with the concnetrates left over after assaying. The low-grade concentrates show no visible gold at all, and thus provide no further information. The high-grade concentrates show gold in fair abundance, most of it intergrown and showing mutual boundaries with native antimony, or occurring as discrete grains. Most of the gold shows the distinctive ruddy tint characteristic of very pure gold, but the occurrence of a few grains which are yellow proves that the fineness is variable.

A simple amalgamation test carried out on a composite sample prepared by mixing the remains of the concentrates confirmed

confirmed that the fineness of the gold is variable. The sample was split into two fractions by sieving, and each ground by hand with mercury. The amalgam and the residual sulphides were then assayed, and the results of the test were as shown in Table 12 below.

Table 12

Sample	dwt./ton Gold	Silver	Value 1000 Au (Au + Ag)
Amalgam (+ 100 mesh fraction)	120.2	12.4	906
Amalgam (- 100 mesh fraction)	832.7	19.3	977
Residual material	38.7	4.8	890

The results of this test are seen to be much the same as those for the Lone Hand deposit. The coarser free gold contains rather more silver than that which is fine-grained, while the sulphides which are left after the free gold has been separated contain in proportion very little gold, and this is relatively richer in silver than either of the other fractions. While the writer has so far been unable, by microscopic study, to confirm the existence of small amounts of pale-coloured gold entrapped in the sulphides, as in the case of the Lone Hand ore, there seem to be good grounds for assuming that this is nevertheless the case, when it is considered that gold appears in the ore in abundance only when the lower-temperature minerals also appear in noteworthy amounts. To support this view, a small lump of massive pyrrhotite collected underground was trimmed to remove as far as possible all adherent quartz, and then assayed. It was found to contain 8.7 dwt.gold per ton and 2.3 dwt. of silver, equivalent to an apparent fineness of 791, which is far lower than the figure characteristic of gold recovered by amalgamation, and close to the value 743, the lowest value determined in the underground samples listed in Table 9.

D. THE JESSIE MINE

Abstract

The Jessie reef is a quartz vein containing a variety of sulphides, as well as sulpho-salts, native antimony and gold. The occurrence of a mineral identified here as aurostibite is recorded. The production data show that the average fineness of recovered gold is low, not exceeding 820, whereas experimental sampling and microscopic examination leave no doubt that the fineness of metallic gold is very variable, and may either be very much higher or lower than the value suggested by production data alone. It is shown that the gold started to precipitate at a relatively early stage in company with sphalerite, when it formed coarse masses with a high content of silver. As vein formation continued, the gold precipitated was alloyed with a progressively smaller amount of silver, and tended to be finer in grain. Experimental sampling establishes a correlation between the silver content of the gold and the richness of the sample.

Introduction and General Geology

The Jessie Mine lies close to the main Gwanda-Beit Bridge road, some 20 miles from Gwanda. Its name is well known in the territory, for the mine has had a long history stretching back to the start of operations in 1899. An account of the history and the geology is given by Tyndale-Biscoe (1940, p.139), and from this source the following excerpts are taken:

"The reef lies in hornblende-schist ......and is a vein of bluish grey granular quartz of lenticular character, mineralized with pyrite, pyrrhotite (strongly magnetic), chalcopyrite and galena to a very variable extent. The pyrrhotite, especially, in many places forms massive veinlets crossing the reef at high angles to its walls. The reef is frequently banded, due to partings of intensely altered country rock."

"The proved length of strike of the reef is 1,200 feet in a north-westerly direction, the dip being south-west at high angles."

The present writer made two visits to the mine during 1957 and 1958, and at the time that specimens were collected, development was progressing on the 17th level.

Plate IX

Handspecimen of Jessie mine ore. Note well defined banding of sulphides and unreplaced wall rock. Half natural size.

Production Data

An indication of the average grade of the ore milled between 1905 and 1940 is given by the average recovery of 3.3 dwt. gold per ton. Figures for 1957-1959 indicate a rather higher recovery, monthly returns showing a range of 3-6 dwt./ton. Analysis of these figures for this latter period shows a variation in the true fineness of amalgam gold from 752 to 818 with the most frequently occurring values between 785 and 810. The fineness of gold recovered by cyanidation is decidedly lower than this, the range being from 560 to 700, and on the average some 150 parts per thousand lower than that of the amalgam gold.

There is no clearly defined relationship between the fineness of amalgam gold and the average grade of the ore as determined by recovery, such as has been detected in some other deposits investigated. The reason for this appears to be the occurrence of notable amounts of coarse-grained gold of very low fineness in the ore, in which respect this ore is remarkable, for gold of lower fineness is, as a general rule, quantitatively less important than purer gold in deposits of this type. This feature is fully described in a later section. Furthermore, the study of polished sections and assay data shows conclusively that the actual range in fineness of gold particles is far greater than that indicated by production figures alone.

The Evidence of Polished Sections

(a) Minerals Present

No single polished specimen shows the complete assemblage of minerals in the ore, but by reference to a number of specimens it is possible to piece together the position, in the paragenesis, of most minerals. There are reversals of order in some pairs of minerals in different specimens, but these do not greatly affect the overall picture. The minerals of the ore are described below in their order of deposition.

The first opaque mineral to crystallize was arsenopyrite, which forms bands and veinlets of closely packed rhombs and acicular crystals, as well as less well defined mossy clumps in which the replacement of vein quartz is incomplete and the crystals are skeletal in character. Many crystals are crowded with unreplaced shreds of quartz or country rock, which were, at a late stage, selected for replacement by several of the younger sulphides and gold. Pyrite followed arsenopyrite, and was in turn succeeded by pyrrhotite, which surrounds and encloses the pyrite and arsenopyrite, usually with some peripheral replacement. Tungstates are represented by small quantities of a member of the wolframite-huebnerite series, which is younger than arsenopyrite, and possibly younger than pyrrhotite, and by scheelite of unknown age forming thin shells around, and blebs in, the wolframite; it is either a younger deposit or an alteration product of wolframite. In some slides the wolframite occurs as prismatic crystals up to a millimetre in length showing perfect lamellar twinning, which is visible even with only one nicol. Chalcopyrite is closely associated with pyrrhotite, but younger than it. Exsolved cubanite is not characteristic of the chalcopyrite in this deposit, but it has been detected in some specimens. Sphalerite is abundant in the ore, and it is the rule rather than the exception that it contains exsolved chalcopyrite. This exsolved material has migrated to the margins of crystals such that large patches of sphalerite are revealed as mosaics of smaller crystals, each of which is framed in a narrow, discontinuous rim of chalcopyrite blebs. Where galena borders sphalerite, the exsolved chalcopyrite has become trapped along the contact, and replaces the galena. Although sphalerite is in the main younger than the primary chalcopyrite, and frequently replaces it, these two minerals certainly crystallized side by side during part of the vein's history, and some sphalerite is encircled by chalcopyrite. An interesting feature characterizing the sphalerite is the occurrence in it of slender laths of pyrrhotite. These are commonly less than 10 microns thick, and more than twenty times as long, and several may occur in the same sphalerite crystal in parallel orientation. While these might conceivably be due to exsolution, it is considered more likely that they represent accidental inclusions, for plates of pyrrhotite of this shape also occur isolated in the quartz, where it is clear that they are not due to exsolution. Galena followed sphalerite, and, like it, forms relatively large areas in polished section, up to one or two millimetres across. It is abundant also as smaller grains and veinlets avidly replacing arsenopyrite and pyrite; in particular, the shreds of vein quartz and host rock occurring as inclusions in these two sulphides have been attacked. Where it occurs in this fashion, the galena is frequently wedge-shaped or triangular in outline, pseudomorphous after the patches of quartz in clusters of tightly packed euhedral arsenopyrite crystals. Particular care was devoted to the identification of a mineral very closely associated with the galena, and sometimes enclosing it and showing the same relationships towards the other sulphides as does galena, such as vigorous attack on arsenopyrite. This mineral, determined as tetrahedrite, shows an olive tint against the white of galena, and is slightly harder than it. It is isotropic, unaffected by the standard etch reagents, and microchemical tests give positive reactions for copper and antimony. The identification was confirmed by determination of the reflectivity, which is 30.7%, matching the value of 31.2% given by Folinsbee (1949). Microchemical tests failed to indicate the presence of silver or arsenic in the tetrahedrite. This mineral crystallized in very minor amounts at about the same time as chalcopyrite, but it is only in the company of galena that it occurs in any abundance. Thus it is in the main a late mineral. A mineral not commonly encountered in Southern Rhodesian ores, and tentatively identified as pyrargyrite, $3Ag_2S. Sb_2S_3$, was detected in a single polished specimen only: extended search failed to reveal it in any others, and it is thus to be considered present in very minor amounts only. This is grey with a bluish tint, and deep-red internal reflection, similar to sphalerite. It reacts positively with 1:1 HNO_3 and 5% KCN, and weakly with 20% KOH. The list of minerals with red internal reflection given by Short (1940) does not include many species, and the identification seems reasonably certain. The presence of tetrahedrite in the ore makes its occurrence probable. The two grains found were too small to permit accurate determinations of reflectivity, but yielded values within 5 per cent of those quoted by Folinsbee for pyrargyrite. Its rarity in the ore leaves its position in the paragenesis in some doubt, but, as far as could be determined, it replaces chalcopyrite and galena.

Gold occurs in all of the specimens examined, but the manner of occurrence is so varied that a special section is devoted below to its description. An interesting occurrence is that of the same mineral which was tentatively determined as aurostibite in the Lone Hand ore. The appearance and physical and etch properties of this mineral are identical in the Lone Hand and Jessie ore specimens, so further description is redundant. It nearly always occurs in intimate association with gold and is contemporaneous with it, as either one may enclose the other. The presence of native antimony has been established beyond question in polished concentrates, by its hardness, colour, isotropism and reflectivity, which latter was determined as 74.6%, matching closely Folinsbee's (loc. cit.) value of 74.4%. Microchemical tests gave positive reactions for antimony in even exceedingly small grains. The mineral was not detected, however, in any of the polished specimens of the ore itself.

(b) Occurrence and Associates of Gold

The study of the gold is of particular interest and significance, for it is associated with a variety of minerals with which it may be intergrown and with which it is therefore presumably contemporaneous. It also shows a very variable silver content, and, like the gold in the Olympus mine, there is a correlation between the silver content and the age of the mineral with which it is intergrown.

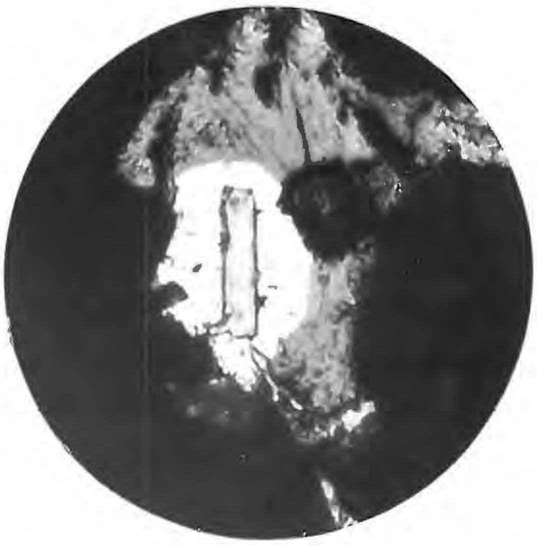
The colour of the gold shows every gradation from the pale silvery yellow of electrum to the deep yellow characteristic of gold over 900 fine, and there are in addition differences in mode of occurrence and grain size in the different types. That gold which, by its textural relationships, is clearly late in the paragenesis, is of a rich golden yellow, whereas that which, by virtue of its textural relationships towards sphalerite is deemed to be earlier, is pale yellow or even creamy, not unlike pyrite.

(i) Silver-rich Gold.

This occurs as coarse-grained patches partly or wholly enclosed in sphalerite (Plate X, Fig. 1) and some of it shows against sphalerite the sinuous outlines characteristic of "mutual boundaries" texture, which is generally accepted as evidence of contemporaneous crystallization. Gold of this type does not commonly occur interspersed with the purer material, but tends to be confined to veinlets of sphalerite, or to occur intergrown with tiny irregular patches of sphalerite in the quartz. In addition to the zinc sulphide, other younger sulphides may wrap around this early gold. Fig. 2 of Plate X illustrates an example where gold is moulded on a euhedral lath of pyrrhotite, and the whole then set in younger tetrahedrite. Plate XI, Fig. 1 shows gold accompanying galena, both replacing arsenopyrite. In this latter case, however, the gold is perhaps a little younger than that accompanying sphalerite.

Coarse gold is encountered from time to time during the daily panning of samples which is carried out as a rough check on the character of the ore being developed. The writer has been shown coarse, jagged pellets, up to one-quarter of an inch across, recovered in this way. Some of this material has a brassy appearance very unlike pure gold, although some, again,

<u>Fig.1</u> Coarse-grained, silver-rich gold enclosed by sphalerite. In both colour and grain size it differs markedly from gold occurring as discrete grains. x 360.



<u>Fig.2</u> Gold (white) surrounding a lath of pyrrhotite (light grey), and in turn enclosed by tetrahedrite (scratched and pitted). x 750.

Fig.1 Pale-yellow gold (light grey) and galena (deeper grey) replacing and sending off tongues into arsenopyrite (medium grey). x 360.

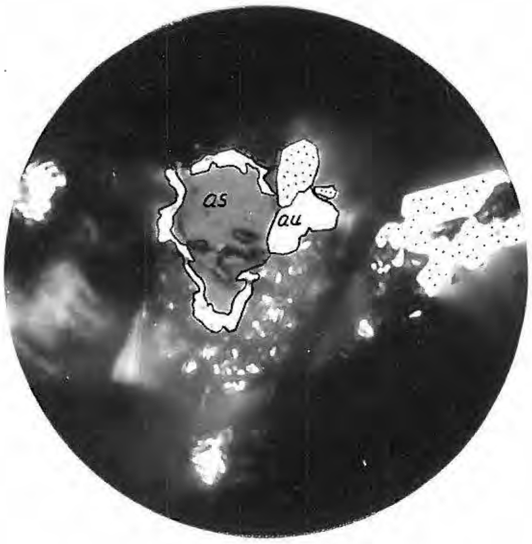


Fig.2 Gold (white) completely rimming aurostibite (?) (grey). Arsenopyrite also in field (stippled). x 750.

Plate XII

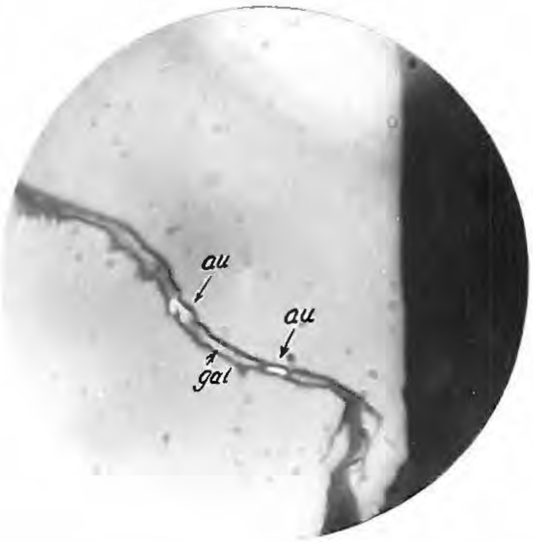


Fig.1 Tiny segmented vein of gold and galena filling a fracture in arsenopyrite. Texture indicative of simultaneous crystallization of gold with galena. x 750.

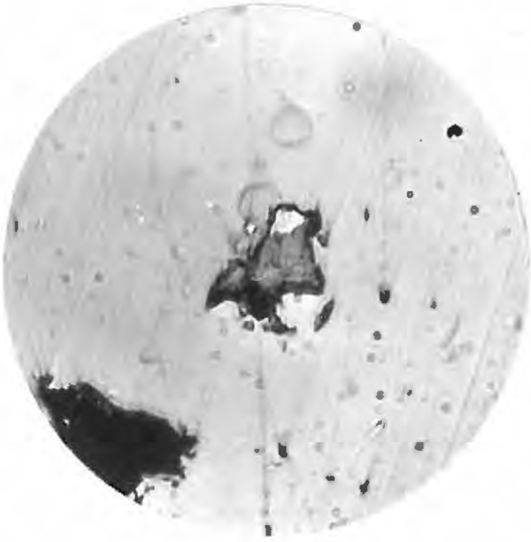
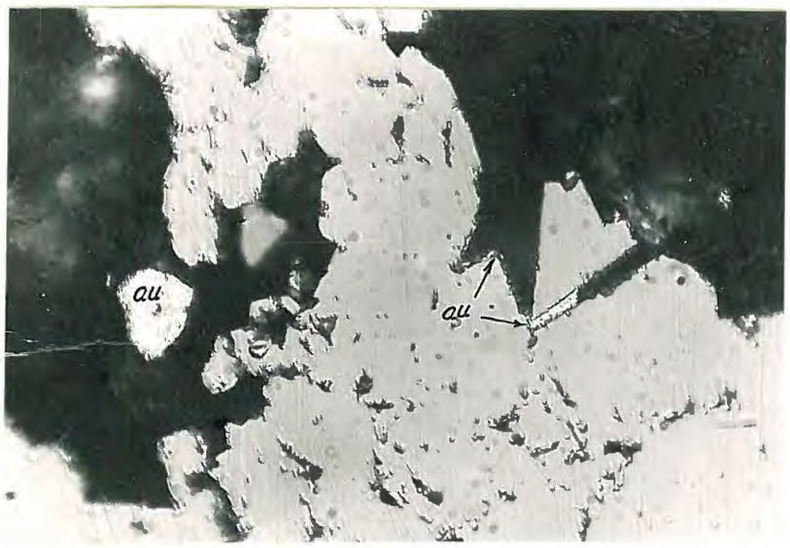


Fig.2 Gold (light grey) closely associated with galena (dark grey) in the interior of an arsenopyrite crystal. x 750.

Plate XIII



Gold occurring as discrete grains, and as coatings on arsenopyrite crystals or filling fractures in it. x 360.

is more yellow than this. Two samples of this coarse gold, given to the writer for study, were submitted for assay. Both were virtually clean metal with only a little adherent quartz. The two specimens were determined as 655.1 and 771.6 fine respectively, and thus the existence of coarse free gold with a high content of silver is established beyond question.

As the colour of this early gold may be exceedingly pale, it is apt to be confused with pyrite in sections free from polishing relief. This error may be guarded against by making frequent use of the microphotometer, when even an approximate reflectivity value makes misidentification impossible.

(ii) Silver-poor Gold

The mode of occurrence of fine gold is very different ~~to~~ from that of silver-rich gold. Where its textural relationships towards other minerals can be interpreted, the gold is found to be late in the paragenesis, and occurs moulded on, or replacing, the several sulphides. A great deal of the pure gold occurs as discrete granules in the vein quartz. It has also been found intergrown with aurostibite (?), a very late mineral, and some of the purest gold with a distinct ruddy tint occurs moulded on aurostibite (?), as shown in Plate XI, Fig. 2. Again, some fine gold is moulded on sphalerite, and although its exact age is not known, it is clearly younger than that which is intergrown with sphalerite. The contemporaneity of some pure gold and galena is proved by the occurrence of these two minerals in the form of segmented veinlets filling microscopic fractures in arsenopyrite, as in Plate XII, Fig. 1. Bastin (1957) considers segmented veins to be evidence in favour of simultaneous crystallization.

In those specimens with abundant arsenopyrite, gold can be detected without difficulty if high-power objectives are employed. Here it occurs as very tiny grains averaging 7 microns in size and seldom reaching 15 microns. These are invariably deep yellow, and favour the shreds and inclusions of quartz and altered host rock which are common in the arsenopyrite. They may share this environment with equally tiny masses of galena, such that the two minerals lie in contact (Plate XII, Fig. 2). Gold also occurs here as fracture-fillings and as coatings a few microns thick (Plate XIII).

It is significant that the arsenopyrite-rich specimens do not show more than traces of the lower-temperature minerals such as sphalerite, chalcopyrite or galena, while even pyrrhotite is uncommon. It is in these specimens only that wolframite, a mineral characteristically early in the general order of crystallization, has been detected. It is the writer's conclusion that in these specimens gold was precipitated late relative to the arsenopyrite and pyrrhotite, but in a high-temperature environment which was not conducive towards precipitation of more than traces of the medium- and low-temperature minerals.

(iii) Grain Size.

It has been shown that silver-rich and silver-poor gold in this ore occur in different ways. A second feature, grain size, also helps to distinguish the two types. The silver-rich gold, close to sphalerite in age, is almost invariably coarser in grain than the purer metal. Measurements made under the microscope support this generalization, for the average grain size of 54 grains of a deep yellow colour is 14 microns, that of a further 26 occurring with arsenopyrite is 7 microns, while that of 16 pale-coloured grains intergrown with sphalerite is 34 microns. Here the measure of average grain size is taken as the square root of the product of the measured length and breadth of the gold grains encountered in polished section.

This tendency towards a reduction in grain size in the later stages of vein formation has been commented upon by the present writer in other deposits described.

(iv) Statistical Data

The difficulties attending any statistical study of gold in polished section need no emphasis due to its sparse occurrence unless the specimens are wonderfully rich. Accordingly, the following observations are considered to be sufficiently suggestive to merit incorporation in the text, even although they do not carry the weight which would have been lent by a greatly prolonged and more detailed study.

Table 13

Manner of Occurrence of 112 Gold Grains in Jessie Ore

Manner of Occurrence of Gold Grains	Colour of Grains		
	Pale Yellow	Medium Yellow	Deep Yellow
Intergrown with or enclosed by sphalerite	16	-	-
Intergrown with or enclosed by galena tetrahedrite	5	-	-
Moulded on or replacing pyrrhotite sphalerite chalcopyrite galena	-	4	5
Moulded on or replacing arsenopyrite (with or without accompanying galena)	-	3	26
Associated with aurostibite	-	-	7
Occurring as discrete grains	-	4	42

Table 13 shows the distribution of all gold grains encountered in polished sections of this ore. These data were obtained by traversing under high-power objectives at intervals of 300 microns, using a mechanical stage. It is seen that the palest gold is intergrown with or enclosed by sphalerite, galena or tetrahedrite, while the purest is associated with aurostibite or occurs as discrete grains, while some is moulded on the early sulphides. A relatively large number of grains occur in the interiors of arsenopyrite crystals, where they may or may not be accompanied by traces of galena.

The data of Table 13 are interpreted as follows. In the early stages of vein formation, the amount of gold precipitated was small, probably not forming grains of visible size. Thus arsenopyrite, pyrite and pyrrhotite show no evidence of contemporaneous gold. As vein mineralization proceeded, chalcopyrite and sphalerite appeared, and were accompanied by silver-rich gold which formed coarse-grained masses which came ultimately to be enclosed by continued crystallization of sulphides. In places gold, chalcopyrite, and sphalerite grew side by side, resulting in the texture characterized by 'mutual boundaries'. With the advent of galena and tetrahedrite, the chemical and physical attributes of the vein-forming fluids were undergoing change so as to cause the gold being precipitated to be of higher fineness. It is logical to assume that this stage of vein mineralization was sufficiently drawn out so that all galena in the ore is not of precisely the same age. Accordingly, some gold associated with galena and tetrahedrite resembles more closely the early gold, and some more closely the later gold. This would account for some of the gold, intimately associated with the galena, being pale, while the rest is of a higher degree of purity, such as that accompanying galena in the replacement of arsenopyrite. In the closing stages of vein formation, very pure gold was precipitated in an environment favouring the concomitant separation of aurostibite and native antimony. It is clearly not possible to assign an age to the discrete gold which does not impinge upon any other ore minerals apart from quartz, but its fine grain and deep colour suggest that most of it is late gold.

Experimental Sampling

Thirteen ore samples were taken for assay in order to gain an indication of the range in gold-silver ratios. These samples were assayed first for gold, subsequently concentrated by panning, and the concentrates then assayed for both gold and silver. In two cases the ore samples were assayed direct for both gold and silver without panning. The results of this experiment are shown in Table 14.

It is seen that the fineness of some gold exceeds that of the highest value recorded for gold recovered by amalgamation, thereby establishing the presence of relatively small pockets of ore in which the gold is considerably purer than average. The highest fineness of amalgam gold has been determined as 819, whereas two assays here show gold above 860 fine. It is noteworthy that these specimens are conspicuously rich, assaying close to 2 and 8 ounces per ton respectively. The experiment also shows that very low-grade specimens are characterized by a high proportion of silver. Thus, four samples, all containing less than 4 dwt./ton, show apparent fineness ranging from about 600 to below 300. To what extent these low values are influenced by the presence of silver other than that alloyed with gold, or analytical error, is not precisely known, although the microscopic examination of concentrates shows that these can be no more than contributory factors, for these concentrates contain more pale gold than the others.

In between those samples showing the extremes of pure gold on the one hand and silver-rich gold on the other, the remainder show fineness values and gold contents which are intermediate in degree. These represent mixtures of both fine and impure gold in different proportions.

Table 14

Assays of Jessie Mine Samples

Sample No.	Sample Assay (dwt./ton)	Conc. Assay (dwt./ton) Gold	Silver	1000 Au / (Au + Ag)
36	162.7	n.d.	n.d.	876
3881	39.5	116.7	18.6	862.5
35	8.0	n.d.	n.d.	792
3882	20.1	40.4	10.7	790.6
3879	9.4	46.3	18.2	717.8
3874	73.0	437.8	191.0	696.2
3876	14.8	40.1	25.8	608.4
3877	2.0	9.3	6.5	588.6
3880	19.8	75.5	55.2	577.6
3875	25.2	164.6	130.9	557.0
3873	1.8	4.0	3.7	519.4
3878	3.6	11.8	13.4	468.2
3883	1.5	23.7	60.1	282.8

The data have been plotted in Fig. 13, which brings out the existence, albeit somewhat loosely defined, of a correlation between apparent fineness and tenor. Such a relationship could not be detected from production data, probably due to the relatively small variation in fineness of amalgam gold arising out of the 'averaging-out', or mixing of gold of different types in the mill.

The statement made above, that the variable apparent fineness of concentrates is due to the occurrence in them of different proportions of gold of varying degrees of fineness, can be substantiated by a grain count. It can also be shown that even the highest indicated fineness of gold as determined by assay (876), falls short of the fineness of some of its constituent grains. Representative samples of the concentrates, mounted in small cylinders of plastic resin and polished, were examined under the

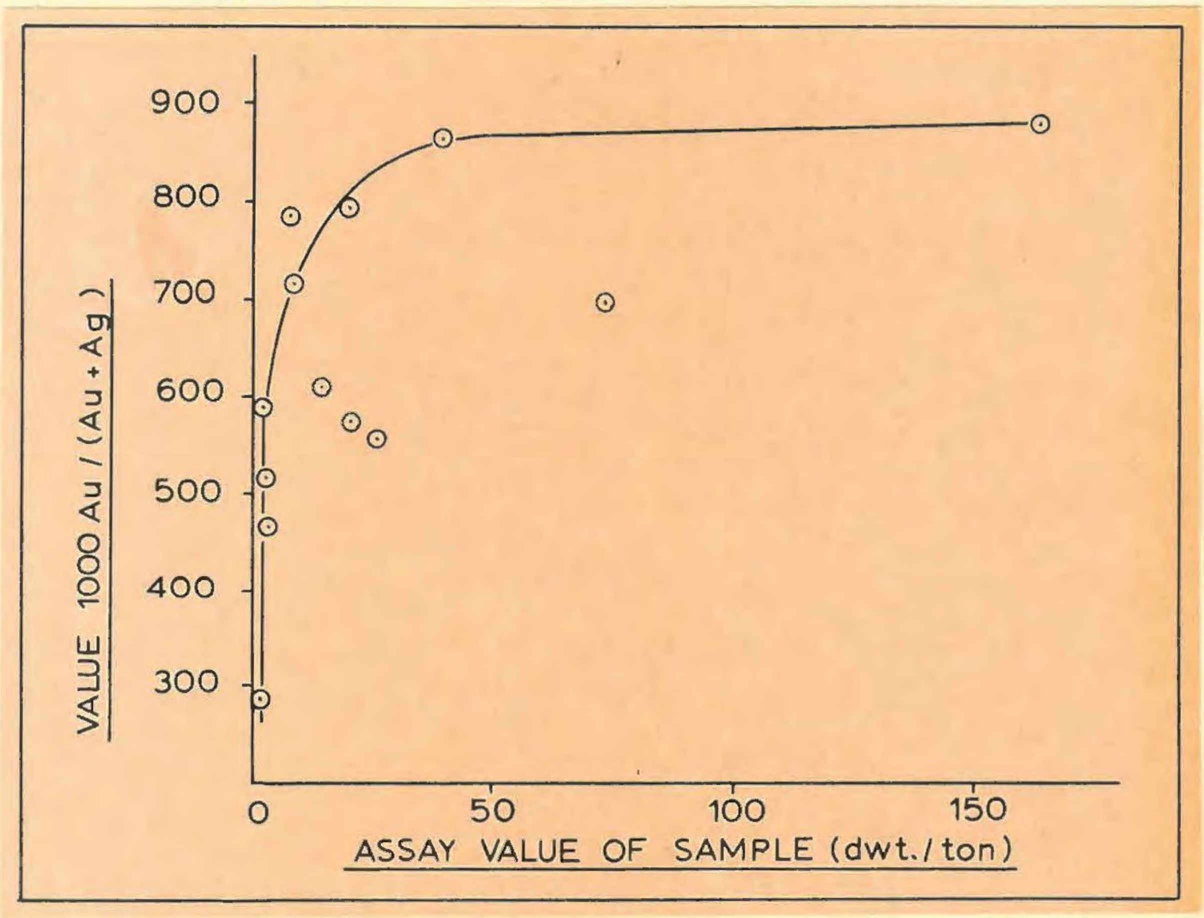


Fig. 13. Apparent Fineness Values Plotted Against Grade of Jessie Mine Samples.

microscope. The results of this examination are given in Table 15, which shows the average distribution of gold grains of different degrees of fineness for every 10 grains encountered. It will be noted that as the apparent fineness of each sample increases, the proportion of pale-coloured grains decreases. At the same time, the reason why some relatively high-grade specimens fall below the mean curve in Fig. 13 becomes clear; these are specimens which contain a particularly high content of coarse-grained, silver-rich gold.

Table 15

Character of Gold in Jessie Mine Concentrates

Assay (dwt./ton) Sample	Concentrate	Apparent Fineness	Occurrence, per 10 grains of gold Pale Yellow	Medium Yellow	Deep Yellow	Reddish Yellow
1.5	23.7	283	6	1	3	-
25.2	164.6	557	4	5	1	-
73.0	437.8	696	3	5	1	2
20.1	40.4	791	1	5	2	2
39.5	116.7	863	1	4	4	1

E. THE TURK MINE

Abstract

The Turk mine lode, a pyritic impregnation in greenstone, shows a correlation between the purity of the gold and the richness of the ore. This is apparent both from production data and from experimental sampling. There is also a suggestion of a general decline in gold fineness with increasing depth. The sulphide mineralogy is exceedingly simple. The manner of occurrence of the gold is described.

Introduction and General Geology

The Turk mine, located some 35 miles north-east of Bulawayo, has been described in some detail by Macgregor, Ferguson and Amm (1937, p. 161), who write as follows:

"The ore body is a lode formed of quartzy impregnations in a strong shear-zone traversing the greenstones. In places it contains quite solid quartz reefs, and it appears that it was these quartz bodies which first attracted attention to the deposit, and that the importance of the impregnated greenstone as a source of ore was not fully realised for some time."

The width of the shear zone averages 50 or 60 feet, and the payable sections are lenticular in shape, approaching a thousand feet along strike, and some 20 to 25 feet in width. Along the shear zone the greenstone is strongly carbonated.

Production and Fineness Data

The production data show that the average grade of this deposit is low. Since 1932 the recovered grade has not risen above 4 dwt./ton, while the average has been closer to 2.5 dwt./ton. In the initial years, however, when attention was directed only to the quartz veins which form part of the lode, the grade was remarkably high, and in 1921, the first year of production, an ounce and a half of gold was recovered per ton of ore. The tonnages treated during these early years were, however, low, reflecting the relative unimportance of this type of ore in contrast with the impregnated greenstone.

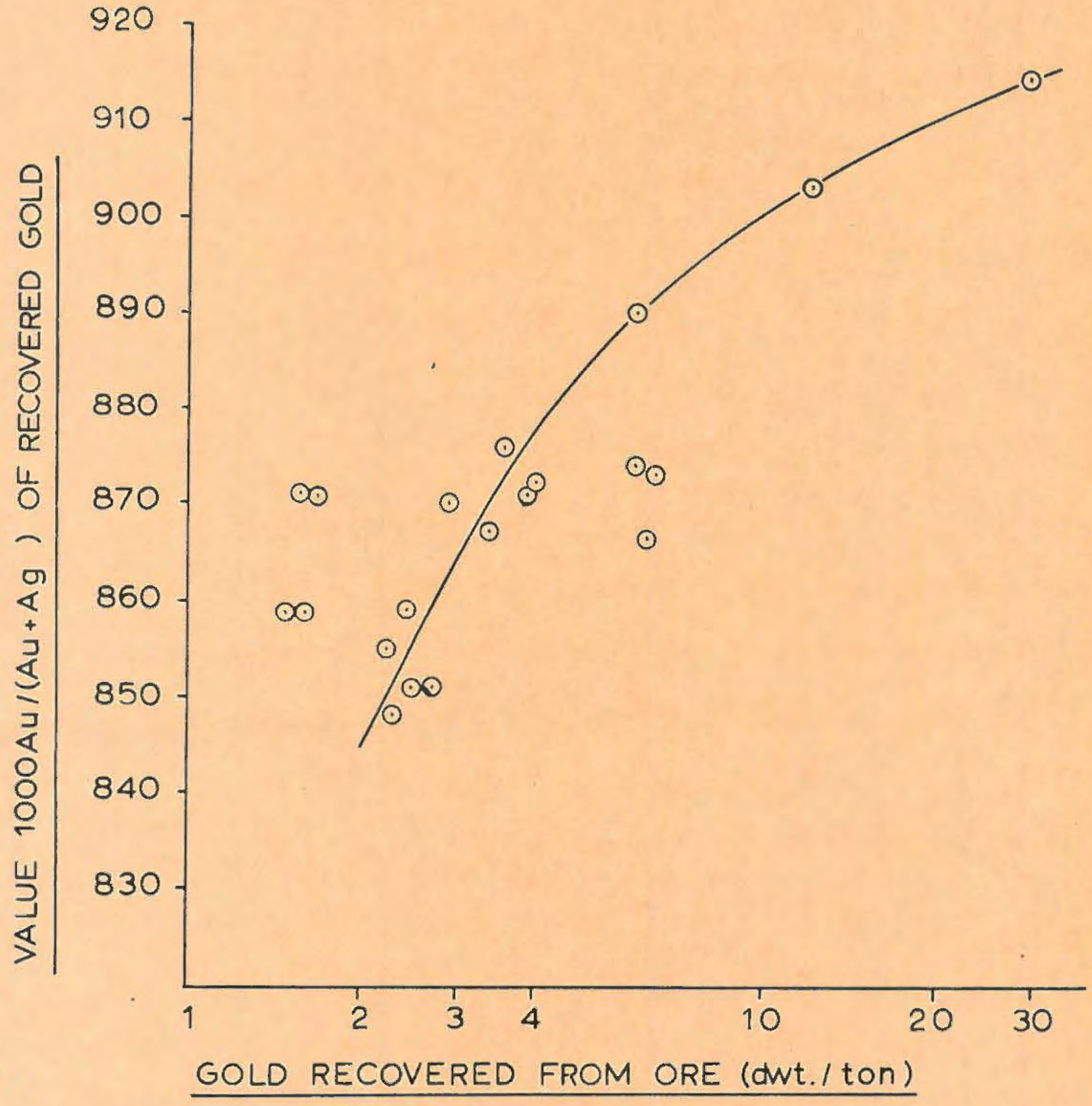


Fig. 14

RELATIONSHIP BETWEEN FINENESS AND GRADE OF RECOVERED GOLD AT THE TURK MINE, 1921 - 1956. EACH POINT REPRESENTS ONE YEAR OF PRODUCTION.

The decline in the fineness of the recovered gold synchronizes with the decline in the average content of gold in the ore. This is well illustrated in Fig. 14, where the fineness of the recovered gold has been plotted against the average recovery for each year during which gold was contributed only by the Turk Lode. In some years, ore from additional sources was mixed with Turk ore, and, accordingly, these outputs have been ignored. Most plotted points are seen to lie close to a mean curve, and the Turk mine thus provides another example in which fineness and tenor vary sympathetically. While it might be argued that during the initial years the high fineness was due to oxidation or secondary enrichment, due attention should be paid to the fact that during this period mining was highly selective: high-grade quartz was crushed and a high proportion of the gold was recovered by amalgamation. In subsequent years much more substantial tonnages of ore of a lower grade were treated by direct cyanidation after crushing, amalgamation having been abandoned with the step-up in tonnage milled in the new plant. In the account by Macgregor, Ferguson and Amm (loc. cit.) there is included a photograph taken underground, showing a very narrow stope on quartz reef, opening out into a very much wider stope later developed when the value of the impregnated rock was realized. This emphasizes the highly selective milling which characterized the early years of the history of the mine.

The decline in the fineness of recovered gold cannot with justification be attributed to changes in the methods of recovery. Thus, in the first year of production, the fineness of amalgam gold was actually a little lower than the fineness of cyanide gold, and thereafter was a little higher than it. The average fineness of both cyanide gold and amalgam gold fell with the decline in the average grade of ore treated.

Experimental Sampling

The Manager of the mine kindly supplied the writer with data bearing on the relative distribution of gold and silver in the ore. Assays were carried out, by the management, for gold and silver in 86 samples taken at 15-foot intervals along the 20th and 22nd level drives in the B Lode West Shoot. The results of this sampling are given in Figure 15 in which the calculated value 1000 Au/(Au + Ag) of each sample has been plotted against the gold assay. Although the majority of points are clustered in the 2-to-6 dwt./ton, 620-to-830 fineness field, and show little in the way of orderly distribution, samples above 830 fine tend to be considerably richer than average, and samples above 860 fine include only those assaying between 9 and 45 dwt. gold per ton. Conversely, all samples below 600 fine are low in grade, and the highest assay recorded in this category is only 3.1 dwt./ton. It is, however, quite likely that the very low apparent fineness values are slightly influenced by traces of silver introduced during assaying.

Here, then, is another clear example where experimental sampling has established a correlation between the apparent fineness and the total gold content in a series of samples representative of all classes of ore. One particular aspect calls for further discussion. The highest value for apparent fineness was found to be 882, which falls short, by 25 parts per thousand, of the highest value determined by actual recovery by amalgamation, during the first years of production when the ore came from shallow depths. This might be due to the maximum range in fineness values not having been realized in the experimental sampling, to the refining action of oxidation near the surface, or to an original decline in the average fineness of the gold with increasing depth at the time of deposition. It does not appear to be possible to establish which factor was most potent without a fuller investigation, but it is certain that the 'specimen' gold itself usually contains a little more silver

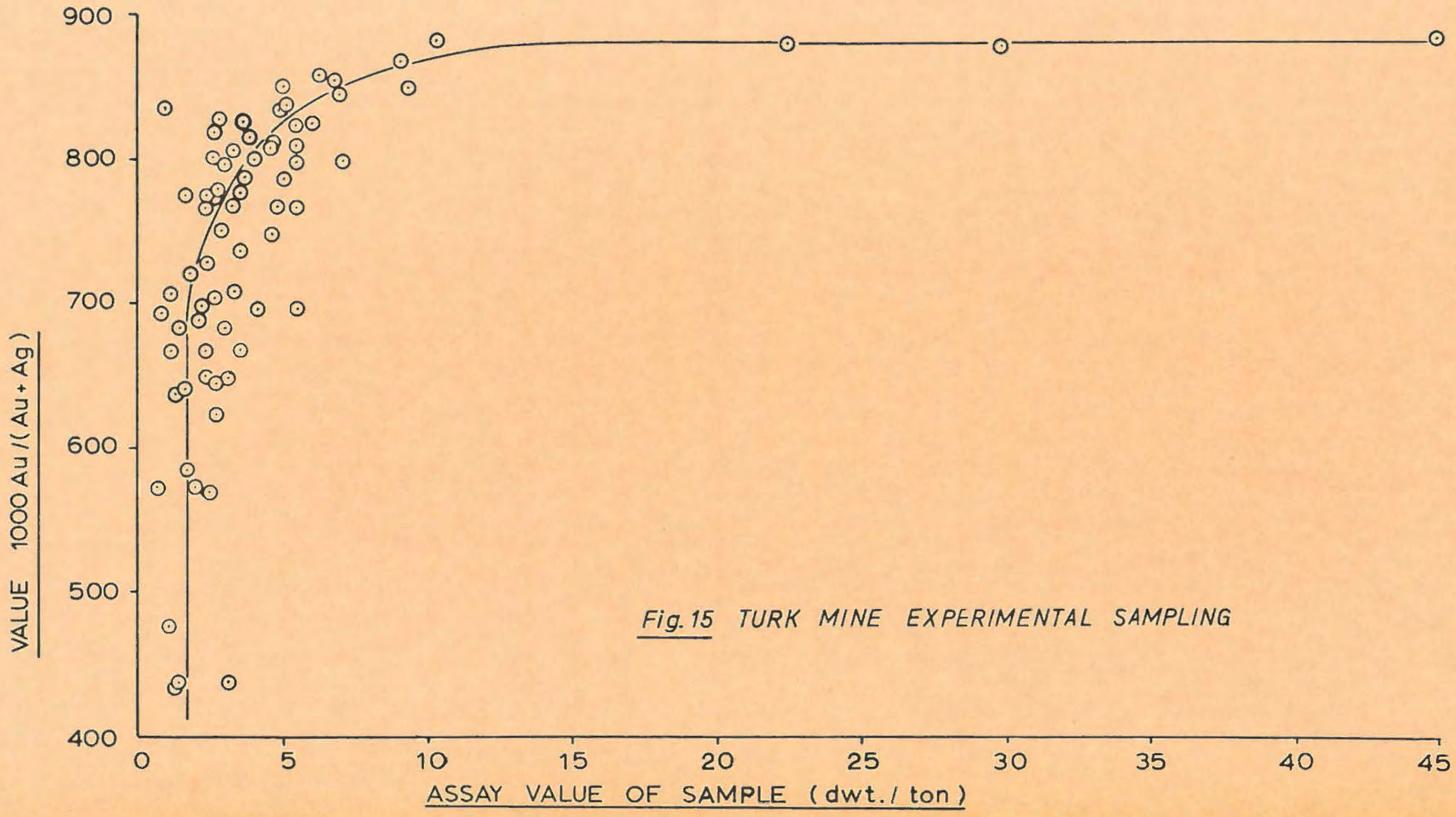


Fig. 15 *TURK MINE EXPERIMENTAL SAMPLING*

at 2,000 feet from surface than in the upper levels. Two hand-picked specimens of quartz, containing abundant visible gold and no other minerals apart from traces of pyrite, were assayed. The first, containing 37 dwt. gold per ton, indicated that the fineness was 860, and the second, containing 140 dwt. gold per ton, gave a value of 895, 12 parts per thousand less than the average fineness of gold recovered by amalgamation in the quartz veins close to surface.

The Evidence of Polished Sections

Specimens of ore collected by the writer on the 20th level reveal a very simple mineralogy. Sparsely disseminated pyrite is the only sulphide to occur in significant amount. Macgregor, Ferguson and Amm recorded the presence of arsenopyrite in small quantities, but none is present in the writer's specimens. The pyrite is in the form of subhedral and euhedral crystals, mostly about 1 mm square, and is often crowded with unreplaced host-rock fragments. Chalcopyrite is present in very small amounts, replacing the inclusions in pyrite and filling any available fractures or the interstices between pyrite crystals. Gold may be detected without undue difficulty under high magnification. It shows a distinct preference for the interiors of pyrite crystals, where it is found as tiny granules a few microns across. The largest grain encountered in this environment measures 13 microns, but most appear to be less than 5 microns. It is a curious feature that the gold seldom occurs as isolated granules, but rather as a ring of tiny satellites surrounding a relatively large central bleb (Plate XIV, Fig. 1). It appears as if the gold was introduced into the pyrite by replacement of the inclusions within it, and it is likely that chalcopyrite and gold are of approximately the same age, as they sometimes occur together, as illustrated in Plate XIV, Fig. 2.

The writer procured several specimens of the vein quartz containing visible gold, from depths greater than 2000 feet below surface. These specimens are of either white or grey quartz containing ribbons of incompletely replaced schistose material. Gold can be seen with the naked eye, in spite of its finely divided state, for grains tend to be clustered together, producing in the quartz yellowish patches or streaks. Under the microscope the only ore minerals detected were pyrite and gold, the latter ranging continuously in size from submicroscopic grains up to about 80 microns. The greak bulk of grains are, however, less than 30 microns in average dimension. It has been mentioned that where gold occurs in abundance in this way, it is purer than that which occurs in the less intensely metallized ore.

Plate XIV

Fig.1 Gold granules (centre of field) in pyrite from Turk mine. Note larger central grain with a halo of smaller granules, a mode of occurrence which seems to be common in this ore. x 360.

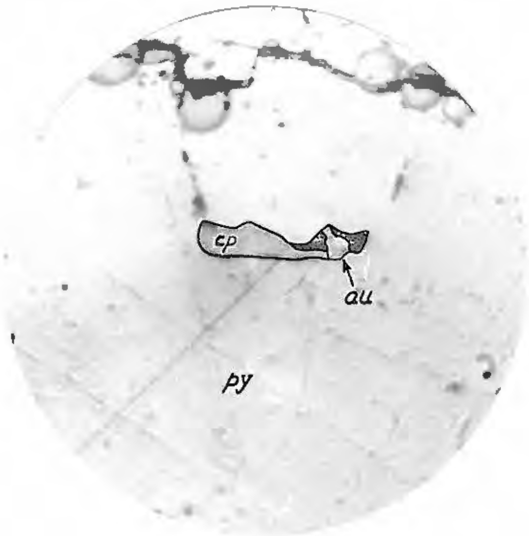


Fig.2 Gold and chalcopyrite replacing a shred of country rock (stippled) enclosed in the core of a pyrite crystal. x 750.

F. THE LONELY MINE

Abstract

This deposit is a quartz reef which contained abundant gold and sparse sulphides in the upper levels, but which failed at about the 25th level. Sulphides appeared in abundance only in depth. It is shown that gold fineness and total gold content declined with increasing depth. Different factors which could be correlated with these changes are discussed. The most significant of these appears to be a change in the habit of the gold. In specimens from the upper levels gold occurs as abundant grains of 'free' gold, whereas in depth it is intimately intergrown with sulphides. A greater proportion appears here to have separated at a relatively early stage in the paragenesis.

Introduction and General Geology

The Lonely mine, in the Bubi District of Southern Rhodesia, achieved enduring fame as a deposit of outstanding richness during the earlier years of gold mining in the territory. In the first twenty years of its life the average annual recovery was never less than half an ounce of gold to the ton, and was for most of this time nearer to an ounce. Unlike the untold number of deposits throughout the country which have showed great promise at shallow depths, but whose values proved to be ephemeral on further development, the Lonely Reef handsomely repaid treatment down to about the 27th level, a depth reached by a relatively small proportion of deposits in this country. Although development was still continued far below this level, the rich ore had been exhausted and the production data reflect the steady decline until the cessation of operations in 1944.

The deposit was described by Macgregor (1928) as a quartz reef, dipping at 80 degrees in the upper levels but flattening to near 60 degrees in depth, occupying a fault plane in limburgitic greenstone and serpentine. A later post-ore fault in the plane of the reef was traced to the greatest depths reached, and encountered in all sections of the workings as a clay seam, causing oxidation of the reef to depths unprecedented in the territory. At the 10th level the ore is said to have been completely oxidized, while partial oxidation of the ore was still apparent below 3,000 feet. Regarding the deeper sections of the workings, however, Macgregor states that "the oxidation takes the form of staining of the joints of the shattered quartz, and does not often involve complete oxidation of the sulphides."

In his brief description of the ore, Macgregor states that pyrite, as small cubes and pyritohedra, was the only sulphide found in the upper levels, and that other sulphides were met with only in depth. Coarsely crystalline sphalerite was encountered on the 25th level either intergrown with quartz or as solid lenses up to six inches thick, and on the 26th level galena and chalcopyrite appeared, cut by veinlets of sphalerite.

Production and Fineness Data

The complete history of production is recorded in the Gold Registers in the office of the Mining Commissioner in Bulawayo. The pertinent production data for the years 1907-1932 were taken from this source, and are here summarized in Table 16. The data for 1933-1944 have been omitted because they cannot strictly be compared with those for the earlier period. This arises out of the incorporation, with mill bullion, of gold produced by treatment of silver-rich mill slags, as well as significant changes in the milling procedure.

Table 16 Lonely Mine Production Data

Year	Gold Fineness			Recovery	
	Mill	Cyanide	Average	Total ozs.	dwt./ton
1907				1,678	35.3
1908				9,446	24.5
1909				13,397	22.7
1910			958.2	11,621	15.3
1911			955.7	21,814	19.5
1912			954.7	37,723	20.0
1913			958.0	52,011	17.6
1914			955.4	44,943	14.6
1915			954.5	36,799	12.9
1916			956.7	41,491	10.3
1917	955.5	949.4	951.2	52,626	18.2
1918	954.1	943.0	947.0	49,560	18.2
1919	950.5	947.0	947.4	71,800	25.9
1920	952.1	946.6	948.7	64,246	21.7
1921	948.6	941.7	943.7	56,625	19.2
1922	943.9	929.5	934.6	51,614	15.8
1923	943.2	929.8	930.7	45,536	13.9
1924	938.1	919.1	922.1	45,452	13.7
1925			903.1	37,299	11.7
1926			891.4	34,543	10.7
1927			910.3	31,137	9.9
1928			924.0	46,201	14.8
1929			932.4	49,368	15.6
1930	923.2	935.2	933.1	45,937	12.8
1931	932.6	936.1	935.5	38,255	9.2
1932	953.5	952.4	952.6	27,565	5.6

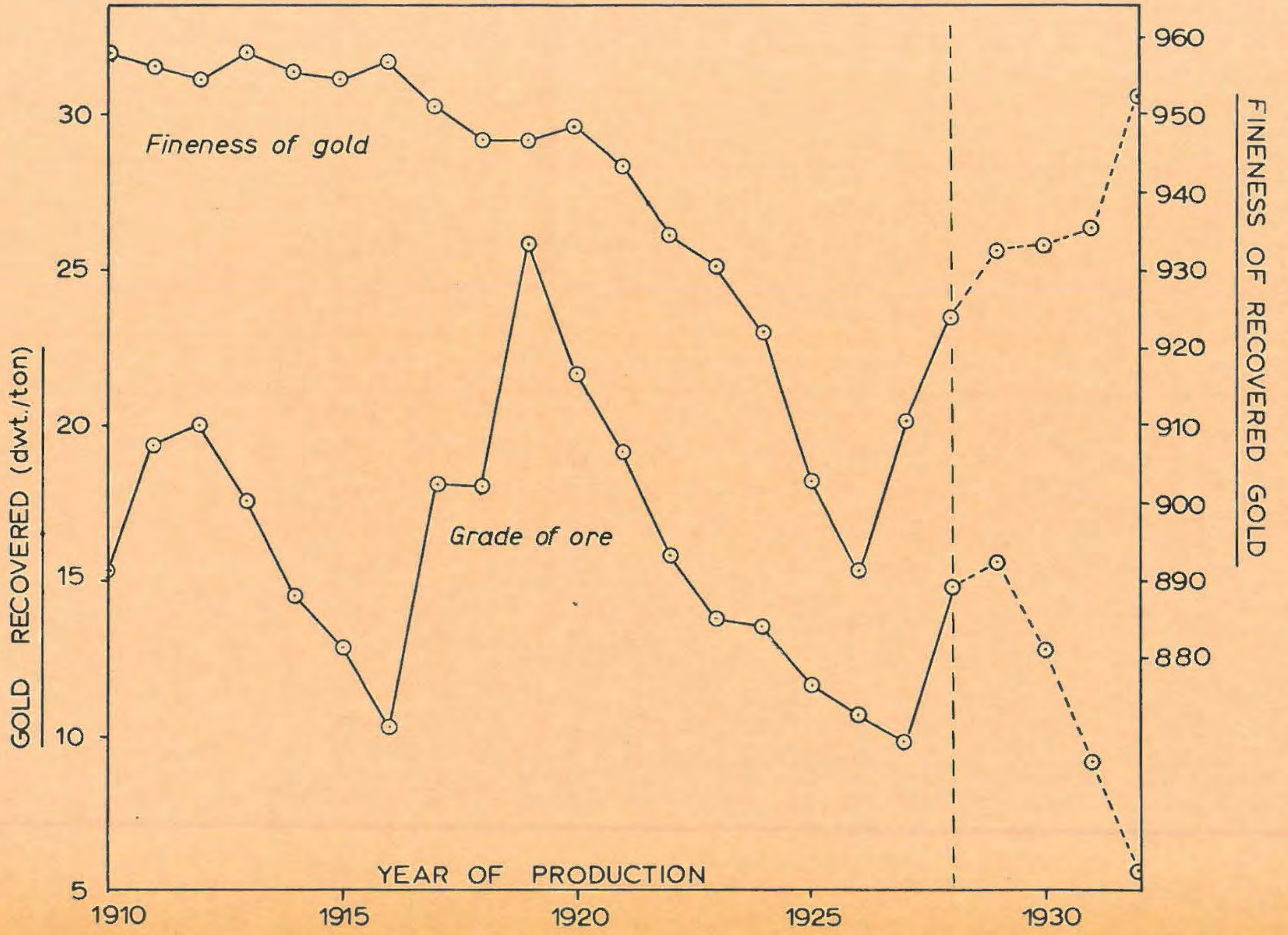


Fig. 16 LONELY MINE PRODUCTION DATA.

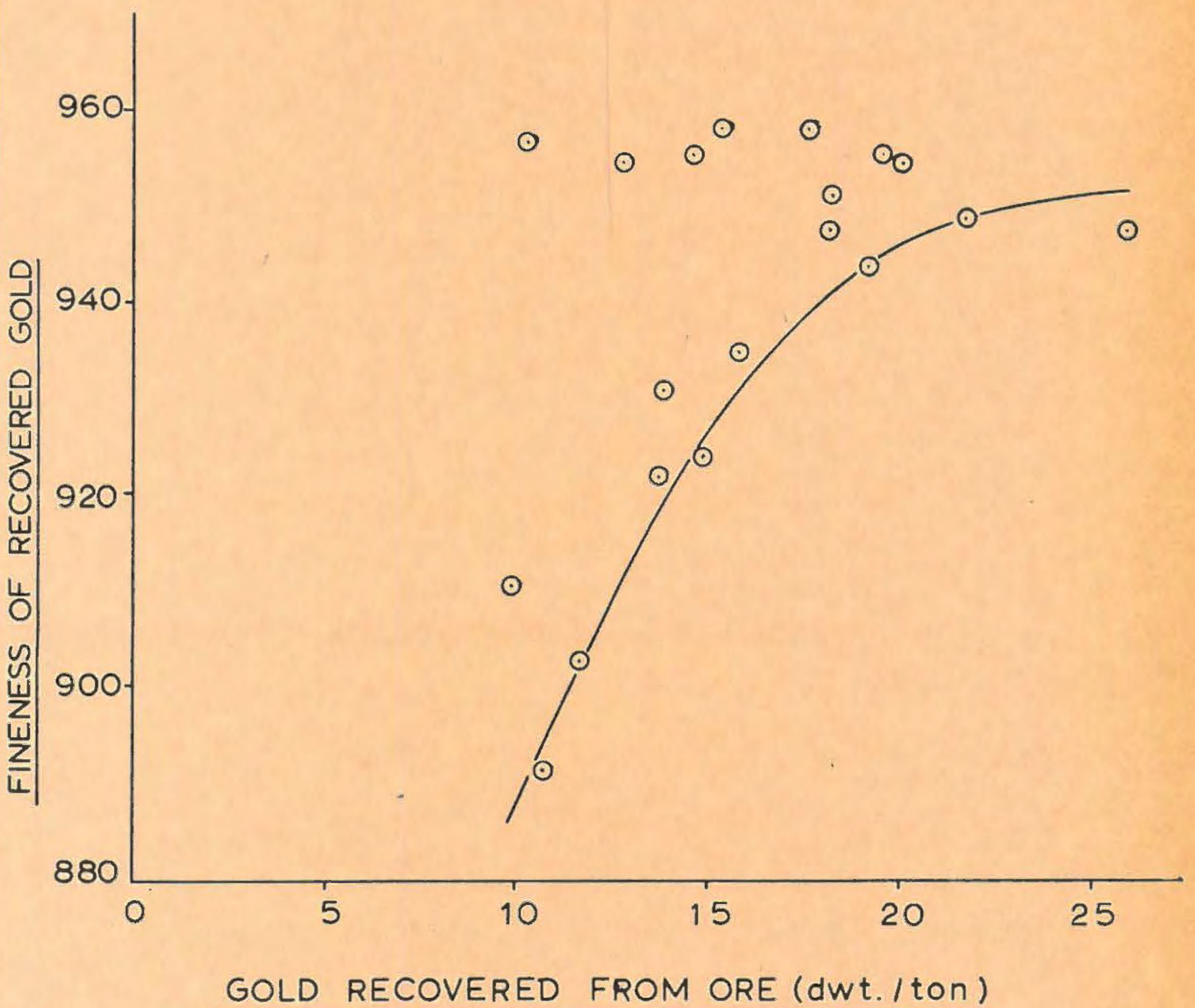


Fig. 17 *RELATIONSHIP BETWEEN FINENESS OF GOLD AND GRADE OF ORE AT THE LONELY MINE.*

The purpose of Table 16 is to illustrate the uniformity of gold fineness from 1910 to 1920 and the rapid decline between 1921 and 1926, running parallel with a steady fall-off in the average grade of the ore in the same period. The differences in the fineness of amalgam and cyanide bullion are generally so small that they may be disregarded, and attention directed to the average figures. The variation is best illustrated in Figure 16, in which year-to-year variations in grade and average fineness are represented graphically. Between 1910 and 1920 the fineness remained fairly constant regardless of the variations in gold tenor; from 1921 until 1928-1929 the two values declined sympathetically, while, after this, there was again no relationship apparent between fineness and tenor. The data have been represented graphically in Fig. 17, in slightly different form, where it is more clearly brought out that while either high- or low-grade ore might contain gold which is relatively pure, high-grade ore is never silver-rich. The shape of the mean curve which can be drawn through the majority of points, and the occurrence of other points well above the curve, but not below it, are characteristics by now familiar from other examples already studied. The sympathetic decline in fineness and average tenor after 1920 can be rather more forcibly brought out by plotting these two variables against each other, using monthly rather than annual outputs, but this diagram has been omitted as it merely repeats in detail Fig. 17.

These variations in gold fineness demand explanation. Macgregor, commenting on them, made no suggestions as to the ultimate cause, and confined himself to the observation that the decline in fineness with increasing depth was the reverse of what was found in the Kolar gold field. However, from the experience gained in the study of similar variations in other deposits, it is now possible to suggest an explanation for these features.

Factors correlated with Variations in Fineness

Any discussion of the probable causes of the variations in fineness must take into account each of the following factors:-

(a) Variations in the method of recovery,

(b) Oxidation of the ore,

(c) Variations in the average tenor of the ore,

(d) Depth, below surface, of source of ore,

(e) Zoning,

(f) Mineralogy.

It is proposed to discuss briefly each of these factors and to assess, where possible, to what extent they may have a bearing on the problem.

(a) Variations in the method of recovery

Excepting additions to the crushing section of the mill, the mine employed the same method of recovery from 1911 to 1927, and during these years the tonnage treated each month by cyanidation was equal to that crushed. After 1927 the tonnage treated by cyanidation reached, in some years, up to four times the amount crushed, due to the retreatment of accumulated residues and treatment of a further considerable tonnage by direct cyanidation. This change in milling procedure is mirrored by a rapid rise in average fineness during 1928-1932, until it equalled the value characteristic of the earlier years of production. The data for these years should thus be disregarded, for gold was during this period being recovered by retreating of material stemming from numerous sources. Accordingly, a demarcating line has been drawn in Fig. 16 to separate returns for this period from those prior to 1928.

(b) Oxidation of the Ore

The influence of oxidation on the purity of the gold alloy is here an unknown factor. The work of several authors, in particular Fisher (1935) points, in general, to the efficacy of oxidation as a refining agent in certain environments. Macgregor, who discussed the oxidation of the ore, stressed the extreme depths to which it has been active in this deposit, although he qualified the discussion with the statement that in the deeper levels "the oxidation takes the form of staining of the joints of the shattered quartz, and does not often involve complete oxidation of the sulphides". While the possibility that oxidation may have played some part in the refining action of gold in the upper levels cannot be denied, it is considered that this effect would have been quite subsidiary to other factors, discussed below, which experimental work now shows to have had a profound influence on gold purity.

It is perhaps relevant to note that Swiegers (1948, p.124) found that, in the Pilgrims Rest district of the Transvaal, Au/Ag ratios were no higher in thoroughly oxidized ores than in sulphide ores.

(c) Variations in the Average Tenor of the Ore

As described on a previous page, there is a correlation between fineness and tenor which is similar to that which has been established in other deposits studied. Portions of the ore body which carry gold of high fineness may range in grade from very high to low, but ore in which the gold is silver-rich has almost invariably a low total gold content.

The cause of this relationship is discussed in a succeeding section. It is held that changes in physico-chemical conditions prevailing during deposition must have influenced both factors.

(d) Depth Below Surface of Source of Ore

Macgregor has established that the decline in gold fineness may be correlated with the increasing depth of the workings. The following discussion appears in his report:-

"The returns show that there has been a slight but gradual drop in the fineness of the gold from the surface downwards. For the gold above the 10th level the average fineness was 958. During the years between 1915 and 1921 a large number of stopes were being worked, and it is not possible to draw any useful conclusions regarding the fineness of the gold from the returns. In 1921, however, ore was taken mainly from the stope above the 21st level, and the fineness was 951. In the next year the stopes above and below the 22nd level were being worked and the fineness was 934; similarly the ore taken in 1923 from the stopes above and below the 23rd level has a fineness of 930. During 1924, 1925 and 1926, when ore at still greater levels has been worked, the fineness dropped to 920, 902 and 891 respectively."

(e) Zoning

The examination of available data suggests a zonal distribution of ore minerals. Macgregor described how pyrite was the only sulphide in the ore down to the 25th level, where sphalerite appeared, and which was then joined by chalcopyrite and galena below the 26th level. The mine sampling statistics showed a drastic reduction in the payable length of ore from 500 - 1100 feet above the 25th level down to 600 feet on the 26th level, 130 feet on the 27th level and thereafter a few hundreds of feet, at best, to the deepest level reached. Again, sampling showed that the average computed value of reef varied anywhere between 11 and 54 dwt./ton from the 27th level upwards, whereas below this the average values ranged merely from 1 to 4 dwt./ton, and the computed reserves showed a reduction in gold content between the 24th and 27th levels from 36,000 ounces to 3,300 ounces per level. All these features serve to create an impression of radical change in the general character of the ore body, under the influence of zoning, at about the depth of the 25th level. Conditions of mineralization appear to have been uniform down to about the 21st level, below which zonal change was heralded by dropping gold fineness. Below this again, where copper, lead and zinc sulphides appeared in significant quantities, the gold fineness dropped below 900.

It thus becomes essential to establish whether there is any discernible difference in the general character and mode of occurrence of the gold in the upper levels, and in the deeper levels where sulphides become conspicuous. This work is discussed below.

(f) Mineralogy

The Lonely mine having closed down nearly 20 years ago, it was impossible to procure such specimens as one would select during a personal examination. However, those that were obtained from the Southern Rhodesian Geological Survey and the National Museum suggest an explanation for the decline in gold fineness which is in complete harmony with observations made independently during the study of other deposits in the territory. Far from denying correlations between fineness, tenor, depth of source and zoning of the ore body, the mineralogy brings out most forcibly that these are merely different responses to the changes in physico-chemical conditions during vein formation.

The ore specimens which the writer was able to gather together fall into two categories:-

(i) Specimens of vein quartz with very sparse sulphides, from the higher levels of the mine, and

(ii) Specimens, rich in sulphides, from below the 25th level.

(i) Vein Quartz from the Upper Levels.

These specimens consist of medium-grained vein quartz with numerous closely spaced films of yellow-green chloritic material (ribbon structure). A typical specimen is shown in Plate XV. Sulphides are present in such small amounts that

Plate XV

Handspecimen of Lonely mine quartz reef from 17th level, showing ribbon structure. Sulphides are too fine in grain to be visible. Natural size.

they could be overlooked on casual examination. With a hand lens, however, strings of tiny pyrite crystals can be seen along the greenish 'ribbons' in the quartz. Under the microscope these pyrite crystals are seen to range in size down to the lower limits of visibility, and to occur either in tiny clusters or in strings. There also occur in the quartz very rare patches, 1-2 mm across, where it is dark grey or black, suggesting the presence of finely dispersed metallic minerals other than pyrite. Several polished specimens were prepared from quartz containing these tiny spots, and ultimately there was revealed an opaque mineral occurring in the form of clusters of minute grains, just sufficiently large to permit determination of their physical properties and reaction with etch reagents, as well as a rough determination of their degree of reflectivity. This mineral, which the writer concludes is bournonite, Cu_2S. 2PbS. Sb_2S_3, is opaque and weakly anisotropic between crossed nicols, when it shows multiple twinning in the form of parallel lamellae. Its colour is white with a bluish tinge, and it appears to be softer than chalcopyrite with which it may be found in contact. The standard etch reagents have no effect on it. A tiny chip of quartz containing this mineral was repeatedly treated with 50% HNO_3 and evaporated to dryness with gentle heat until the quartz became colourless, indicating that the ore mineral had passed into solution. The solution, tested according to the scheme of Short (1940, p.270) gave positive results for copper, lead and antimony, thus supporting the identification as bournonite. The reflectivity, determined to be approximately 32.5%, is reasonably close to the value of 34.5% assigned by Moses or 35.5% assigned by Folinsbee (1949) to bournonite. Occurring with the bournonite are tiny grains of chalcopyrite, which are definitely older, for the former either encloses the chalcopyrite completely or forms discontinuous rims around it. A third mineral, with higher reflectivity and lower degree of hardness, occurs intimately intergrown with the bournonite. Its identity could not be established, due to its very finely divided state. In colour it is silvery white and between crossed nicols it is isotropic.

Chief interest in these specimens centres around the gold. The specimens procured proved to contain abundant finely divided gold, although none whatever is seen in unpolished specimens, even in the face of careful search with a hand lens. The gold occurs in clusters of exceedingly small but abundant grains, usually close to the strings of tiny pyrite crystals, and, quite definitely, most of the gold is concentrated in the ribbons of chloritic material rather than in the quartz. A statistical count, embracing 558 grains, showed 432 (77.4%) of the grains to occur discrete in the gangue, 51 (9.1%) to be touching pyrite or moulded to its outlines, and 73 (13.1%) to be wholly enclosed in pyrite. A great proportion in this latter category do not appear to occupy fractures in the pyrite, and are almost spherical in shape. 2 grains were found intergrown with an unidentified, opaque, grey mineral.

The colour of gold grains in these specimens is a rich golden yellow, and no variation in colour could be detected. Where grains of chalcopyrite occur in the same field with gold, the former are by contrast pale yellow with a faint greenish tinge. An assay of a composite sample of this ore gave an apparent fineness value of 940 and the gold content was 17.4 dwt./ton.

The range in size of gold grains was investigated statistically. The length and breadth of each grain were measured, and the average dimension expressed as the square root of the product of the two measurements. While this does not necessarily correspond to grain size such as would be determined by sieving, it is a useful index for studying the frequency of occurrence of grains of different sizes. The results of this investigation are shown in Table 17, and also a rough indication of the proportion of gold contributed by each fraction. This latter was arrived at by assuming that the mass of each grain is proportional to the cube of the average dimension. While this would introduce only a small error in the case of equidimensional grains, the error clearly becomes progressively more serious as the grains assume tabular or lath-like habits. The actual error introduced cannot be estimated, but examination of the measurements shows that approximately 45 per cent of all grains have a length-to-breadth ratio of 1.0, a further 40 per cent a ratio between 1 and 2, and the remainder a ratio above 2.0.

Some conclusions of a general nature can be drawn from this data. By far the greatest number of grains are exceedingly small, more than 70 per cent being less than 5 microns in size. As the average size increases the number of grains decreases, and ultimately the number whose average dimension exceeds 20 microns is only 1.5 per cent of the total. At the same time, the proportion of the total mass of gold contributed by the small grains is almost negligible, for those grains below 5 microns in size represent only 4.3 per cent of the total gold in the ore. The largest proportion of gold is contributed by the relatively small number of large grains: those above 20 microns constitute more than 50 per cent of the total mass of gold. In general terms, then, the ore is characterized by finely divided gold; the actual size of the largest grain seen in any of the polished sections is 65 x 20 microns. To what extent these measurements are characteristic of the ore body cannot be determined without a larger collection of specimens.

Table 17

Grain Size of Lonely Mine Gold

Particle Size (microns)	Number of Grains	Percent. of Grains	Volume Factor (V)	Percent. x (V)	Weight per cent	Cumulative Weight Percent.
1	90	16.1	1	16	0.0	0.0
2	112	20.1	8	161	0.3	0.3
3	81	14.5	27	392	0.7	1.0
4	77	13.8	64	883	1.5	2.5
5	47	8.5	125	1063	1.8	4.3
6	31	5.6	216	1210	2.1	6.4
7	23	4.1	343	1406	2.4	8.8
8	25	4.5	512	2304	3.9	12.7
9	15	2.7	729	1968	3.4	16.1
10	17	3.0	1000	3000	5.1	21.2
11	8	1.4	1331	1863	3.2	24.4
12	4	0.7	1728	1210	2.1	26.5
13	4	0.7	2197	1538	2.6	29.1
14	4	0.7	2744	1921	3.3	32.4
15	2	0.4	3375	1350	2.3	34.7
16	3	0.5	4096	2048	3.5	38.2
17	3	0.5	4913	2457	4.2	42.2
18	3	0.5	5832	2916	5.0	47.4
19	1	0.2	6859	1372	2.4	49.8
20	0	0.0	8000	0	0.0	49.8
21	2	0.4	9261	3704	6.4	56.2
22	0	0.0	10648	0	0.0	56.2
23	2	0.4	12167	4867	8.3	64.5
24	1	0.2	13824	2765	4.7	69.2
25	0	0.0	15625	0	0.0	69.2
-30	0	0.0	19683	0	0.0	69.2
-35	3	0.5	35937	17969	30.8	100.0

Edwards (1955) has described the variation in grain size of gold in ore from the Hill 50 Gold Mine in Western Australia. The same increase in the number of particles with decrease in grain size is reported, while the bulk of the gold here is also contributed by the coarser particles. In the present writer's examination a decrease in the number of particles below 2 microns is indicated by the measurements. This is at variance with Edwards' conclusions, and also with those of Joralemon (1951) at the Getchell mine; in both cases there was found a steady increase in the number of gold particles down to the 1 micron fraction. It is more than likely that the present writer's findings for the 1 micron fraction are inaccurate. With the equipment and polishing apparatus available, it is possible that many grains of this size are either not rendered visible or are overlooked, causing the number of grains in this fraction to be underestimated by a few per cent, whereas those around or greater than 2 microns would not be missed.

(ii) Sulphide-bearing Specimens from below the 25th Level

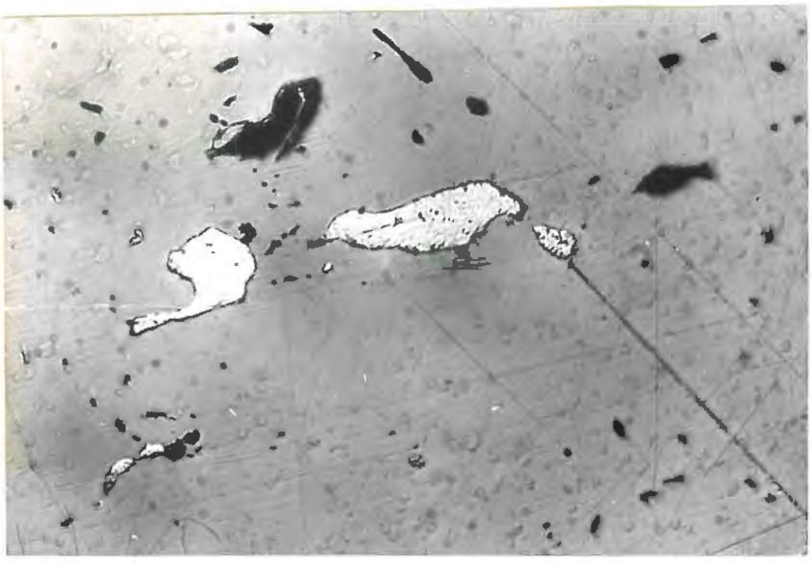
Two specimens of ore with abundant coarse-grained <u>chalcopyrite</u> and <u>sphalerite</u>, and one of sphalerite without chalcopyrite were available for study. The mineralogy proved to be fairly straightforward although the paucity of material leaves in doubt the identity of one mineral which is present.

Chalcopyrite-rich specimens show a coarse intergrowth with sphalerite, and these two minerals occur in about equal proportions with quartz. Either sulphide may form patches up to several centimetres across, but each patch is a mosaic of smaller grains. In addition, <u>pyrite</u> was detected under the microscope as tiny grains enclosed by the other sulphides, and <u>galena</u> as tiny euhedral cubes in quartz, possibly pseudomorphous after pyrite, as galena in ores of this type tends, in general, to be without crystal faces. The presence of <u>pyrargyrite</u> as exceedingly tiny grains is suspected, but this could not be confirmed. The chalcopyrite is unaccompanied by cubanite, but this is not unexpected, as no pyrrhotite occurs in the ore. The sphalerite, which is younger than the chalcopyrite, contains exsolved chalcopyrite occurring as plates and blebs aligned with geometric precision.

Although the specimens are not rich in gold, sufficient was detected to establish its nature and mode of occurrence, and in these respects it contrasts most strikingly with gold from higher levels. In all, ten grains were located. All are wholly enclosed in chalcopyrite without visible fractures, and their appearance suggests that they are contemporaneous with chalcopyrite (see Plate XVI). The crystallization of chalcopyrite appears in places to have been protracted, such that it is intergrown with galena and gold and all three are contemporaneous. No gold was found with pyrite or in quartz in these specimens, and sphalerite appears also to be barren. The colour of the gold is a pale yellow, and while, in the upper levels, chalcopyrite appeared pale by contrast with the gold, the reverse is now the case. The gold is silvery, indicating a much higher content of silver.

There are differences in grain size which deserve comment. In a preceding section the variation in grain size of gold in the vein quartz was discussed in some detail, when it was pointed out that the proportion of the total number of grains with their average dimension greater than 5 microns was small. Yet of the ten grains described here, two are larger than any so far encountered (75 x 20 microns and 52 x 28 microns respectively), and five of the ten exceed a mean dimension of 12 microns. In the specimens from higher levels only 6 per cent of the total number were found to exceed this particular size. It is clear, then, that there is a tendency for grains of gold intimately associated with the chalcopyrite to be larger in size, as well as richer in silver, than those occurring with pyrite or as discrete grains in the upper levels.

Plate XVI



Pale-yellow gold enclosed in coarsely crystalline chalcopyrite from deeper levels of Lonely mine. This gold is considered to have crystallized at a relatively early stage. x 360.

It may be concluded from this study that, in the deeper portions of the ore channel, gold was precipitated in only small amounts, and then in company with chalcopyrite and sphalerite. This gold alloyed with more silver than that which was precipitated higher up in an environment in which sulphide minerals were deposited in only exceedingly small amounts. Here, too, conditions favoured the throwing-down of gold in copious amounts. Consequently, the most significant changes in the character of the ore body with increasing depth are a decrease in the fineness of the gold, a decrease in average grade, and a change in the manner of occurrence of the gold grains.

G. THE BLANKET 'A' MINE

Abstract

This deposit is a hypothermal impregnation of arsenopyrite with subordinate ferberite, pyrite, pyrrhotite and chalcopyrite, in greenstone. The fineness of recovered gold is remarkably constant, and the study of polished sections shows that there is a scarcely perceptible variation in the colour of the visible gold in the ore. This uniformity of composition is correlated with its invariant position late in the paragenesis, in which respect it differs from deposits thus far described where the fineness varies widely. The study of borehole core samples suggests that pyrrhotite contains small amounts of gold and a relatively greater proportion of silver, and this view is confirmed by assays of separate samples of pyrrhotite and arsenopyrite. While arsenopyrite has been most effective as a precipitant of gold, pyrrhotite appears to have been ineffective.

Introduction and Outline of Geology

The Blanket 'A' mine is one of a long line of mining claims along a zone of mineralization extending for about 10 miles along the strike of the schist belt north-west of Gwanda. This particular deposit has many features in common with the other deposits north-west and south-east of it along the same line, particularly with regard to the character of mineralization and structure, although the host rock may vary from place to place.

The deposit was not described by Tyndale-Biscoe (1940) in his account of the Gwanda area, but a comprehensive examination in the form of mapping and sampling of the underground workings was carried out by the writer during a series of visits between 1955 and 1957. Briefly, it may be designated an impregnation of arsenopyrite with subordinate pyrite and pyrrhotite in biotite-actinolite schists of the Greenstone Series which here strike north-west and dip south-west at about 70 degrees. The sulphide mineralization takes the following forms:

(i) Coarse-grained, roughly parallel sets of veins of arsenopyrite in contorted rock. These veins are individually up to two inches thick, closely spaced and follow the grain of the country rock, forming strongly mineralized zones, reaching up to several feet in width. Plate XVIII, Fig. 2, illustrates the contortion which may characterize these veins.

(ii) Thinner veinlets, partings and lines of arsenopyrite crystals along the cleavages of the host rock, forming zones which may be of considerable width. These are illustrated in Plates XVII and XVIII. The passage from inferior to superior ore is typically marked by the transition from material of this type to the coarser-grained sulphide ore described above.

(iii) Disseminated, fine-grained sulphides in a hard, fine-grained, silicified greenstone superficially resembling a quartzite, but formed by the metasomatic introduction of quartz and albite. These bodies are irregular in shape, often cutting across the general strike of the greenstones against which sharp contacts are shown. They may locally be crowded with unreplaced remnants of the latter, which have their longest axes aligned parallel to each other and to the regional strike. This type of ore has generally a moderately high gold content, and the unreplaced residuals are, in particular, liable to be very heavily impregnated with sulphides.

Mineralization appears to have been related to the development of openings in the rock, as it is often found to be best developed where structures are present which would have facilitated the passage of ore fluids. Thus, strongest mineralization often occurs where there is local flexing with divergence from the regional strike, and the weak drag folds which are seen in the workings are usually favourable structures.

The overall picture, then, is one of narrow but high-grade lenses and pods of ore within a broad zone of mineralization. In places, the sampling indicates an overall average of 2-3 dwt. gold per ton over widths of close upon 100 feet. Such great widths are not common in the territory.

Plate XVII

Mineralized greenstone exposed in stope on 2nd level of Blanket 'A' mine.

Fig.1 Mineralized greenstone. Face of drive on 2nd level, Blanket 'A' mine.

Fig.2 Contorted mineralized greenstone. Face of drive on 2nd level, Blanket 'A' mine.

Fineness of Recovered Gold

Gold is recovered by barrel amalgamation of a heavy concentrate representing the first-cut from James tables, and cyanidation of the residues. One-half to two-thirds of the gold is recovered by the amalgamation, but the ore as a whole tends to be refractory, retaining from 20 to 30 per cent of its gold in the residues after treatment. The average recovery from the ore stoped is of the order of 2-3 dwt./ton.

The silver content of the gold recovered by amalgamation is remarkably constant. Eleven separate outputs during 1955-1956 show the true fineness to vary from 901 to 921, of which ten outputs range between 901 and 913. The grand totals of gold and silver recovered by amalgamation during this period indicate an average fineness of 908.8. The fineness of the gold recovered by cyanidation would at first appear to vary more widely than this. Twenty-three outputs indicate a range in 1000 Au/(Au + Ag) values from 833 to 946. It is clear, however, that this variation arises, not so much out of variations in the composition of the gold in the ore, as variations in conditions of smelting. In addition to the gold outputs from cyanidation, small recoveries are periodically made by the retreatment of accumulated slags and matte. Although not invariably so, these are mostly characterized by a high silver content, and the 1000 Au/(Au + Ag) value may fall as low as 783. If the grand totals of the gold and silver recovered by cyanidation and from slags and matte are used, the average fineness of gold recovered is 913.8, a figure almost identical to that characterizing amalgam gold.

There can be no hesitation, then, in stating that the fineness of the bulk of recovered gold varies between very restricted limits. In this respect it differs from deposits like the Olympus, Lone Hand and Jessie mines in which the silver content of the amalgam gold varies between wide limits, and in which this variation in silver content may be correlated with variations in the tenor of the ore. It becomes of particular importance, then, to establish the causes of this fundamental difference, and the most satisfactory answer seems to be given by the detailed study of the manner of occurrence and position in the paragenesis of the metallic gold in the sulphide ore.

The Evidence of Polished Sections

The study of a number of polished sections varying in tenor from high-grade to low reveals an uncommonly simple assemblage of minerals. The assemblage is typically what would be expected in a hypothermal deposit, and the low-temperature sulphides and sulpho-salts are not represented.

(a) Minerals Present

Arsenopyrite was the first mineral to crystallize by replacement of the country rock. It varies in form from acicular idiomorphic crystals to a mosaic in which crystal faces are seldom developed, due to the interference during growth between neighbouring crystals, especially in ore in which arsenopyrite constitutes more than 90 per cent of the specimen. Growth-zoning is clearly defined by rows of inclusions parallel and concentric to the faces of idiomorphic crystals (Plate XX, Fig. 1). In size, these are usually less than 3 mm. The arsenopyrite was followed by a grey, opaque mineral which is present in only small amount, and which is considered to be ferberite. This is moderately anisotropic, shows weak colour pleochroism with one nicol and is scratched only when applying firm pressure with a sharp steel needle. It is unaffected by all standard etch reagents. Insufficient material was found for a positive wet test for tungsten. The reflectivity, relative to arsenopyrite, pyrite and pyrrhotite standards, was determined as 20.3 per cent using the standard values of Moses (Short, 1940, p. 295) and 19.2 per cent using the standard values of Folinsbee (1949). In these tables the

Plate XIX

Handspecimen of mineralized greenstone schist, Blanket 'A' mine. Arsenopyrite is the chief sulphide, but pyrite and pyrrhotite are present in subordinate amounts. Two-thirds natural size.

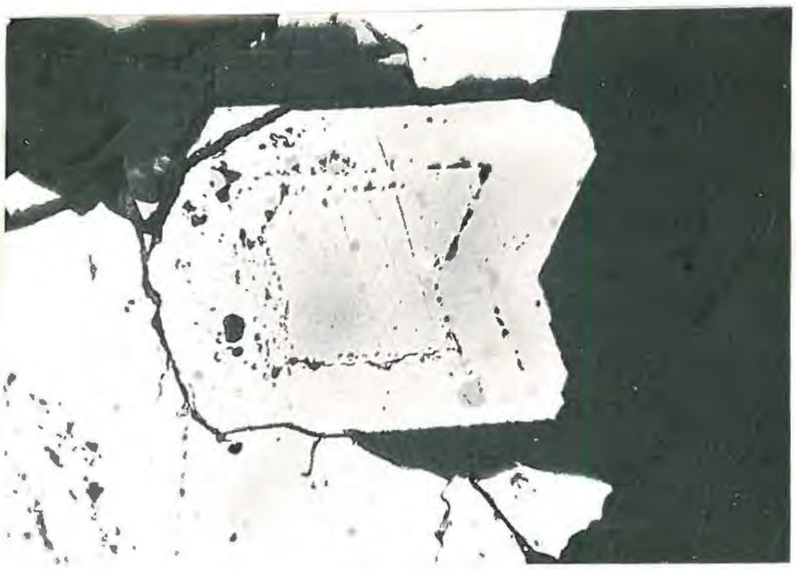


Fig.1 Zoning of twinned arsenopyrite crystal defined by rows of inclusions of unreplaced host rock. Inclusions are in turn partially replaced by pyrrhotite and chalcopyrite. x 360.

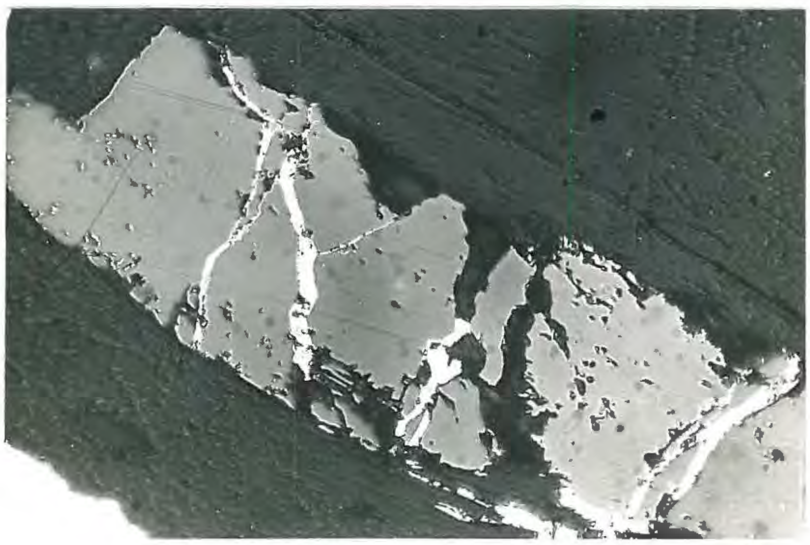


Fig.2 Vein of ferberite (grey) criss-crossed by tiny stringers of pyrite (black patches are pits and cracks in specimen). x 360.

reflectivity of ferberite is given as 19.0 per cent and 17.9 per cent respectively, showing that, within experimental error, the mineral in question corresponds with ferberite. It occurs as isolated crystals or veinlets within the host rock, but also as coatings around arsenopyrite. Pyrite followed, and is always allotriomorphic, favouring the interstices between arsenopyrite crystals and filling the fractures in them, or in ferberite (Plate XX, Fig. 2), or more rarely, replacing the arsenopyrite. Pyrite is also crowded with shreds of unreplaced host rock, and frequently occurs as mossy clumps representing the early arrestment of the replacement of the rock in which it occurs. Pyrrhotite followed pyrite, enclosing and replacing it, but it is worth recording that these two minerals never appear in quantity in the same specimen: one or the other is always present in overwhelming amount. It would be going too far, however, to suggest that the two minerals are mutually exclusive. The last sulphide to commence crystallization was chalcopyrite, which is only a minor constituent of the ore, occurring in the interstices between older crystals, but most frequently surrounding, replacing or occurring close to pyrrhotite. Gold, the last mineral to form, is detected without difficulty in all high-grade specimens, forming films, perhaps only a few microns thick, in fractures in pyrite and arsenopyrite, or tracing out the tortuous paths of inter-grain boundaries. Much of it is in the form of pellets in the gangue. There is no suggestion that this microscopically visible gold is anything but a late mineral, as it is never intergrown with earlier minerals, nor was it enclosed by other crystals at the time of their growth.

(b) Textures and Structures

The texture is an interesting one in that it represents growth in a solid medium. For that reason the sulphides, particularly arsenopyrite and pyrite, are crowded with unreplaced remnants, often zonally disposed. The residual patches of host rock trapped between growing idiomorphic crystals are for the same reason often polygonal, being bounded by straight edges meeting in re-entrant angles (Plate XXI, Fig. 1). With the advent of the younger sulphides, these remnants, and more particularly the inclusions in arsenopyrite , were subjected to further replacement by pyrrhotite, chalcopyrite and gold. The zoned crystals are thus sometimes characterized by regular, oriented 'inclusions' of these minerals. The misinterpretation of these zonal inclusions of chalcopyrite and pyrrhotite would lead to the adoption of an incorrect paragenetic sequence, of which the prolonged crystallization of arsenopyrite to the last stages of sulphide mineralization would be an essential feature. Such an interpretation would undoubtedly be incorrect. This late-stage replacement of inclusions also accounts satisfactorily for the rare occurrence of gold in shreds of host rock enclosed in the interiors of arsenopyrite crystals, where there are no visible fractures to account for their presence.

Fracturing has been an important feature accompanying mineralization. This may be correlated with the buckling which has been responsible for the superior mineralization in certain sections of the workings, and which was continued throughout the deposition of arsenopyrite, but became less prominent in the later stages of mineralization, although some specimens of pyrrhotite are weakly fractured. In freshly blasted faces underground, discordant pyrrhotite veinlets can be seen cutting obliquely across the arsenopyrite seams which follow the grain of the host rock. In polished section, fractures are found in arsenopyrite, most commonly healed with younger arsenopyrite or with pyrite.

(c) The Occurrence and Fineness of Gold

As has been pointed out, the gold seen in polished section shows a marked preference for the inter-grain boundaries

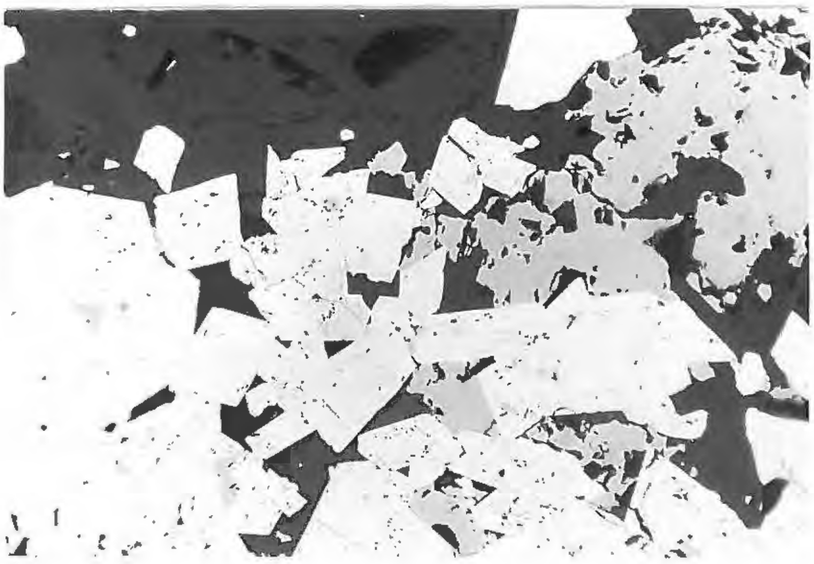


Fig.1 Development of a mozaic by interference between growing arsenopyrite crystals. Note polygonal areas of host rock partially replaced by pyrrhotite, also assuming polygonal shapes. x 120.

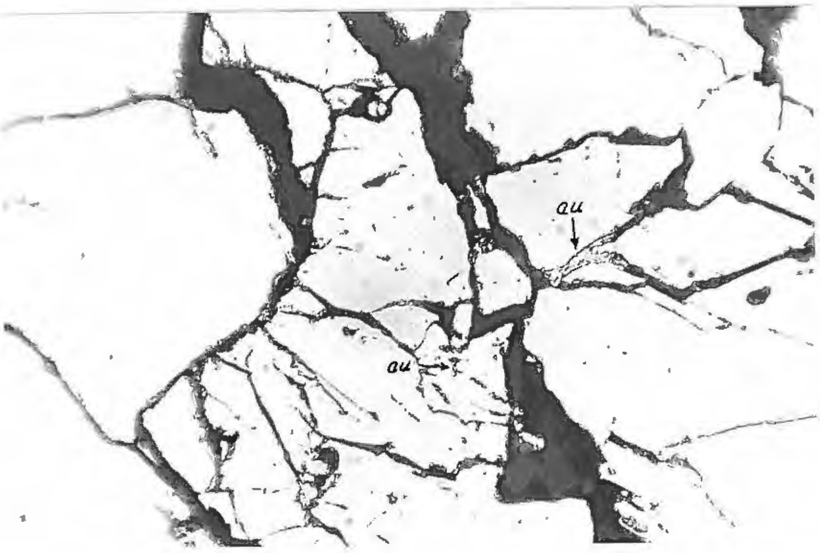


Fig.2 Ramifying veinlets and scattered granules of gold in fractured arsenopyrite. x 360.

Gold coating arsenopyrite crystals and penetrating fractures. x 360.

of arsenopyrite. A lesser proportion fills fractures (Plate XXI, Fig.2), replaces host rock remnants in sulphides or occurs as discrete grains. In polished section it has been found to vary in grain size from 1-2 mm down to the lower limit of visibility under the microscope, and in fractures it may form films only 1-2 microns thick (Plate XXII). It has been pointed out that the Blanket 'A' deposit differs from others examined in that the composition of both amalgam and cyanide gold does not appear to vary much. The microscope confirms this conclusion, and at the same time assigns gold to last place in the paragenesis. No textural evidence suggesting early gold has been found. In other deposits in which the gold varies in fineness between wide limits, evidence has been forthcoming in each case to show overlapping of crystallization of gold with each of several sulphides, and hence a relatively long period of crystallization. In these cases early gold contains a high proportion of silver, and late gold tends to be purer. In the case of the Blanket 'A' deposit there is, then, full justification for correlating the uniformity of gold composition with a uniform age.

Arsenopyrite can be shown to have been an efficient precipitant of gold, whereas pyrrhotite was ineffective. In the following test, coarsely crushed ore was hand-sorted, depending on the proportion of sulphide present, into different categories, each of which was then crushed further and grab-sampled. The test indicated the following distribution

Table 18. Sorting Test on Blanket 'A' Ore

Nature of Fraction	Weight (lbs.)	Assays (dwt./ton) Sample A	Sample B
Highly mineralized	329	7.7	4.0
Moderately mineralized	985	1.9	1.8
Weakly mineralized	310	1.0	0.9

There is no doubt, then, that the gold content is proportional to the amount of sulphide present. However, the indifferent character of pyrrhotite as a carrier of gold was repeatedly confirmed during underground sampling. In certain sections of the workings, where sulphide mineralization was as heavy as any found, but restricted to pyrrhotite, repeated sampling revealed no more than a pennyweight of gold. The gold values are associated with arsenopyrite.

The microscope confirms the conclusion reached on a previous page that "the fineness of the bulk of recovered gold varies between very restricted limits". Polished, mounted James table concentrates, which give an excellent mixed sample of gold from different working faces, show a scarcely perceptible variation in the colour of grains, which is a rich golden yellow. In these concentrates gold is abundant and there is ample material on which to base this observation.

Further information on the distribution of gold and silver in the ore is given by assays of core samples from an exploratory drillhole which passed from very lean ore into a narrow shoot of moderately rich ore, and then back into lean ore below. In Table 19 the borehole footages, the average gold assays of each two-foot length of split core, and the total gold and silver assays of three-inch lengths of core, selected from each two-foot section, are given. In Fig. 18, the data have been plotted graphically, and although these are scanty, it is clear that the apparent fineness increases rapidly as the total gold content of the samples increases. This is true even if allowance is made for the silver introduced into the sample with the litharge used in assaying.

Table 19. Assays of Sections of Diamond Drill Core Passing Through a Small Shoot of Ore, Blanket 'A' Mine.

Sample No.	Location	Average Gold Assay (dwt./ton)	Specimen Assay (dwt./ton)		$\frac{1000\ Au}{(Au + Ag)}$
			Gold	Silver	
3893	89'- 90'	0.8	0.7	0.3	700.0
3892	90'- 92'	0.5	tr.	tr.	-
3891	92'- 94'	1.0	tr.	tr.	-
3890	94'- 96'	6.2	4.0	1.6	714.2
3889	96'- 98'	10.6	9.2	1.6	851.8
3885	98'-100'	23.5	16.3	2.9	848.9
3886	100'-102'	11.6	8.2	2.1	796.1
3887	102'-104'	1.1	tr.	tr.	-
3888	104'-106'	1.4	tr.	tr.	-

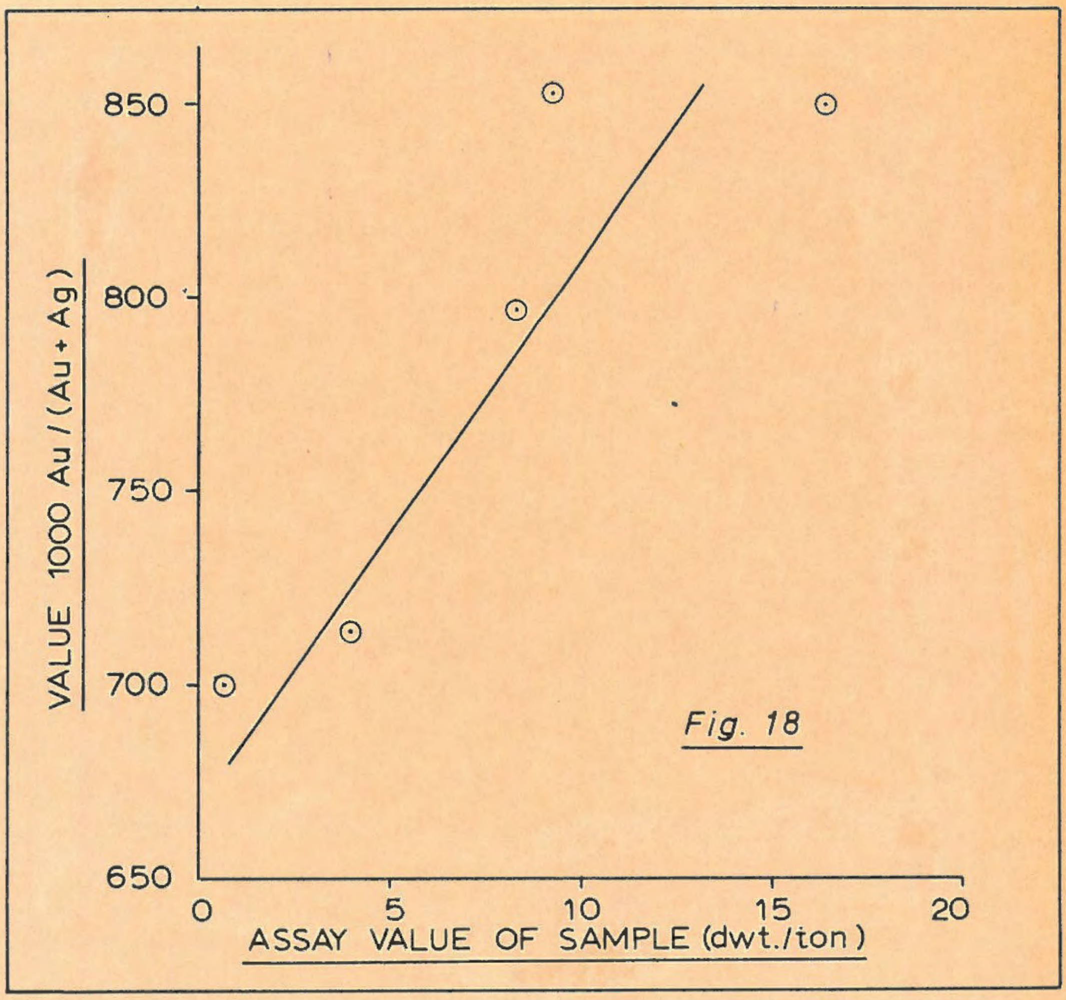


Fig. 18. Graphical Representation of Table 19.

It is at first surprising that the Blanket 'A' ore should show this type of variation, in view of the earlier conclusion that the true fineness of the recovered and visible gold is almost constant. It is also significant that the highest value for apparent fineness by total assay does not exceed 852; this is some 60 parts per thousand lower than the figure characteristic of recovered gold. Polished sections prepared from the borehole cores do not, however, reveal gold of a low fineness, even although very tiny veinlets and grains are abundant and easily detected under high magnification. The colour and manner of occurrence of the visible gold ~~is~~ are identical to ~~that~~ those in all other specimens previously studied. Very significant, however, is the abundance of pyrrhotite in each of these core specimens. In some, the amount present approaches that of arsenopyrite. In view of the high purity of the visible gold in these specimens, which contrasts with the relatively low apparent fineness as determined by assay, it seems logical to assume the existence of silver in these specimens, over and above the relatively small amount in the visible gold occurring in the fractured arsenopyrite.

The abundance of pyrrhotite in these core specimens suggests the association of the excess silver with that mineral. Protracted examination of specimens polished to an excellent surface, however, failed to reveal any such visible gold in pyrrhotite, so in order to test this conclusion, assaying was resorted to. Two specimens of ore containing approximately 80 per cent of pyrrhotite, with only minor amounts of other sulphides, were carefully trimmed to remove as much foreign matter as possible, and assayed. The assays showed 1.6 dwt. and 2.1 dwt. gold per ton respectively, the apparent fineness values being 516 and 313. On the other hand, a very clean sample of arsenopyrite, which under the microscope showed only minor pyrite and traces of pyrrhotite and chalcopyrite, but abundant gold, assayed 79.6 dwt. gold per ton, and the determined apparent fineness was 907. This latter figure is almost identical to that characterizing the average of gold recovered by amalgamation i.e. 908.8.

The conclusion seems inescapable that the low apparent fineness of the borehole cores is due to an excess of silver in that gold which is associated with pyrrhotite. The following estimates, while being purely hypothetical, suggest how gold could most reasonably be assumed to be distributed between pyrrhotite and arsenopyrite in the core samples.

Table 20. Probable Distribution of Gold and Silver

Sample No.	Gold Occurrence	Distribution (dwt./ton) Gold	 Silver	Apparent Fineness
3886	Whole sample	8.2	2.1	796
	Arsenopyrite	7.4	0.8	903
	Pyrrhotite	0.8	1.3	380
3885	Whole sample	16.3	2.9	849
	Arsenopyrite	15.5	1.6	906
	Pyrrhotite	0.8	1.3	380
3889	Whole sample	9.2	1.6	852
	Arsenopyrite	8.7	0.9	907
	Pyrrhotite	0.5	0.7	420

In this example, the apparent fineness value for pyrrhotite used in the calculation is within the range indicated by the assays of pyrrhotite, and the proportion of gold contributed by it commensurate with a total pyrrhotite content in the sample of 10-30 per cent.

The nature of the gold associated with pyrrhotite, if it does indeed exist as a silver-rich type, remains obscure. It may be that it exists as exceedingly tiny particles not visible under the microscope. It is perhaps relevant, in this connection, that even in the face of experiments in treatment procedure conducted by the Government Metallurgist, Bulawayo, not less than 10 per cent of the gold in the ore always remains unrecovered. This may indicate the existence of some very finely dispersed gold in the sulphides, which cannot be recovered.

Fig. 19 presents in diagrammatic form the results of the investigations described on previous pages. Attention is directed to the variation from a very low apparent fineness in specimens of clean pyrrhotite, to high values in nearly pure arsenopyrite, with intermediate values where both arsenopyrite and pyrrhotite are present. Gold recovered by amalgamation and cyanidation is likewise of high fineness, and the diagram includes two samples of panned, thoroughly oxidized ore, for which the fineness values fall between the limits defined by the sulphide samples. This last observation suggests that there has probably been no refining of gold in the oxidized ore.

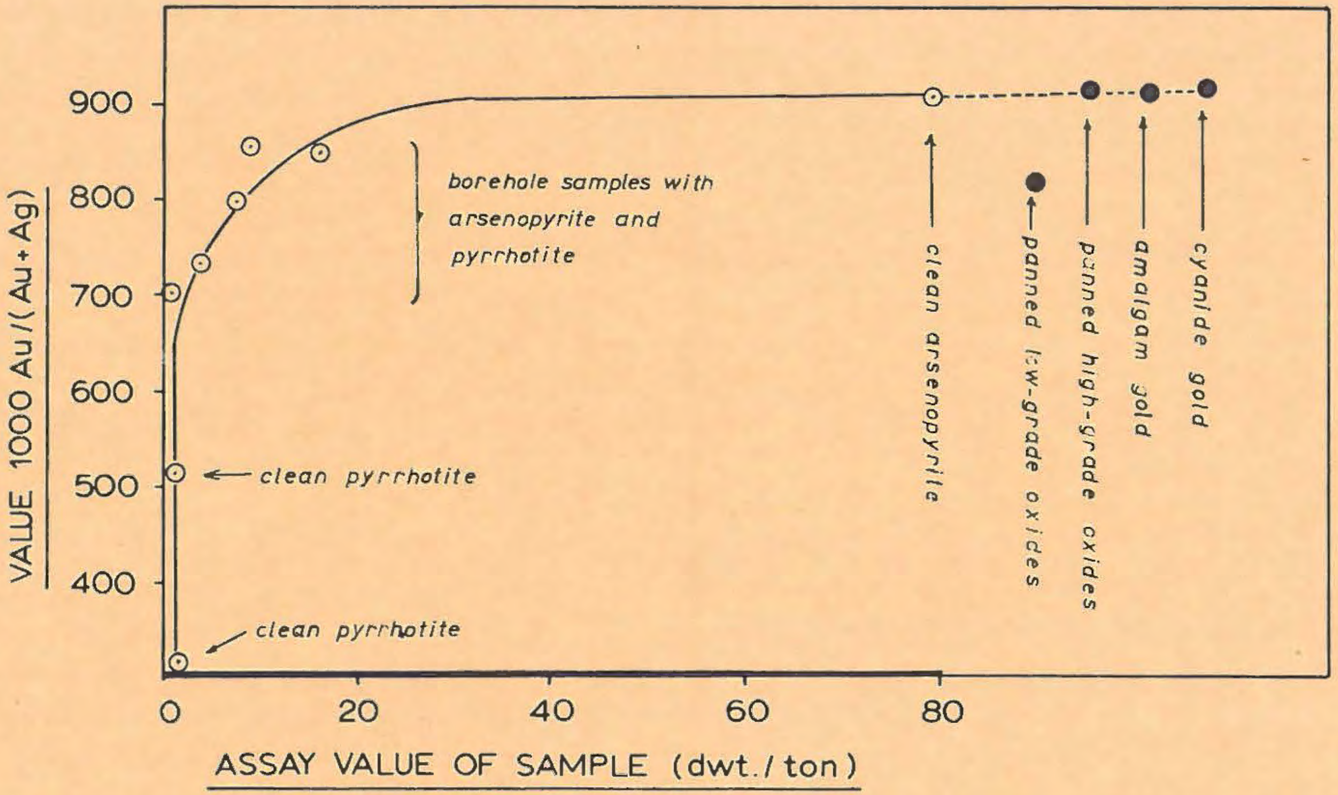


Fig. 19 DISTRIBUTION OF GOLD AND SILVER IN BLANKET 'A' ORE

H. THE MAKANGA MINE

Abstract

The Makanga mine is characterized by the association of galena with gold of high purity. Production data point to a decrease in the fineness of native gold with the decrease in the average tenor of the ore. The possible existence of the gold telluride, calaverite, is noted.

Introduction and General Geology

The Makanga mine was a small, relatively high-grade mine, situated some fourteen miles to the south-east of Bulawayo. It is a lenticular quartz vein containing galena, with traces of pyrite and chalcopyrite, the gold being coarse and associated with galena. The country rock is composed of Basement sediments, and the quartz vein cuts across their strike and dips at an angle varying from 25 to 40 degrees.

Production and Fineness Data

Production was started in 1954, and an average of close on an ounce of gold per ton of ore recovered in the initial months. Values proved, however, to be ephemeral and the gold content fell off sharply within a few hundred feet from surface. This fall-off, according to the owner, was accompanied by the appearance, in significant quantities, of sphalerite in depth. After only two years, the payable reef was exhausted and the underground workings abandoned.

Table 21 shows production data for 1956, and the fineness of gold recovered by amalgamation. Fig. 20, in which fineness is plotted against recovered grade, shows that there is a sympathetic variation between these two factors, even although the total variation in fineness is not great (888 to 927).

Table 21 Makanga Mine Production Data (1956)

Date	Tons	Recovery		$\frac{1000\,Au}{(Au + Ag)}$
		Ounces	dwt./ton	
Jan.	180	183	20.3	927
Feb.	150	64	8.5	920
Mar.	250	41	3.3	908
Apr.	250	92	7.4	888
May	250	44	3.5	905
Jun.	230	84	7.3	919
Jul.	350	65	3.7	898
Aug.	300	44	2.9	912
Sep.	300	203	13.6	922
Oct.	250	59	4.7	901
Nov.	200	28	2.8	899
Dec.	230	46	4.0	909

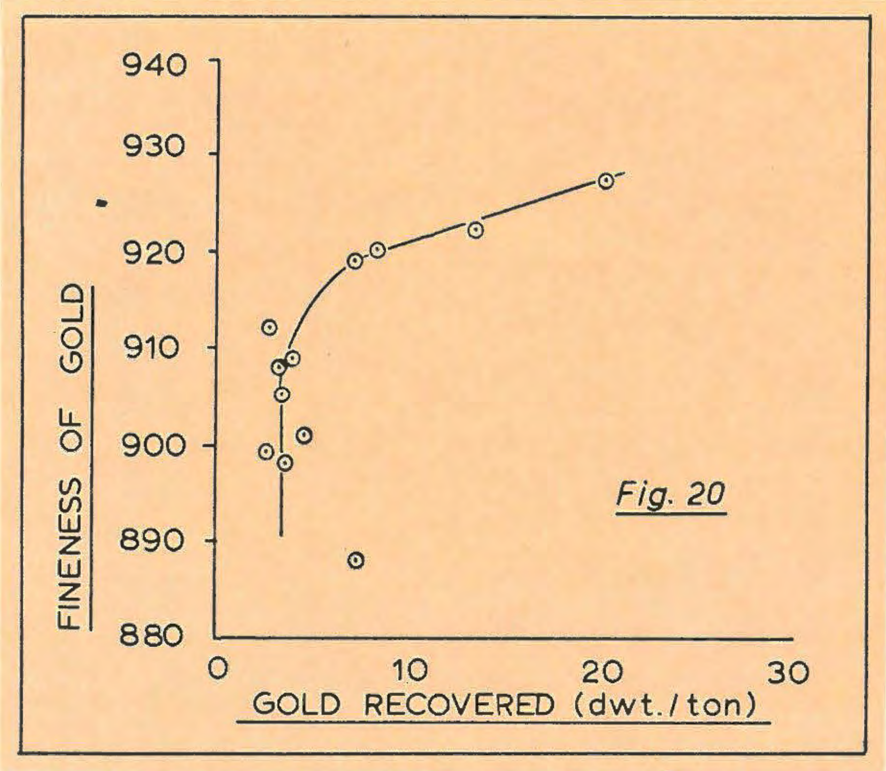


Fig. 20. Fineness of Amalgam Gold Plotted against Value Recovered. Makanga Mine, 1956.

Mineralogy

At the time of the writer's visit the underground workings were no longer accessible, and ore specimens could not be collected in situ. The only material available was somewhat oxidized, with both galena and pyrite somewhat altered. Polished sections show abundant *galena* and a little fine-grained *pyrite*, as well as coarse-grained *gold* of a rich, golden-yellow colour. The galena carries tiny inclusions, reaching a maximum size of 50 microns, which are sometimes angular but generally oval in shape. Attempts to identify this mineral were not wholly successful. The hardness is close to that of galena, and the colour is a pale yellow. It is weakly, but perceptibly, anisotropic against galena, and the reflectivity of several small grains is of the order of 63-68 per cent. It reacts only with $FeCl_3$ and KOH. All of these properties correspond closely with *calaverite* $(Au,Ag)Te_2$, excepting the reaction with HNO_3, which Short (1940) states is positive, although it has been noted (Short, 1937, p.668) that under certain conditions calaverite does not react uniformly. It is also possible that electrolytic effects might prevent calaverite from reacting with nitric acid when it is wholly enclosed by galena, in the same way in which galena is prevented from reacting with $FeCl_3$ when in contact with bornite (Short, 1940, p.96).

The occurrence of silver in the ore, in some form other than that alloyed with gold, is shown by assaying. A hand-specimen rich in galena and deep-yellow gold assayed 675.5 dwt. gold per ton and 193.7 dwt. silver. The apparent fineness is thus 773, far lower than that indicated by the colour of the gold or the fineness of the amalgam bullion.

I. THE ANTELOPE MINE

The Antelope mine was the only mine of importance in the Antelope Gold Belt, an inlier of Basement schists, sediments and serpentinites in the Old Granite, some 60 miles to the south of Bulawayo. The mine was operated by a company between 1913 and 1919, after which it was taken over by smallworkers.

An account of the mine and the ore is given by Phaup (1932, pp. 66-108), who describes the deposit as a pyritic ore body intermediate between a true quartz reef and a replacement body. The ore bodies are lenticular in habit, varying from mere streaks to widths of 15-16 feet. The gold values were found to have been erratic, and the sulphide content likewise variable. According to Phaup, the chief minerals associated with the gold are magnetite (4 to 36 per cent), pyrite (2.5 to 16 per cent) and pyrrhotite (2 to 41 per cent).

The mine started producing in 1913, by which time development had reached the 10th level, and by the time that it was abandoned by the company, operations had reached the 14th level. Gold was recovered by amalgamation of crushed, roasted ore, and cyanidation of the amalgam tails after further fine grinding. Production data for the period 1914-1919 are summarized in Table 22, and plotted graphically in Fig. 21. While the data are scanty, it is nevertheless apparent that fineness and tenor are related. The mine records subsequent to 1919 are of little use in the present study, as only amalgamation was practised, and extraction was accordingly very incomplete.

Another feature of the ore calls for special comment. Phaup has discussed the unusual assemblage of minerals in the ore, describing how red garnet may be the dominant mineral in parts of the reef, how hornblende and actinolite may make up a quarter of it in some places, while pyrrhotite may exceed 40 per cent in others. Phaup comments that garnet "is a mineral which belongs to the zone of greatest metamorphism where physical conditions do not favour the formation of gold reefs ...." As regards the gold, 70 per cent or more of it is intimately associated with the sulphides; the pyrrhotite, it is stated, may contain more than half an ounce to the ton. Very little gold is present in the quartz. These facts speak for the precipitation of gold in a deposit formed at particularly high temperatures, and the close association of the gold with the sulphides. It is significant that the gold fineness is decidedly low for a deposit of hypothermal character, and the conclusion must inevitably be drawn that gold deposited at high temperature is not necessarily poor in alloyed silver.

At the time of the writer's visit in 1957 the shaft had long since been closed and all underground workings were inaccessible. The few samples of ore which could be gleaned from the waste dump proved, on polishing, to contain only an insignificant amount of very finely divided gold in fractured pyrite, and no useful conclusions could be drawn from the microscopic study.

Table 22. Antelope Mine Production Data

Year	Recovery Ounces	dwt./ton	Amalgam Gold 1000 Au/(Au + Ag)
1914	22,591	11.0	848
1915	24,393	10.2	845
1916	21,794	9.4	848
1917	22,094	11.1	849
1918	18,405	9.2	841
1919	12,481	8.0	809

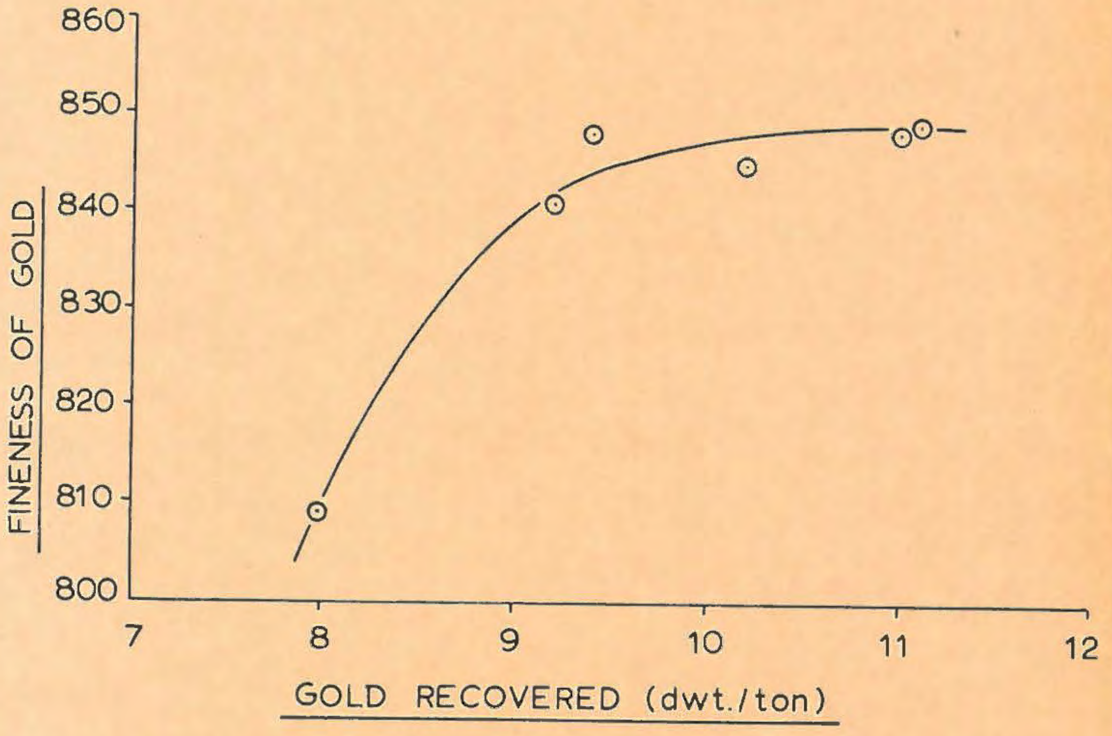


Fig. 21 RELATIONSHIP BETWEEN FINENESS OF GOLD AND GRADE OF ORE AT THE ANTELOPE MINE.

J. WANDERER MINE

The gold deposits of the Wanderer mine, near Selukwe, occur, according to Zealley (1919, pp. 82-85) in strongly shattered zones traversing banded ironstone, conglomerate and greenstone, and contain quartz and pyrite. The average grade of the ore treated was low. For example, in 1911 the treatment of 220,000 tons of ore yielded an average of 1.98 dwt./ton, with the residues assaying 0.61 dwt./ton. The following note appears in Zealley's description:

"It is stated that the fineness of the gold varies generally from 890 to 915, and that the higher the grade of ore the better the fineness, i.e. there is more silver in the low-grade ore."

To what extent this relationship has been caused by secondary redistribution of the gold cannot be assessed, for Lightfoot (1934, p.100) states that the ore was "entirely oxidized and consisted of secondary gold deposited in a belt of shattered rock."

(CHAPTER IV contd.)

OTHER RELEVANT INVESTIGATIONS

Brief mention should be made of other investigations which have indicated that relationships between gold fineness, tenor of metallization and age of the gold, similar to those described on foregoing pages, exist in other deposits. Precise data pertaining to this topic are not easily gathered, for, unless the statistical studies are supported by mineragraphic work, the information is incomplete.

Bruce (1943) described the variations in the Au/Ag ratios in mines of the Porcupine and Kirkland Lake areas and gave details regarding the average contents of gold and silver in the ores between the years 1917 and 1940. His investigation was chiefly concerned with possible changes in gold-silver ratios with depth, and it appears as if the well defined relationship that exists between fineness and tenor in two of the deposits was overlooked. Certainly, he does not refer to it. The present writer has re-plotted, in Fig. 22, the data which Bruce published, so that this latter relationship becomes more apparent. It is seen that in the case of the Hollinger, Dome, McIntyre, Wright-Hargreaves and Kirkland Lake mines the gold-silver ratios do not vary greatly from year to year. There is also very little variation in the average value of the treated ore and any relationship between fineness and tenor is obscure in these deposits. In the Lake Shore and Teck-Hughes mines, however, variations in both average tenor and gold-silver ratios are pronounced and there is clearly a relationship between these two values. Low-grade ore is characterized by relatively silver-rich gold, while rich ore contains proportionately less silver. The very detailed metallurgical studies by the staff of the Lake Shore mine (Bloomfield and others, 1936) established that both fineness and the manner of occurrence of gold particles are variable. A small proportion of the gold occurs as minute

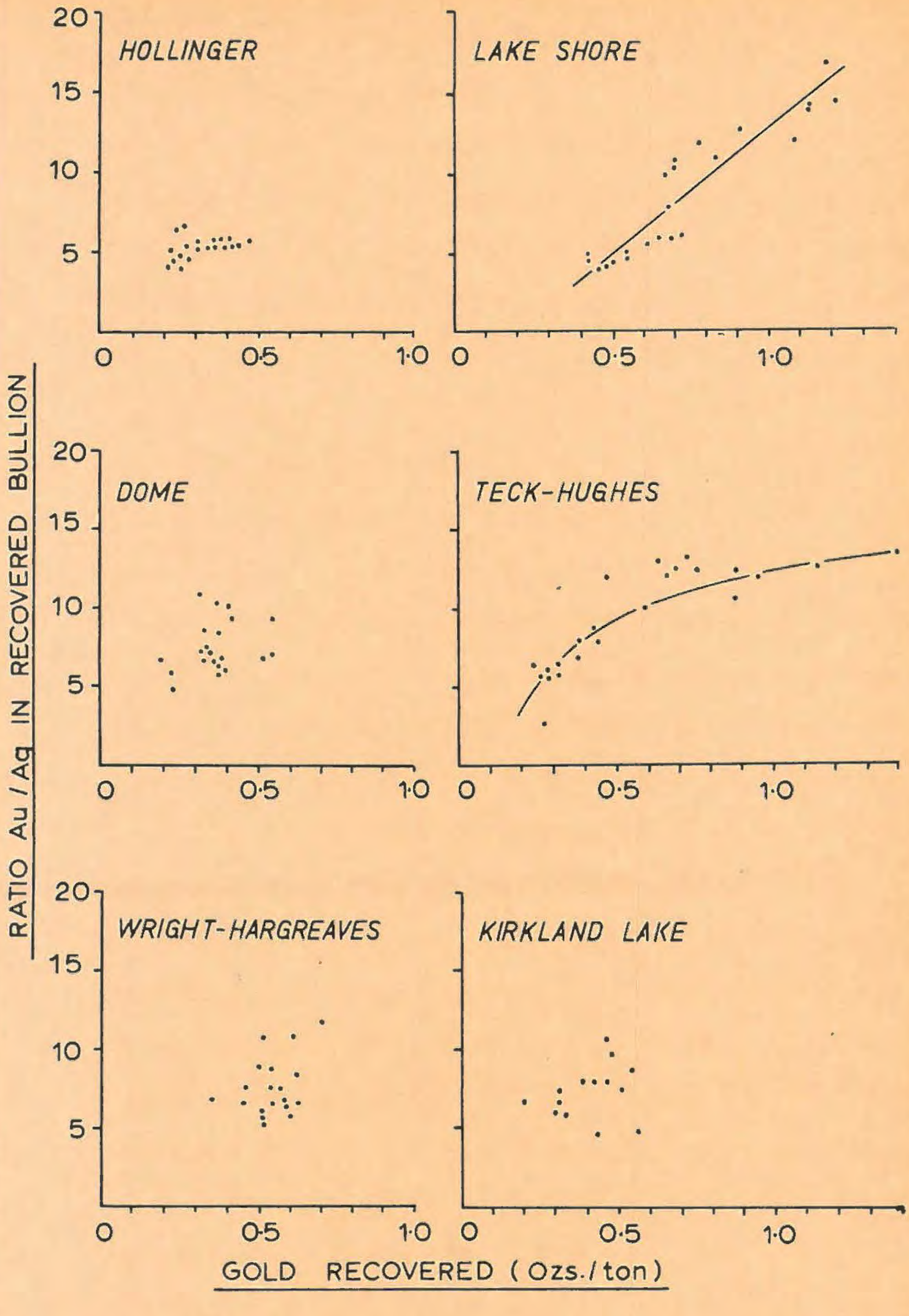


Fig. 22 GOLD-SILVER RATIOS OF BULLION PLOTTED AGAINST GOLD RECOVERIES FOR SOME ONTARIO GOLD MINES. (DATA FROM BRUCE, 1943).

particles in pyrite and it was concluded that this gold was contemporaneous with pyrite, while most of the gold is younger, occurring as 'free' particles or associated with tellurides. Microscopic examination established that the former is richer in silver than the latter. This relationship between fineness, tenor and the relative ages of the gold grains is similar to that which has been observed and described in several Southern Rhodesian deposits, on foregoing pages.

Wilson (1944) investigated the distribution of elements in ores from Goldfield, Nevada, with the aid of a spectrograph. He found that gold, silver, bismuth and tin are closely associated as regards their distribution. It is interesting to note that where intensity ratios of silver (which are directly proportional to the amounts of silver present) are plotted against the gold content, determined by fire assay, a smooth curve is produced. The shape of the curve indicates that a steady increase in gold content is not accompanied by a uniform increase in the amount of silver: the richer gold samples contain a little less silver in proportion than the poorer samples. The study unfortunately does not include mineragraphic data.

The detailed investigation of the Getchell mine, Nevada, by Joralemon (1951) showed that the fineness of recovered bullion ranges from 666 to 993, but averages 910. Visible gold varies in size from fractions of a micron to nearly one millimetre, and although a small proportion occurs in the sulphides, most of it is intimately associated with magnetite and carbon in a carbonaceous gumbo. The relationship between gold and silver is of particular interest, for although silver, which could have alloyed with gold, was available while deposition was taking place, electrum is rare and silver occurs as the native metal. Joralemon suggests that, at the low temperatures at which the deposit was formed, the tendency for the formation of electrum decreases. He notes (p.295) that "in general the amount of silver in the ore varies inversely with the amount of gold. Extremely rich portions of the ore body contain less silver than the portions of average grade. There is no zonal relation other than this between gold and silver." He notes further (pp. 297-298) that there are two modes of occurrence of visible gold. In the first, gold was deposited early in the period of formation of realgar. Silver and the rare electrum were probably more or less contemporaneous with this earlier, low-grade phase of gold mineralization. In the second, later type, extremely rich lenses of gold were formed, and gold and magnetite are intimately associated.

Edwards' (1958) examination of the Maude and Yellow Girl gold mine, Victoria, led to important conclusions regarding the fineness of the gold. These have been quoted in Chapter II. He considered that the fineness was here controlled by the temperature of deposition, the availability of silver and the concentration of other elements with which the silver could combine. The ore shows considerable variation in gold-silver ratios, commonly from 10/1 to 1/100, but individual assays indicate the presence of pockets of almost pure gold. These pockets do not necessarily contain an appreciable amount of gold, although it is of exceptional purity.

Other less complete investigations into the variations in gold fineness are discussed in subsequent pages. These are generally concerned more with the mineral associates of gold than with its purity in relation to tenor of metallization.

CHAPTER V

GOLD FINENESS IN RELATION TO THE ASSOCIATED ORE MINERALS

In the previous chapter a correlation was established, in several deposits, between the fineness of gold and the age of the ore minerals with which the gold is most intimately associated. It was shown that, in general, gold which was considered to have been precipitated at an early stage in the formation of the deposit, tends to have more silver than that which is precipitated in the final stages. The following very brief survey deals with each of the commonly occurring ore minerals in turn, and is an attempt to determine to what extent each is associated with gold of a particular quality. The data have been drawn from the writer's own work, and relevant literature. It is to be regretted that this survey is not more comprehensive, but the lack of precise data regarding either the fineness of gold, or its manner of occurrence in the ore, has made it difficult to produce more evidence than is given here.

Arsenopyrite

Judging from available evidence, the fineness of gold which occurs in intimate association with arsenopyrite may vary from low to high, although it is in the majority of cases high. The most likely explanation for this feature appears to be the variability in the age of the associated gold, and, if the conclusions reached in the previous chapter are valid, the greater the amount of 'early' gold deposited with the arsenopyrite, the lower is the average fineness likely to be.

However, the recognition of a possible relationship between the fineness of gold and its occurrence with arsenopyrite is complicated by the difficulty experienced in establishing the relative ages of the two minerals from the textures. No such uncertainty prevails where gold occurs moulded on arsenopyrite or occupies fractures in it; here gold is clearly the younger.

But when gold occurs as minute blebs, perhaps only a few microns across, within the arsenopyrite, and its position in the host appears not to be influenced by fractures or by inter-grain boundaries rendered visible between crossed nicols, doubt must always exist whether the gold is contemporaneous with the arsenopyrite, or has entered into the sulphide crystals at a later stage by the mechanism of replacement. Warren and Cummings (1937) have, for example, accepted that this habit indicates contemporaneity. With reference to certain ores of British Columbia, they state:

"the gold ..... has been deposted contemporaneously with the associated metallic minerals, of which arsenopyrite, pyrite or pyrrhotite are the most important. The precious-metal grains are scattered without any apparent relationship to crystal boundaries, contacts or fractures of the metallic mineral or minerals with which they are associated" and "the gold is present as native gold, usually in minute grains rarely approaching one-tenth of a millimetre and most commonly less than five microns in their maximum dimension".

Warren and Cummings found that gold of this type was more characteristic of contact metamorphic and hypothermal deposits, whereas gold of the other type, occurring in fractures in the sulphides, is more characteristic of mesothermal and epithermal ores. It could be argued, however, that their evidence suggests that ingress, by relatively younger gold, to the host sulphides, is more easily gained through the mechanism of diffusion at the high temperatures of formation of the former class of deposits than at the lower temperatures of the latter. The diffusion of gold through sulphides is, for example, known to be appreciable within even a few hours at 600°C (see Coleman, 1957, pp. 417-418). Ödman (1939, p.98) describes the occurrence of tiny particles of gold of irregular shape which occur in abundance in arsenopyrite, in ore from the Holmtjarn mine, N. Sweden, but he considered that the gold was contemporaneous with chalcopyrite, tetrahedrite and boulangerite and was introduced by "some process of replacement or molecular migration" (p.104).

Stillwell and Edwards (1946) have established the presence of sub-microscopic gold in the Dolphin East Lode, Fiji, and they suggest that it may have been deposited at a very early stage of mineralization. Although the ore is not rich in silver as a whole, a number of exceedingly tiny grains of gold, a few microns in diameter, were found in the arsenopyrite. These are creamy in colour, and much paler than the occasional particles observed in the gangue. It may well be that gold of this pale colour is contemporaneous with arsenopyrite.

The writer is reluctant to suggest a community of age for the gold blebs and the arsenopyrite crystals in which they occur, in those Southern Rhodesian deposits which have been examined, on the grounds that in rich specimens, where abundant gold occurs moulded on arsenopyrite or replacing its margins, closer examination will nearly always establish the existence, close by, of some tiny blebs in the arsenopyrite, and these are not related to fractures. Unless there are significant differences in the colour and grain sizes of the different grains, the acceptance of different ages for the two types of gold seems unjustified.

Some of the ore from the Jessie mine, Gwanda district, contains arsenopyrite in abundance, as acicular crystals and less well formed skeletal crystals, forming lenticular streaks in the ore. Gold is abundant in these specimens, as small grains whose rich golden colour testifies to their high fineness. This gold is clearly much younger than the arsenopyrite, as it occurs in places together with galena along fractures in arsenopyrite host crystals, but some is found also in the interiors of crystals, where it replaces shreds of country rock (see Plate XII, Fig. 2). Although gold and arsenopyrite are closely associated here, and gold occurs as 'inclusions' in arsenopyrite, the gold must be considered to be much younger.

All but a small proportion of gold in the Blanket 'A' mine, Gwanda district, is associated with the arsenopyrite. The relationship between the two minerals is the same as in Jessie mine ore, except that in the Blanket ore a greater proportion of the metal gilds the crystal faces of the sulphide. The gold here is over 900 fine, and is quite definitely later than arsenopyrite (see Plate XXII). Arsenopyrite from the Magano mine, which belongs to the same general zone of mineralization as the Blanket 'A' deposit, contains more gold and proportionately less silver than the pyrrhotite in the ore. The apparent fineness of the former was determined to vary in different specimens from 800 to 834, and gold associated with pyrite shows the same order of fineness (790 to 848). A sample of pure pyrrhotite, however, gave an apparent fineness value of only 744. In this case the purer gold does appear to be associated with the arsenopyrite and pyrite.

Ore from the Posho mine, in the Tuli group, contains abundant arsenopyrite, pyrrhotite and chalcopyrite, but the first-mentioned mineral greatly exceeds the others in proportion. Apparent fineness values range from 810 to 884 in three specimens assayed. Production data indicate that its average fineness is about 775. Polished specimens reveal that the gold occurs as very minute grains, threads and scales in and around the arsenopyrite crystals. The gold is clearly younger, and judging from the way in which gold, chalcopyrite and pyrrhotite are intergrown, they are of approximately the same age.

These few examples have been quoted to illustrate that, although the gold may superficially appear to be most closely bound up with arsenopyrite, the small traces of other minerals which accompany it as fracture-fillings or as replacements of other inclusions within the older sulphide, show that its age is variable.

Several published references to the fineness of gold associated with arsenopyrite emphasize the variability of that value. Horwood (1937) mentions the occurrence of gold showing a distinct preference for arsenopyrite in ores containing arsenopyrite, pyrrhotite, chalcopyrite, sphalerite and galena, in the Argosy mine, Ontario. Gold was the last of the minerals to form, and is generally associated with arsenopyrite or galena. He notes that it occurs "close to or along crystal boundaries and within crystals." The gold is 920 fine. Junner (1920, p.220) stated that in the Walhalla-Wood's Point auriferous belt, gold associated with arsenopyrite is "usually of good quality", and he gives a value of 960-970. H.G. Ferguson (1924, p.106) attributed the high purity of gold associated with arsenopyrite, realgar and orpiment to the selective precipitation of gold, rather than silver, by arsenical minerals. He considered that the gold might have been deposited contemporaneously with the arsenical minerals. J.C. Ferguson (1934, pp.77-78) gave the fineness values for a number of mines in the Filabusi district of Southern Rhodesia. These figures illustrate that gold occurring in veins bearing arsenopyrite varies widely in fineness, from less than 800 to over 960 fine. Arsenopyrite from the Mother Lode (Knopf, 1929, p.37) has associated with it gold (839 fine) which is purer than that occurring with pyrite, but less so than that associated with galena or tellurides.

It is clear that arsenopyrite is not characterized by the association with it of gold of any particular degree of fineness, and that this probably arises in turn out of the variable age of that gold.

Pyrite

Although pyrite is in a vast number of ores an important host or associate of gold, its presence is by no means an essential requisite in gold ores, and, in many, gold shows no preference whatever for pyrite (Schwartz, 1944, pp. 385-387). The recognition of a relationship between the fineness of gold and its intimate association with pyrite faces the same difficulties, as regards the relative ages of the two minerals, encountered in the case of arsenopyrite. The remarks made under the discussion of that mineral are equally applicable to pyrite, and the fineness of the associated gold shows variation equally as great.

The references to gold filling fractures in pyrite are so numerous that specific mention of examples would be redundant. It should be appreciated, however, that there are important references which state that gold and pyrite may be contemporaneous. Graton and McKinstry (1933, pp.12-14) state that, in the Hollinger mine, a large proportion of the gold in the ore is in intimate association with pyrite, and that "some of the gold appears to have been deposited contemporaneously with the pyrite and some after it." Bruce (1943) showed that the fineness of the gold bullion from this mine ranges from about 800 to 870. It occurs both as fracture-fillings and as rounded and irregular blebs within pyrite grains. However, spectrographic analyses of pyrite from a number of Canadian gold deposits, including the Hollinger mine, led Auger (1941, p.412) to the conclusion that "gold was not precipitated at the same time as the pyrite". He suggested that gold was introduced by later replacement or along fractures, and that it could form either isolated units or narrow veinlets in the pyrite. The work of Head (1934) points to the deposition of very fine-grained gold as flakes and wire-like threads on the crystallographic planes of growing pyrite crystals in some low-grade, refractory deposits.

Very pale gold with a high silver content is known to occur in pyrite, in the form of very minute inclusions. At the Lake Shore mine (Bloomfield and others, 1936, pp. 291-295) the existence of two distinct forms of native gold was established by microscopic examination. One form occurs as minute grains, most of which are less than 5 microns across, in pyrite crystals which do not contain inclusions of other minerals. These inclusions are generally of irregular shape and uniformly distributed throughout the pyritic ore, and were considered to have crystallized at the same time as the pyrite. This gold is paler, and shows a different rate of reaction with KCN, in comparison with the other principal variety which occurs as coarse grains of 'free gold' and as inclusions in the telluride, altaite. Another occurrence of pale gold occurring as tiny inclusions in pyrite was described by Stillwell and Edwards (1946, p.42) in the case of the Dolphin East Lode, Fiji. In ore from the Lone Hand mine, Gwanda district, the present writer has observed very pale-coloured gold deep in fractured pyrite, in the massive sulphide ore which lines the walls of the main ore body. This massive ore consists of arsenopyrite, pyrite and pyrrhotite, with only traces of chalcopyrite, and contains no sphalerite, tetrahedrite or aurostibite (?) which characterize the richer ore, in which the assemblage of minerals indicates lower temperatures. It was concluded that the gold in the massive sulphide ore had been precipitated earlier than that which is bright yellow in colour and which occurs commonly in association with the lower-temperature minerals.

The examples quoted above have two features in common. In each, the fine-grained gold is pale yellow in colour, presumably due to a high content of silver, and there are grounds for supposing that the gold precipitated at a relatively early stage in the sequence of mineralization.

There is a wealth of data to show that the fineness of that gold, which may be regarded as younger than the pyrite with which it is associated, varies widely. A few examples will suffice. Knopf (1929, p.37) indicated that, in the Mother Lode, gold occurring with pyrite is of lower fineness than that occurring with any of the other minerals. Ferguson (1934, pp. 87-88) gave data showing that gold occurring in pyritic deposits in the Filabusi area varies from just over 500 fine to nearly pure. Gold from the Turk mine, Queen's Road area (see Chapter IV), is close to 860 fine, and the way in which it accompanies chalcopyrite in the replacement of pyrite suggests that it may be of the same age as chalcopyrite. In the Sabi and Canada mines, near Shabani, gold occurs as 'mustard gold', i.e., as myriads of exceedingly tiny grains in cherty quartz, and the only associated sulphide appears to be pyrite. Judging from production data, its fineness in the former deposit varies from 845 to 865, while in the latter it is 895 to 920 fine. In the Abercorn mine, near Gwanda, the fineness of the recovered gold was close to 905, and the gold is seen, in polished section, to have vigorously replaced pyrite, and to have been accompanied by galena. The manner of occurrence is similar in the Big Ben mine, a short distance away, but here the fineness is 929. In the Freda mine, Tuli area, gold has attacked pyrite, and was accompanied by tetradymite. The fineness is 940. Specimens of Lonely mine ore (see Chapter IV) contain fine-grained gold replacing pyrite, while some gold occurs as isolated blebs in pyrite. The fineness in this ore ranges up to close on 960.

The position with regard to pyrite may be summed up as follows. As in the case of arsenopyrite, there are occurrences on record of silver-rich gold which appears to be either included in pyrite or closely associated with it in such a manner that its separation at a relatively early stage seems not unlikely. Where a hiatus intervened between the precipitation of pyrite and gold, the fineness of the gold shows such variability in different deposits that it is impossible to discern any consistent correlation between fineness and its association with pyrite.

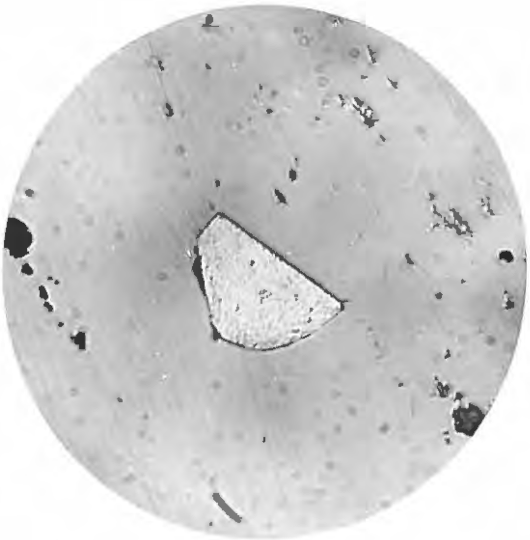
Pyrrhotite

Pyrrhotite has not been found to be a favoured host for gold in more than a few deposits in Southern Rhodesia, but it is seldom wholly devoid of gold.

The best example of auriferous pyrrhotite which the writer has encountered occurs at the Empress mine, Mashaba. This is an impregnation of pyrrhotite in banded ironstone, in which the ore body attains exceptional size. Microscopic study establishes the intimate association of gold with pyrrhotite, although it is difficult to establish the exact age relationships between the two minerals. In this deposit gold occurs in abundance in specimens of almost pure pyrrhotite which may weigh several pounds. Polished specimens show that the gold occurs either along, or close to, the contacts between the individual crystals of pyrrhotite forming a mosaic, and that the gold grains are very commonly bounded by plane faces (see Plate XXIII). The manner of occurrence suggests that the gold grains are older than part of the pyrrhotite, and are genuine inclusions. Crystal faces are also shown where the gold occurs enclosed in the rare chalcopyrite which forms small patches and veinlets between pyrrhotite crystals. It is of particular significance that this hypothermal deposit, in which the gold seems to be of early crystallization, contains gold which is of low fineness. Under the microscope it is distinctly paler than gold which is 900 fine. The annual outputs between the years 1947 and 1959, during which period recovery was by amalgamation alone, show the fineness to vary from 796 to 885.

Ferguson (1934, p.88) found that gold in pyrrhotite-bearing ore bodies of the Filabusi area was generally of good

Plate XXIII



Crystal of gold partially bounded by crystal faces, deeply set in pyrrhotite, Empress mine. x 360.

quality, but no data are given regarding the age relationships between the two minerals.

In Chapter IV attention was directed to the low fineness of the gold which was recovered from the Antelope mine. This deposit, which seems to contain only high-temperature minerals, was characterized by the close association of gold with the sulphides, in particular pyrrhotite. Pyrrhotite was here found to contain more than half an ounce of gold to the ton of ore.

Samples of pyrrhotite from a number of other localities, in which pyrrhotite occurs in company with several other sulphides, were examined, but in very few was any gold visible in this mineral, on polished surfaces. Assays generally confirm that less gold is associated with it than with any of the other common ore minerals. It also emerges that the apparent fineness is generally lower than that of gold associated with other ore minerals. In Blanket 'A' mine ore, the fineness of recovered gold is 909, but samples of pyrrhotite, carrying only a few pennyweights of gold to the ton, gave apparent fineness values below 520. Arsenopyrite and pyrite from the Magano mine, which belongs to the same general zone of mineralization as the Blanket 'A' mine, contain more gold and proportionately less silver than the pyrrhotite in the ore. Apparent fineness values in the former minerals were found to vary from 790 to 848, whereas a sample of pure pyrrhotite gave an apparent fineness value of only 744. The Freda mine, Tuli area, yields gold which is 936-940 fine according to the production data, but an assay of pyrrhotite-rich ore, although showing nearly an ounce of gold to the ton, gave an apparent fineness value of only 802. Specimens of Valley mine ore, Gwanda, indicated that pyrrhotite carries less gold and considerably more silver in proportion than the other sulphides. Selected samples of ore from the Posho mine, Tuli group, showed that where pyrrhotite makes up about 80 per cent of the ore, the apparent fineness of the gold is about 800. A sample containing close upon

60 per cent of pyrrhotite and 25 per cent of chalcopyrite gave a value of 810, and a sample consisting of 60 per cent of arsenopyrite and only 30 per cent of pyrrhotite gave an apparent fineness value of 884. Production data relating to the Cheque mine, which lies not far from the Blanket 'A' mine, show that the fineness of the recovered gold rises as high as 969, but may fall fully 100 points below this. The microscopic examination of ore specimens showed that some gold is always in intimate association with pyrrhotite. One such specimen, in which gold occurs wholly enclosed in pyrrhotite, or forms segmented veinlets with it, gave, on assay, an apparent fineness value of 895, close to the lower limit indicated by the production data. Ore from the Lady Lina mine, also in the Gwanda district, yielded gold 850-913 fine. This value is quite noticeably lower than that of the other mines in the immediate vicinity. Polished specimens of the ore show a close association of gold, pyrrhotite and chalcopyrite, but the association is most marked between the first two.

These data all suggest that where gold has a close association with pyrrhotite, or is earlier than it, the fineness is somewhat low. When samples of pyrrhotite are tested by assaying, it is commonly found that the ratio Au/Ag is lower than that in any other mineral. Whether this is due to the presence of gold particles of particularly low fineness in the pyrrhotite, or to excess silver in some other form cannot easily be determined, for the samples are most commonly of low grade and do not show gold under the microscope. While the silver content of low-grade specimens might be slightly over-estimated due to the silver contained in assay litharge, low fineness in pyrrhotite cannot be wholly attributed to this cause. The occurrence of some samples of pyrrhotite, which are relatively rich in gold, and which still give relatively low apparent fineness values, suggests that the gold particles themselves carry much silver, and that the low apparent fineness values are not merely due to an original small content of silver in pyrrhotite which only acquires significance when the gold content is particularly low. Furthermore, the recovery, by amalgamation, of silver-rich gold from ores in which gold occurs as inclusions in pyrrhotite lends support to the 'prima facie' conclusion that pyrrhotite is very commonly an associate of silver-rich gold particles.

Chalcopyrite

The association with chalcopyrite of gold containing a notably high proportion of silver seems to be fairly general, and several examples illustrate that where gold is of the same age as chalcopyrite, it has a higher silver content than later gold in the same ore.

In the Olympus mine, near Mtoko (see Chapter IV) there is excellent evidence that some proportion of the gold is older than the chalcopyrite which encloses it, for the former inclusions are bounded by crystal faces, and many grains are of octahedral habit. A close study of the distribution of gold grains in the ore demonstrated that 44 per cent of them are either enclosed by chalcopyrite or very intimately associated with it. Most of this gold is pale in colour, in contrast with the deep golden colour of that which is later, such as that associated with tellurides. The average fineness of the recovered gold was low, by Rhodesian standards, and varied between the limits of 780 and 880. Ore from the Lonely mine contained chalcopyrite in significant amounts only in the deeper levels more than 2,000 feet from surface. Gold occurs in the chalcopyrite as inclusions of irregular shape, and is distinctly paler in colour than that which occurs replacing pyrite in the upper levels. This feature is consistent with the drop in the average fineness of the gold from over 950 fine in the upper levels to below 900 in the deeper levels, In the case of the Turk mine, it has been demonstrated that there is cause to suppose that gold and chalcopyrite are of the same age. The fineness in this deposit tends to be somewhat low, ranging from 850 to 880 at the levels at present being developed. The average fineness of gold in the Balmoral mine, near Filabusi, was stated by Ferguson (1934, p.87) to be 923, but more recent outputs of gold recovered by amalgamation show that it varies from 855 to 913. The examination of ore specimens collected underground showed that gold grains occurring in the quartz gangue are quite definitely purer than those which occur wholly or partly enclosed by chalcopyrite. Some of the gold in this latter category has almost a silvery tinge, and was estimated to be about 750-800 fine. The Valley mine, near Gwanda, produced gold relatively rich in silver. As shown in Table 1, 20 separate outputs by amalgamation indicated a range in fineness from 685 to 797. At one time copper was also produced. The mine has been closed for many years, and the writer was unable to collect samples from the reef underground. A number of specimens from the waste dump were polished, but the number of gold grains seen in these particular samples proved to be so small that no useful conclusions could be drawn from the study. However, the chief sulphides were found to be pyrite, pyrrhotite and chalcopyrite, and samples which were assayed indicated that the gold is chiefly associated with pyrite and chalcopyrite, whereas pyrrhotite contains only negligible amounts of gold. The association of silver-rich gold and chalcopyrite seems reasonably certain.

With reference to deposits in the Filabusi area, Ferguson (1934, p.88) noted that those which are heavily mineralized by chalcopyrite have given the poorer quality gold. In his description of the gold and copper ores of south-western Oregon, Lowell (1942, p.571) noted that some gold of the Ashland mine "varies from a pale yellow to a deep yellow colour and is probably silver-bearing". Chalcopyrite was stated to be one of the minerals with which gold is intimately intergrown, and (p.581) the two minerals crystallized together during part of the mineralization. Peterson (1942, p.487) recorded the presence of pale-coloured gold associated with chalcopyrite as inclusions in arsenopyrite, in the Vipont mine, Utah. He indicated that gold and chalcopyrite are of the same age. Chalcopyrite and gold are said to be closely related in time in the Kennedy mine in the Mother Lode system (Hulin, 1930, pp. 353-354), and to have been deposited together during the last stages of mineralization, with gold outlasting the chalcopyrite. The fineness of gold in the Kennedy mine is known to vary from 789 to 837 (Knopf, 1929, pp. 65-66), and so the correlation of low gold fineness and the contemporaneity of gold with chalcopyrite seems justified. In the Howey mine, Ontario (Mather, 1937, p.148), gold is said to have been deposited together with chalcopyrite, and the chalcopyrite to have continued to crystallize long after the gold in the ore. It was specifically stated, in this description, that the colour of the gold varies from golden to pale yellow.

In his account of the deposits of the Pilgrims Rest district, Transvaal, Swiegers (1949, p.99) noted that "chalcopyrite is by far the most important copper mineral" in the ores. No argentiferous sulphides were found, and he considered (p.124) that silver is present only in the form of an alloy with gold. Concentrates from the different mines indicate a variation in Au/Ag ratio from 15.9:1 to 1.1:1 (940 to 530 fine), and it is significant that the lowest Au/Ag ratio is, according to analyses, encountered in concentrates which are richest in copper. These latter concentrates average 26.6 per cent copper.

To summarize, it may be said that, in a number of accounts where the data are sufficiently precise to show that gold and chalcopyrite are in part contemporaneous, there are references to the high content of silver in the gold. The study of examples in this country lends strong support to the contention that the association of silver-rich gold and chalcopyrite is typical of hypothermal deposits.

Sphalerite

In many ores chalcopyrite and sphalerite have overlapping periods of deposition, and it is therefore not remarkable that gold which is contemporaneous with sphalerite is very similar in composition to that which is found with chalcopyrite. The best example which the writer has encountered was found in ore from the Jessie mine, near West Nicholson, in the Gwanda district. The gold in this deposit varies widely with respect to its content of silver, but those grains, which were considered to be genuine inclusions in sphalerite, are conspicuously more silvery in colour and larger in size than those which the textures prove to be younger than sphalerite. The colour of these former grains is creamy yellow, and fineness determinations carried out on hand-picked grains showed that a high silver content was characteristic.

Junner (1920) found that gold of low fineness characterized those deposits of the Walhalla-Wood's Point auriferous belt in which sphalerite predominated. Mather (1937) stated that gold in the Howey mine varies from golden to pale yellow. His table of paragenesis shows partial contemporaneity between sphalerite and gold. The average fineness of amalgam gold from Gilpin County, Colorado, is 790-800 (Bastin and Hill, 1917, p.120). It is stated by Bastin (p.110) that in the galena-sphalerite ores galena, sphalerite, chalcopyrite and gold crystallized contemporaneously.

Galena

Galena is of particular interest in this discussion, for it appears to mark a stage in the paragenetic sequence of hypothermal ores after which the fineness of gold being deposited rises sharply. The gold, depending on whether it antedates galena, is contemporaneous with it, or is later, may show a variation in fineness from low to high.

Junner (1920, p.221) and Ferguson (1934, p.88) both state that an abundance of galena in deposits of the Walhalla-Wood's Point, and Filabusi areas, respectively, can be correlated with low fineness of the gold recovered. Knopf (1929, p.37) however, found that gold associated with galena in a gangue of quartz and dolomite in the Mother Lode was higher in fineness than that occurring with arsenopyrite or pyrite, but not as pure as that occurring with petzite. The gold of the O'Brien mine (Mills, 1954) has a fineness of 860-950. According to Bell (1931, p.638) "gold appears to have been connected with the last phase of metallic mineralization" in this deposit. He stated that galena is a rather rare mineral in this deposit, but is most commonly found in the high-grade sections. Malcolm (1912, p.94) stated that "Nova Scotia's gold is very fine"; examples show a variation from 930 to over 980 fine. Regarding the manner of occurrence of the gold, he noted that "gold is very commonly associated with arsenopyrite and almost invariably with galena, often forming large nuggets."

Ore from the Jessie mine contains, locally, abundant galena. From such textural features as segmented veinlets, inclusions and so on, part of the gold in the ore is considered to be contemporaneous with galena. Different grains of this gold range from silver-rich to silver-poor. The Makanga mine, near Bulawayo (see Chapter IV) produced gold varying in fineness from 888 to 927. Polished specimens of this ore reveal abundant coarse-grained gold and galena occurring together with minor amounts of pyrite and calaverite(?). Specimens of ore from the now-abandoned Abercorn mine, near Gwanda, show that the gold started to crystallize before galena, and thereafter continued to crystallize side-by-side with it (Plate XXIV). No definite evidence was found that gold continued to separate after galena had ceased to do so. The fineness of gold in this deposit reached a maximum of 905. In the Big Ben mine, close by, the ore is very similar in character, but the gold slightly purer (929 fine). This appears to be consistent with the fact that there is a definite tendency for some of the gold to wrap around crystals of galena in several specimens of very rich ore which were polished. In ore from the New Coburg mine, which is also in the immediate vicinity, gold occurs intergrown with galena. The galena-gold contacts, seen under the microscope, are almost invariably well defined planes, to which the cleavages of galena lie parallel. In a few cases, the planes along which the two minerals are in contact give way to a series of tiny steps formed by the edges of tiny cubes. The writer was unable to decide whether gold precipitated directly on the faces of galena crystals, or replaced the galena and was guided by the cleavages of galena in so doing. In either event, the gold appears to be later than the galena, but is in turn older than both sylvanite and bismuthinite, which replace it. (Plate XXV, Fig. 1). The gold is of the same age as native bismuth, with which it is intergrown, with neither mineral developing crystal faces against the other (Plate XXV, Fig. 2). The fineness of gold is in this case 940. These three deposits, the Abercorn, the Big Ben and the New Coburg form a series demonstrating a slight increase in fineness of the gold, which can apparently be correlated with slight differences in the relationship of gold to galena.

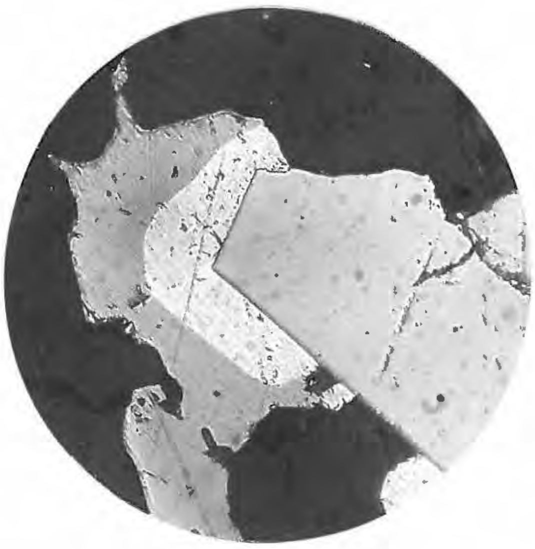


Fig.1 Gold moulded on euhedral pyrite, with both these minerals being in turn enclosed by galena. Textural relationship indicates that gold here started to crystallize before galena. Abercorn mine. x 360.

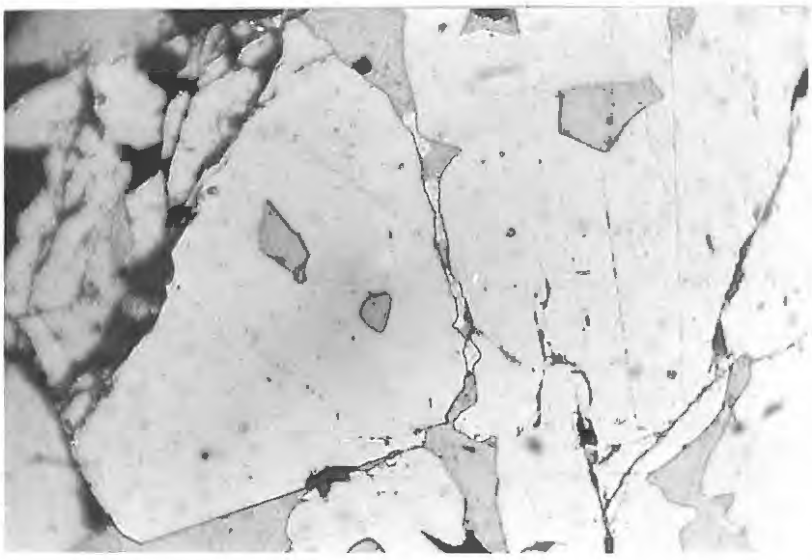


Fig.2 Segmented galena-gold vein filling a fracture in pyrite, Abercorn mine. Texture indicates that here gold and galena crystallized together. x 360.

Fig.1 Gold (pale grey) partially replaced by bismuthinite (bt). The large grain on the right, indistinguishable in the photograph from bismuthinite, is galena (gal). Note native bismuth (bi) in gold. New Coburg mine. x 360.

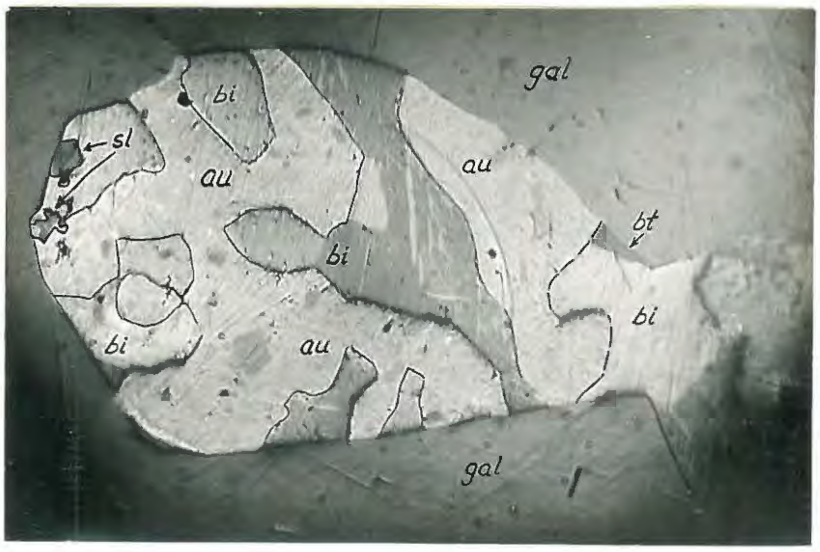


Fig.2 Unusual intergrowth of native bismuth (bi, showing twinning) and gold (au) set in galena (gal). Note straight margin against galena (lower edge), and replacement of gold and bismuth by bismuthinite (bt) and sylvanite (sl). New Coburg mine. Crossed nicols. x 360.

Sulpho-salts

As far as can be determined from the very limited data available, the fineness of gold in association with sulpho-salts varies in the same way as it does in the case of galena. Sulpho-salts have been encountered in only a few deposits, and then only in small quantities, so that the relations between this class of minerals and gold are not clearly known.

Late Minerals

Evidence is forthcoming from a number of sources to show that gold, which occurs very late in the paragenesis, has,very frequently, a high degree of purity. Gold in this category might be defined as that which crystallized in the presence of minerals such as tellurides, antimony or bismuth, or after them.

Tellurides

In the Olympus mine the average fineness of the gold varies from 780 to 880, but the purest gold in the ore is that which occurs either as discrete grains or with tellurides in such a manner that it should be regarded as contemporaneous with them. It was established (Chapter IV) that one third of the gold is closely associated with telluride minerals, and that most of this has a deep golden-yellow colour, in contrast with that which occurs with chalcopyrite,when it is distinctly paler in colour. Gold in the Freda mine, in the Tuli group, occurs together with tetradymite and another unidentified mineral, replacing pyrite. The three younger minerals also form segmented veinlets filling fractures in pyrite, and in so far as segmented veinlets filling fractures may be taken as evidence of simultaneous crystallization (Bastin, 1957, p.17) these minerals are of the same age. They also form isolated blebs in the pyrite, or occur moulded on it.

The fineness of this late gold is uniformly high, and production data over several years indicate a range from 936 to 940.

It has already been mentioned that at the Lake Shore mine, Ontario, (Bloomfield and others, 1936) gold of two distinct types occurs. The purer gold, which occurs in coarser particles, may commonly be associated with the telluride, altaite. Bruce's statistics (Bruce, 1943) for the Lake Shore mine show that the fineness of the gold bullion varies from about 835 to 945. According to analyses given by Knopf (1929, p.37) the purer gold in the Mother Lode system is associated with petzite in a dolomitic gangue. Although only 899 fine, it is conspicuously purer than that occurring with arsenopyrite, pyrite or galena. Sharwood (1911, p.29) has commented on the remarkable purity of gold deposited either contemporaneously or alternately with tellurium minerals. He states that "to this class may belong the deposits of Goldfield, Nevada, where free gold (some of it almost absolutely pure) is associated with a complex antimonial sulpho-salt of copper containing bismuth and tellurium, named goldfieldite ...." He remarks further (p.29) that "in many instances where native gold has been found of exceptional purity, it has been associated with tellurides." It is not, however, clear to what extent he included gold released by the decomposition of gold tellurides in this generalization. In their detailed description of these ores, Tolman and Ambrose (1934, pp. 274-277) stated that two types of gold are present. One is yellow in colour and contains silver, the other is reddish and microchemical tests failed to indicate in it the presence of silver. They state that gold is either contemporaneous with the gold-silver tellurides petzite, hessite and sylvanite, or later than them, and is definitely later than goldfieldite. The two types of gold may occur together with sharp boundaries between them, but gradations between the two also occur.

It is interesting to note that Lindgren (1937, p.363) gives the following sequence in his generalized paragenesis for hydrothermal ores: silver, bismuth, electrum, tellurides and native gold. This does appear to suggest that there is weighty evidence that electrum is characteristically earlier than tellurides, whereas pure gold follows the latter.

Native Antimony and Bismuth

It has been found that where gold occurs late in the paragenesis, with either or both of these two minerals, its fineness is high. The case of gold in the New Coburg mine has been quoted above. Here gold is later than galena, and intergrown with native bismuth (see Plate XXV). It is of moderately high purity, being consistently close to 940 fine. The occurrence of gold in intimate association with native bismuth and probably also native antimony in Horn mine ore was fully discussed in Chapter IV, where it was shown that as the proportion of bismuth increases in the ore specimens, the gold content also increases, and the apparent fineness determined by assay also rises close to a maximum of 960.

Aurostibite

The rare mineral aurostibite, $AuSb_2$, has been described by Graham and Kaiman (1952) as a mineral deposited late in the sequence of mineral deposition, occurring together with bright-yellow gold in ores of the Giant Yellowknife and Chesterville mines. The present writer has encountered a late mineral which closely resembles aurostibite (see Chapter IV) and which has tentatively been identified as such, in ores of the Jessie and Lone Hand mines in the Gwanda district. In both of these deposits aurostibite (?) and gold may occur intergrown, and where they occur in this form, the rich colour of the latter testifies to its exceptional purity.

Late Magnetite

The Getchell mine, Nevada (Joralemon, 1951, p.304) is an epithermal deposit which yields gold bullion in which the ratio of Au/Ag is 10:1. It is of interest to note that gold and late magnetite were the last minerals to crystallize, and that (p.280) the two minerals occur in close association. Both continued to crystallize after all sulphides had ceased to do so.

CHAPTER VI

DISCUSSION : THE GEOLOGICAL FACTORS CORRELATED WITH VARIATIONS IN FINENESS.

The factors which different writers have correlated with variations of gold fineness are numerous. Those which have most commonly been held to be important are discussed below, and an attempt is made to assess to what extent the observations made in different areas are consistent. Considering the complexity of the problem, there is no cause for surprise when it becomes apparent that much of the evidence is contradictory. The views of the present writer are given, and it is believed that some of the paradoxes which have been encountered can be resolved.

GRAIN SIZE

Sharwood's determinations of the fineness values of gold grains of different sizes (Sharwood, 1911, pp. 781-782; Fisher, 1945, p.556) indicated quite clearly that in the Homestake mine ore the purity of the grains tends to increase with size. For convenience, his findings are reproduced here in Table 23. Although the greatest difference between the fineness of very large grains and that of tiny grains is only 2.3 per cent, the feature is so consistent in gold from different levels of the mine that it must be accepted as a characteristic of the ore. Fisher (1945, p.555) commented on this as follows:

"A similar increase in purity of gold with grain size has also been noticed in other gold deposits. Variations in temperature at the time of deposition may be capable of explaining these differences in the case of primary ore for the presence of large grains or crystals of gold suggests higher and more uniform temperature - with resultant higher fineness - for their formation than would be expected for fine grains."

Table 23

Fineness of Gold in the Homestake Mine
(From Sharwood (1911))

Part of Mine	Grain Size of Gold	$\frac{1000Au}{(Au + Ag)}$
Surface workings	Coarse Medium (on 100 mesh) Fine (through 100 mesh)	831 823 823
400, 500 and 600 ft. levels	Coarse Medium (on 50 mesh) Medium (on 100 mesh) Fine (through 100 mesh)	849 836 836 826
700, 800 and 900 ft. levels	Coarse Medium (on 100 mesh) Fine (through 100 mesh)	850 838 833
1000 ft. and deeper levels	Coarse Medium (on 100 mesh) Fine (through 100 mesh)	842 840 832

Further investigation has disclosed that the conclusion quoted above runs contrary to fact in so many cases that it loses value as a principle of broad application. The case of the Lake Shore mine in the Kirkland Lake area might be quoted, where small particles of gold, generally only a few microns across, occur embedded in pyrite and have a higher silver content than larger particles occurring discrete or with tellurides (Bloomfield and others, 1936). In this case, although the larger particles are purer than the smaller, the age and temperature relationships are the reverse of what would be expected from Fisher's generalization. Mills (1954) demonstrated that, in the O'Brien mine, Quebec, the average fineness of gold increased with depth whereas the average size of particles decreased, and hence the smaller particles are purer than those which are larger. The present writer's investigation of the gold in the Jessie mine (Chapter IV) indicated that the coarser particles of gold are decidedly richer in silver than the smaller. In the Olympus mine (Chapter

IV) the largest gold particles were found to be intimately associated with chalcopyrite, and other grains, particularly the purer grains occurring isolated in quartz or with tellurides, were quite definitely smaller. It was also described how crushed samples of high-grade ore from the Horn mine, Gwanda, were sieved and the free gold in different fractions separated by amalgamation. Gold particles greater than 100 mesh averaged 906 fine, whereas those less than 100 mesh averaged 977 fine. A similar test carried out on Lone Hand mine ore showed that gold grains larger than 100 mesh averaged 969 fine, whereas gold finer than 200 mesh averaged 985 fine. Gold in the 100-200 mesh fraction gave an intermediate value of 982.

These few observations are perhaps sufficient to show that probably no general conclusions can be drawn from studies of grain size in relation to variations in fineness, for the size and purity of grains must be controlled by the amount of gold available at any particular stage of mineralization, and it can be considered reasonably well established that gold is not strictly confined to any one position in the paragenesis. In any event, it is certain that the basic assumptions which led Mackay (1944, p.58) to assert that "the possibility of small particles of the primary metals having a higher silver content than large primary particles seems unlikely", are invalid.

Thus, while a definite correlation may be established between grain size and composition of gold grains in any one deposit, it is certain that this relationship may not hold good for other deposits, even when they are of very similar character in other respects.

DEPTH AND TEMPERATURE

Fisher (1945, p.561) has claimed that "fineness of gold shows a general increase with depth of deposition, which implies high temperature and pressure, and appears to be correlated more closely with temperature." This conclusion was based on a broad comparison of deposits of the epithermal, mesothermal and hypothermal types, supported by instances where gold fineness appears to show steady decline with increasing distance from the source. While it does not detract from the value of that work, the present investigation has indicated certain discrepancies which cannot be explained unless the influence of temperature is given less prominence.

The chief objections to singling out temperature as the factor of paramount importance in controlling gold fineness are listed below:-

(i) While gold fineness increases with depth in some deposits, it may also decrease in others. The Kolar gold field (Pryor, 1923) and the O'Brien mine (Mills, 1954) belong to the first category. The Morning Star mine, Victoria (Threadgold, 1958) belongs, for example, to the second. Here the fineness is stated to have dropped from 805 in the upper levels to 785 below the 14th level. A.B. Edwards (personal communication) writes that "some of our mines show not so much zoning of individual gold crystals as variation in silver content with depth - generally a tendency for the silver content to rise slightly with depth. This is apparent in ores in which the gold is 800 to 850 fine - or even richer in silver. Our ores with gold 900 to 970 fine show little evidence of change with depth." The Lonely mine (Chapter IV) showed a conspicuous drop in gold fineness from 958 in the upper levels to 891 in the deeper levels below 2,000 feet from surface. The Turk mine (Chapter IV) appears to yield gold which is consistently richer in silver at 2,000 feet from surface than gold from lesser depths.

Bruce (1943) indicated that the silver content of gold may increase with depth in certain gold mines of Ontario. In these cases quoted above it is difficult to explain the upward increase of fineness purely by temperature changes. The necessary conclusion that temperatures increased with increasing distance from the source in each of these cases seems illogical. A comment made by Lindgren (1926, p.87) in his discussion of Spurr's vertical succession, is perhaps relevant: "The order of deposition is not simply a function of temperature. The precipitation is a function of temperature, pressure, time, concentration and accompanying components in the system."

(ii) Not all gold in hypothermal deposits is invariably of high fineness. Although the mineralization in these may unquestionably be of high-intensity type, characterized by the presence of arsenopyrite, pyrrhotite and chalcopyrite containing exsolved cubanite, the gold fineness is nevertheless in some cases within the range usually associated with epithermal deposits. The statistical study of the fineness of gold in the ores of the Gwanda district, for example, established the existence of low-fineness gold in several deposits, and the more detailed examination of some of these demonstrated that there is no reason to consider them as anything but hypothermal. Similarly, the Antelope mine (see Chapter IV) which is characterized by high-temperature ore minerals, and which contains garnet as a gangue mineral, produced gold which was only 809-849 fine. Conversely, in some low-intensity epithermal deposits gold and silver may occur in the ore as separate metals rather than as an alloy (Joralemon, 1951). These facts can in no way be reconciled with the view that the tendency for gold to alloy with silver invariably increases at lower temperatures.

(iii) The variability of gold fineness in any one deposit may be regarded as an established fact. Specifically, however, the explanation of this in terms of temperature variations encounters difficulties in those cases where the average fineness varies apparently haphazardly along strike over distances of only a few feet or even much smaller distances.

(iv) The fact that a deposit is hypothermal in character is no guarantee that all of the gold in it precipitated at particularly high temperatures. Lindgren (1937, p.368), for example, quotes work by Borchert which suggests that calaverite at Kalgoorlie (a hypothermal deposit) actually crystallized at a lower temperature than that from Cripple Creek (an epithermal deposit).

(v) The correlation between gold fineness and the relative ages of gold grains in any one ore, as described in Chapter IV, is the most convincing evidence that temperature is not the only operative factor controlling fineness. As this aspect is more fully discussed in a succeeding section, it should be sufficient to state at this stage that the change from low fineness to high fineness, with the successive deposition of ore minerals in normal paragenetic order, is quite the reverse of what would be expected if temperature alone controlled fineness.

PARAGENESIS AND AVAILABILITY OF SILVER

Evidence has been presented (Chapters IV and V) to support the view that the purity of gold particles can be linked with the stage at which deposition occurred during mineralization. This evidence has accumulated during the study of deposits which are hypothermal in character; it is not known whether similar relationships prevail in deposits which are mesothermal or epithermal. Bearing in mind that hypothermal deposits tend, in general, to be deficient in silver and are in this respect rather different from epithermal and mesothermal deposits, the hypothesis outlined below is intended to be applied only to the former class of deposits. To what extent the conclusions are applicable to deposits containing abundant total silver can be determined only by more extended study.

(a) Paragenesis of Gold

In those few cases where opinions have been stated by different investigators, it has been implied that the normal sequence during vein mineralization is from purer gold in the earlier stages to silver-rich gold in the later stages. Thus Edwards (1958, p.130) in his description of the Maude and Yellow Girl mine demonstrated that the fineness of the gold varies from 685 to 950, and concluded that "... some gold ... was deposited along with the arsenic in the opening stages of mineralization, and entered into solid solution in the arsenopyrite and pyrite. From the paragenesis, it would be expected that very little silver was associated with this early gold." Reference has already been made to Fisher's views. He concluded that high temperatures cause the gold grains to be purer and larger than those formed at low temperatures. Mather (1937, p.141) described gold in the Howey mine, Ontario, as follows:

"Free gold occurs generally in a finely divided state, and is megascopically visible in only four hand specimens. Under the microscope it was identified in four fifths of all specimens examined. In polished section the colour varies from golden to pale yellow. van der Veen states that the pale colour of certain free gold is due to the silver it contains in solid solution; this is verified by the occurrence of the pale yellow type as blebs in polybasite .... Microchemical tests show that the amount of silver present is insufficient to form electrum. The difference in colour and therefore in composition can be correlated with difference in age; the golden yellow type is older and the pale yellow is younger."

The logic upon which the latter conclusion is based seems less than convincing, in view of the fact that polybasite is shown (p.148) to be amongst the last of the ore minerals to crystallize, and did not start to separate until all gold had ceased to do so.

The present writer has found that, in the case of the Southern Rhodesian deposits which he has studied, the position is the reverse of what has been implied in the references quoted above. The relationship is illustrated in Fig. 23. This diagram is presented with the full realization that it is open to severe criticism on many counts, but it remains, nevertheless, the least complex way of summari~~s~~zing the data, and depicts the change from silver-rich gold deposited early in the paragenesis, to purer gold in the later stages. No particular deposit has been selected as a model in the construction of the diagram, and the fineness values used for plotting the curve should be considered to be significant in a relative rather than an absolute sense.

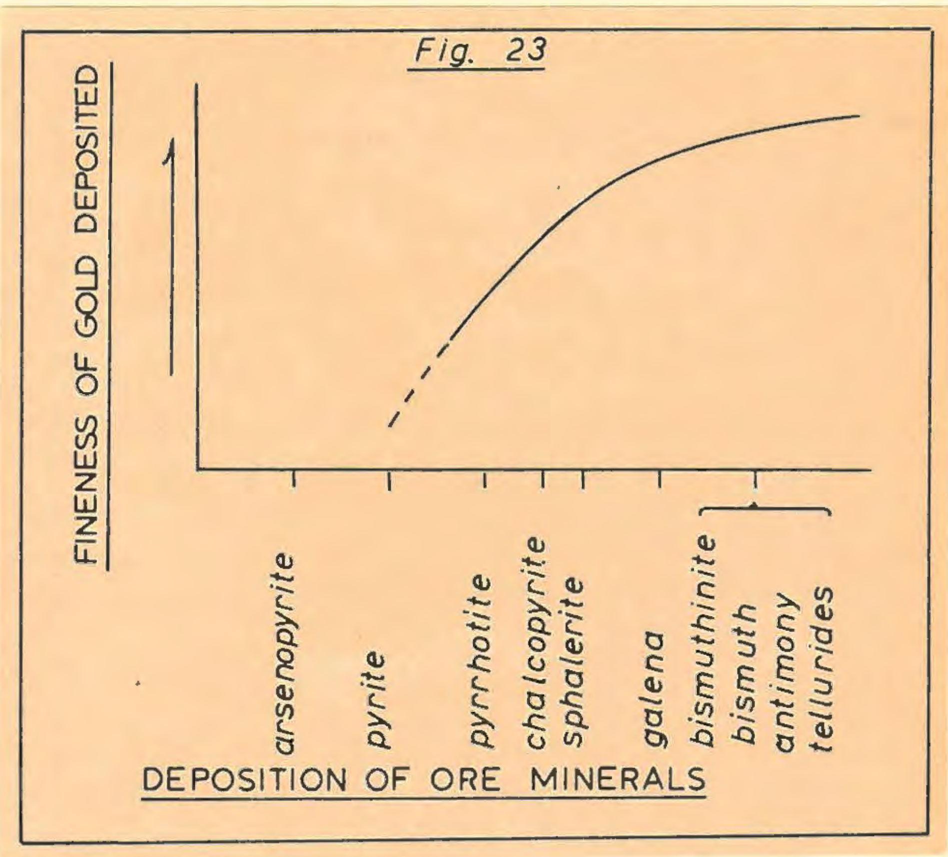


Fig. 23. Variation of Gold Fineness in Relation to Paragenesis of Ore Minerals.

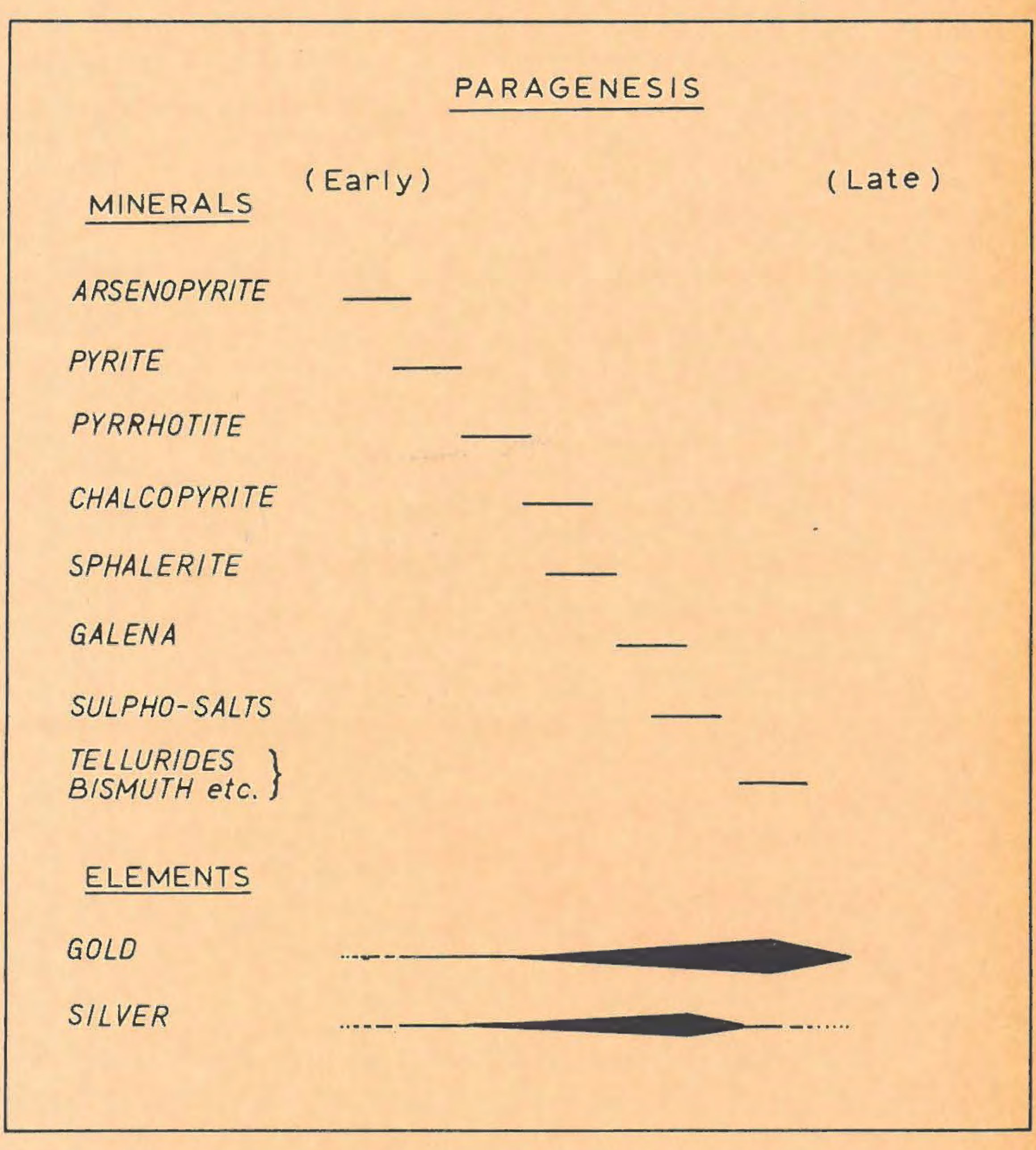


Fig. 24 PARAGENESIS OF GOLD AND SILVER IN RELATION TO THE COMMON ORE MINERALS. GENERALIZED DIAGRAM BASED ON SOUTHERN RHODESIAN EXAMPLES.

Whereas Fig. 23 depicts the variations in true fineness of gold particles, Fig. 24 is more closely related to apparent fineness values. An idealized paragenetic sequence is shown in the customary way, but the relative abundance of the elements gold and silver has been indicated by lines whose thicknesses vary according to the relative amounts considered to have been deposited at different stages.

The data on which the diagram is based have been drawn from microscopic study, the assays of samples of minerals and concentrates, and of samples taken underground. Thus, the microscope can be used to demonstrate that although gold has a long period of deposition and may accompany different ore minerals, its rate of deposition generally accelerates towards the later stages of metallization. When the final phase is entered there is a sharp decline in the rate of deposition, and the grains become exceedingly small although they may be very numerous. The proportion of silver relative to gold may be deduced partly from the rough estimates of gold fineness made under the microscope, and the textural evidence, but chiefly from assays of specimens which have already been examined microscopically.

It will be recalled that in Chapter IV a sympathetic variation in gold content and gold purity was demonstrated in several deposits. This may now be interpreted to mean that throughout the greater part of the course of mineralization in hypothermal deposits, gold and silver are deposited at an increasingly greater rate, but that the increase shown by gold is greater than that shown by silver. Accordingly, in the earlier stages the gold may alloy with considerable amounts of silver, but the proportion of silver does not keep pace with that of gold in the later stages, and fineness is constrained to rise. It is considered that, in the waning stages of metallization, the decline in the amount of silver separating from the ore fluids is well advanced before the decline in gold is appreciable. This leads to the growth of progressively smaller particles of gold, of perhaps exceptional purity, just before metallization ceases altogether, and probably accounts for the occurrence of small pockets of ore which are found to contain only small amounts of gold and practically no silver. From what evidence is available, such pockets are not uncommonly encountered during sampling.

(b) Silver-rich Gold and other Silver Minerals in Hypothermal Deposits.

The hypothesis outlined above is capable of explaining the observed variations in gold fineness in the majority of deep-seated Rhodesian deposits. The change from gold of low purity to gold of high purity with the progress of metallization in ores which are basically silver-poor is seen to be a function of the availability of silver. The most convincing proof that this is the case is the fact that the disparity between true fineness and apparent fineness values is negligible in those specimens of rich ore in which the gold is demonstrably late; this shows that there was insufficient silver available to form silver minerals other than silver-bearing gold in the late stages.

Some complexity is introduced where the amount of silver in the ore is apparently in excess of the amount which occurs alloyed with gold, or where the average fineness of the gold is rather lower than that normally expected in hypothermal deposits. These two contingencies may now be considered.

In the former case, where there are significant discrepancies between the true fineness of gold particles in the ore and the apparent fineness of the samples in which they are contained, the following factors bear on the problem:

(i) Where there are only unimportant differences between the average fineness of the gold particles separated by amalgamation, and the apparent fineness of the residual sulphides, these may legitimately be ascribed to the occurrence of very small, perhaps sub-microscopic, particles of silver-rich gold embedded in the sulphides, which are not recovered by amalgamation. These particles probably represent gold which separated at an early stage, but which were prevented from attaining any appreciable size. Disparity between the fineness of amalgam gold and that of cyanide gold may perhaps in many cases arise in this way.

(ii) Modifications of paragenetic order. The presence of native gold and silver-bearing minerals in the ore does not necessarily imply that they are of the same age. Silver may, for example, be introduced in some abundance after the deposition of gold has ceased, in which case silver minerals will be found to be later than the gold. Silver introduced at this stage would be unable to alloy with gold, and gold should then occur as inclusions in these minerals.

(iii) The partition factor. Edwards (1958, p.131) suggested that the concentration of other elements in the mineralizing solutions, with which the silver could combine, would influence the fineness of gold, and hence it would be logical for silver-bearing minerals and gold of moderately high fineness to occur together.

(iv) The ability of gold to alloy with silver. Very little information is available with regard to the power of gold to alloy with silver under different conditions. Fisher (1945) has claimed that at lower temperatures gold has a greater ability to alloy with silver than at higher temperatures, whereas Joralemon (1951, p.296) holds that at very low temperature gold and silver will not alloy, but will be precipitated as the separate metals. This is said also to characterize the precipitation of gold and silver from cyanide solutions. M.S. Fisher (1935) showed that under supergene conditions gold is precipitated as almost pure metal. The subject clearly requires further investigation.

Turning to the second of the contingencies previously cited, that which concerns the occurrence of gold of low average fineness in hypothermal deposits, one cannot fail to be impressed by the fact that each of several examples quoted has one feature in common. That is, notable quantities of gold occur in intimate association with, or are enclosed by, the sulphides chalcopyrite, sphalerite or galena. Thus, in the Olympus mine, abundant coarse gold particles occur either as crystals bounded by faces in the interiors of chalcopyrite crystals, or indenting the margins of chalcopyrite crystals. In the Jessie mine there is abundant coarse gold which occurs with sphalerite, while in the Lonely mine ore the change from high-quality gold to low-quality gold was marked by a change in the manner of occurrence of gold from that of discrete grains to grains enclosed in chalcopyrite. Other examples were quoted in Chapter V. The conclusion seems inevitable that the low average fineness of gold in these ores is brought about by an unusual abundance of gold which is precipitated early in the paragenesis, for gold of high purity does also occur, but is quantitatively less important than it is in ores where the average fineness is high. What factor has caused gold, and to a lesser extent, silver, deposited in the earlier stages of precious-metal metallization, to become as abundant as that deposited in the penultimate stages is not known. The influence of that factor is nevertheless very conspicuous. These ores in which the average gold fineness is low appear to carry only very little silver in excess of that required to account for the low gold fineness. For example, in the Olympus mine the average apparent fineness values are only about 50-100 parts lower than the average fineness of gold particles, and in the Jessie mine approximately 100 parts lower. Considering that part of this difference may be accounted for by the occurrence of very tiny gold particles of silver-rich gold enclosed in sulphides, the silver occurring in some other mineralogical form is perhaps very small.

(c) The Causes of Silver Deficiency

An important question which arises out of this discussion concerns the underlying cause of the relative paucity of silver in these deposits, particularly in the later stages of mineralization. Are hydrothermal fluids in the hypothermal environment fundamentally deficient in silver, or does the silver merely exhibit a reluctance to separate from the ore fluid? It is obviously not possible to resolve this question by the examination of ore specimens, but evidence from a different source suggests that the second of the alternatives may be the correct one. Thus, if the upper five zones, representing the Tertiary precious-metal veins, be ignored, Emmons' well known reconstructed vein system (Emmons, 1924, p.983) shows that silver tends in general to be carried far from its magmatic source, whereas gold is freely deposited at depth. "Gold is unique among the metals .... in that it is deposited lower down on the walls of large batholiths than others", (loc. cit., p.989). A similar picture is presented by Emmons in his subsequent paper (1926) dealing with the different groups of metalliferous lodes, which he distinguishes on a basis of their positions relative to their parent batholiths. Silver is shown to increase steadily in amount with distance from the deeper parts of the batholiths which produced the mineral veins. Joralemon (1951, p.304) ascribed the decreasing tenor of silver metallization in the late stages of the formation of the Getchell deposit, Nevada, to increasing solubility of silver. "Hydrothermal solutions, on rising, may be expected to change gradually from alkaline to some degree of acidity. As a consequence, gold will tend to be deposited as soon as sufficient sulphide ions are removed, but silver sulphides and sulphosalts, being soluble in acid solutions, will no longer be deposited but will be swept along the channelways" (loc. cit., p.304). There is, however, a hint that there is an actual deficiency of silver in the fluids forming deep-seated deposits, for Emmons (1924, p.989) does state that "there is evidence ... of a separation of metals in the magmatic chamber; gold, with other metals in smaller amounts, is deposited well down on the walls, while much gold and most of the other metals on segregation tend to move to the cupolas and ridges of the roofs of batholiths."

(d) Resolution of Some Paradoxes

At the beginning of this paper it was pointed out that a paradox arises when the explanation of the downward decrease of average gold fineness in some deposits is sought in terms of temperature variations. It seems illogical to suggest that the increase in fineness with increasing distance from the source in deposits of this class should be due to an increase in temperature as higher levels are reached by the ore-depositing fluids. In view of the evidence which has thus far been presented, it is here offered for consideration that, in deposits of this class, the gold in the deeper levels crystallized early, in the company of sulphides, and that, with increasing distance from the source, the chemical attributes of the ore fluids changed so that a greater proportion of the gold deposited was 'late' gold, following the sulphides. The result of this would be an increase in the average fineness of the gold towards the surface. These conditions appear to have been fulfilled, for example, in the Lonely mine deposit.

Changes in the opposite sense would bring about an increase in average fineness with depth. As pointed out in a following section, the exact nature of these changes is unknown, and the non-committal phrase 'changes in the chemical attributes of the ore fluids' is preferred. It may be that the changes in question include changes in the concentration of sulphide in the fluids.

By the same mechanism, the inconsistent relationship between grain size and gold fineness might be explained. If it be assumed that grain size is chiefly a function of the availability of gold and the temperature of deposition, the grain size and composition of the gold grains will depend largely on the stage at which gold is most rapidly being supplied to the focus of deposition. Where gold was freely precipitated throughout a long period, it would be expected that the early-formed grains would be larger, and also richer in silver, than those which formed later at the lower temperatures which would favour the formation of smaller grains. The assumption that lower temperatures are conducive towards the formation of smaller grains,than ~~at~~ high temperatures,appears to be valid, for the first-formed minerals in ores, even where they are not present in great quantity, do appear to form larger crystals than the later-formed minerals. Also, epithermal deposits are notably finer in grain than, for instance, hypothermal deposits. In the case where the larger grains of gold in a particular ore are purer than those which are smaller, it may well be the case that grains have grown larger and purer by zoning, i.e., by the continued deposition of shells of purer gold around early-formed nuclei - the later shells being purer than the earlier shells. It would be expected that, in this case, larger grains would not be conspicuously purer than smaller grains.

Selective precipitation of gold and silver by different ore minerals does not appear to supply an answer to variations in gold fineness, or to the variations in total gold and silver content. If selective precipitation were important, it might be expected that associated with each mineral in the ore there would be gold of a characteristic fineness. But this is not the case; the correlation between the fineness of gold particles and their occurrence with the associated minerals appears to hinge only around their relative ages. The experiments which have tested the relative efficacy of different sulphide minerals as precipitants of gold and silver (Palmer and Bastin, 1913; Grout, 1913) do not suggest any clear relationship between the precipitating power and the observed variations in fineness of the associated gold. In any event, these experiments are applicable to supergene rather than hypogene deposition.

The chief weakness of the hypothesis outlined above might be considered to be the lack of supporting chemical evidence. However, in view of the diversity of opinion that still exists concerning even the most fundamnetal characteristics of ore-depositing fluids, there is little to recommend the proffering of any theoretical mechanism to account for the facts. It might, however, be relevant to point out that the change from low fineness to high, during mineralization, appears to run parallel with the waning of the deposition of sulphides and the ascendency of tellurides, native metals and other non-sulphides. One is tempted to apply the alkali sulphide hypothesis of Smith (1943) to the problem, for this is concerned with the solubility of gold and silver in solutions of alkali sulphide.

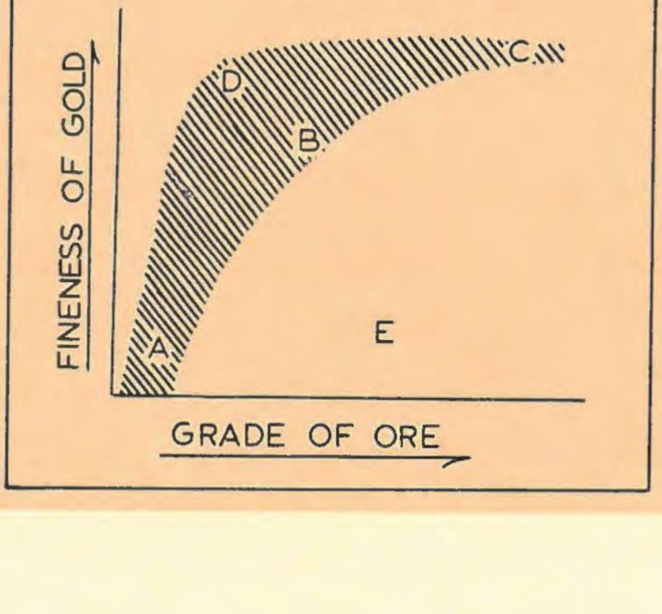
TENOR OF METALLIZATION

The relationship between the average grade of ore and the purity of gold, which exists in a number of deposits, is easily explained once it is accepted that two features characterize the precipitation of gold. These two features are, respectively, the increase in purity of grains from the earlier stages towards the later stages, and the tendency for the rate of precipitation to increase as the last sulphides, tellurides and native metals separate. Ore shoots, or smaller lenses of high-grade ore, are thus identifiable with portions of the vein system which, for one reason or another, have allowed the passage of ore fluids until the latest stages. This is clearly a function of permeability. Those parts of the ore channel which have become filled at an early stage will contain only gold which has been precipitated relatively early; as a result the amount of gold will be small and its fineness will be low. But in those portions of the ore channel where 'clogging' by gangue and sulphides has been less complete, ore fluids will continue to pass and to deposit gold until the latest stages. This late gold will be relatively pure. The total amount of gold will be greatest in these sections, and, although the average fineness will be high, careful examination will usually establish a range in the purity of the constituent grains. It would be expected that small pockets of ore would occur, which contain gold of exceptional purity, but perhaps not in great quantity. These would represent the last gold grains to form before metallization ceased altogether.

It is possible to relate this sequence to the fineness-tenor diagrams which were employed in Chapter IV. Fig. 25 is an idealized diagram of this type, which may be considered to represent either the fineness of amalgam gold plotted against the average grade determined by recovery, or the apparent fineness of small samples plotted against their gold content determined by assay. The area in which the majority of plotted points fall, in practice, is represented by shading.

The area 'A' represents the low-grade specimens containing only a small proportion of those minerals which occur late in the paragenesis; chiefly the high-temperature minerals such as pyrite and pyrrhotite are present. Area 'C' represents specimens containing an abundance of low-temperature minerals and late gold, or perhaps only gold, whereas the area 'B' will represent specimens containing gold grains whose composition varies considerably; diversity of mineral species is to be expected. Ore specimens which contain only small amounts of late gold, low-temperature minerals and probably only traces of early-deposited sulphides should fall in area 'D'. The total gold content of these specimens would be low because only that gold which separated in the waning stages of metallization would be found in them. In practice, it has been found that area 'E' is generally unoccupied. In view of the discussions above, this is to be expected, for gold is not normally precipitated in greater abundance in the earlier stages than in the later stages. Thus, an abundance of gold, containing about the same proportion of silver as that characterizing the area 'A', is not to be expected.

Fig. 25



In view of this relationship which is apparent in individual deposits, an attempt has been made to determine whether a similar relationship might not characterize groups of deposits. The fineness values for a number of deposits in the Gwanda district have been recorded in Table 1. Using all possible care, the average grade of the ore was established for each producer, for the year during which the highest fineness value was recorded. This estimate was based on the tonnage milled, and the total amount of gold recovered by amalgamation, cyanidation and the treatment of concentrates. The

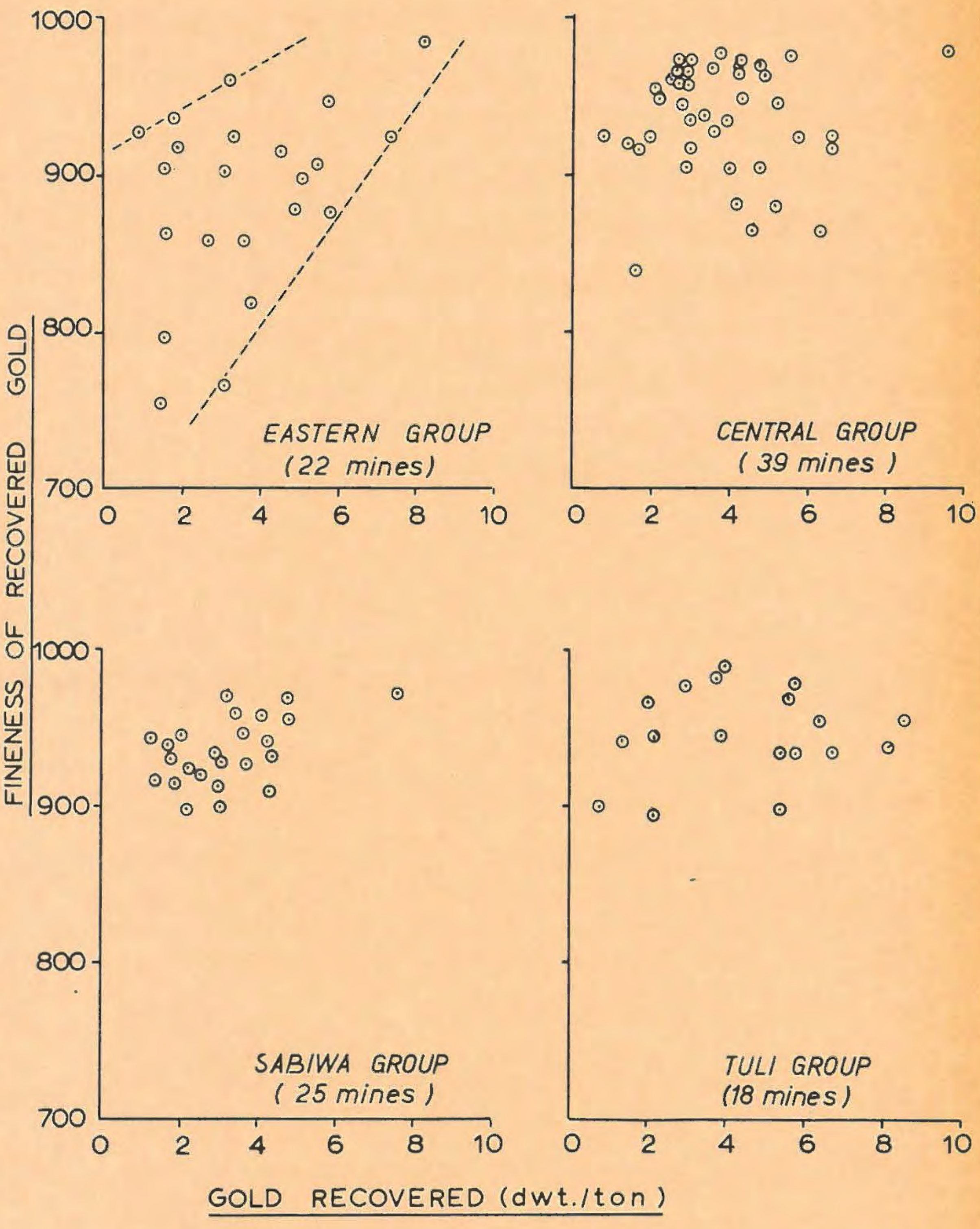


Fig 26 FINENESS OF GOLD PLOTTED AGAINST GRADE OF ORE FOR DEPOSITS IN THE GWANDA DISTRICT.

value of the residues was an unknown factor. Where the tonnages of sands treated were found to exceed the tonnages crushed during that year, the output from cyanidation was adjusted proportionately, or that particular producer struck from the list. In this manner some estimate of the average grade and the highest fineness value for a particular period could be made. The manifold inaccuracies are fully appreciated, and require no emphasis. To some extent, however, these are counterbalanced by the fact that most of the mines were typical smallworker operations; grade-control was not practised, and the pressing need for an output generally ensured that ore was milled as it became available. Conditions such as these mean that wide fluctuations in average grade of treated ore are to be expected and the chances of proving a broad relationship between fineness and tenor, if it exists, would be improved. The results of this investigation are shown in Fig. 26, and the interesting fact emerges that, where the fineness of recovered gold shows greatest variation, as in the Eastern group, there is a definite suggestion that it is related to the average grade of the deposits. Where the total variations in fineness are in the first instance too small to spread the plotted points in the diagram, this relationship is not obvious. It might be mentioned that a few producers, for which data are available, do not figure in the diagram. These deposits are of outstanding richness, and their average recovery exceeded the range 0-10 dwt./ton. These deposits might owe their exceptional richness to special factors, and their exclusion seems justified.

THE DEPTH ZONES OF ORE DEPOSITION

The writer's investigations have been confined to deposits which are hypothermal in character, and no opportunity has arisen to study those which are typically mesothermal or epithermal. Reasons have been given for laying less emphasis on temperature as an important factor controlling fineness, and more on the chemical attributes of the ore fluids. It is, however, difficult to reconcile these conclusions with the established fact that gold fineness does become progressively lower in the series hypothermal-mesothermal-epithermal, since gold of moderately high fineness does occur in many mesothermal and epithermal deposits in which there is no paucity of silver. That,is, some factor other than the availability of silver restricts the amount of silver which will alloy with the gold.

The following conclusion is inevitable:-

(i) Temperature, even if it is not the most important factor, is nevertheless potent in determining gold fineness at the time of its deposition, or,

(ii) The chemical environment in which gold is precipitated differs fundamentally in the different depth zones.

With regard to the first alternative, it could be concluded that while high temperature does, in general, lead to the precipitation of gold with a low silver content, as advocated by Fisher (1945), the other factors which the present investigation has stressed cause the discrepancies such as the occurrence of silver-rich gold in hypothermal deposits, silver-poor gold in epithermal deposits and the paragenetic relationships of gold grains of different degrees of fineness in any one deposit. This compromise has much to recommend it, and is perhaps the most acceptable at the present time.

The literature is not, however, without suggestive hints that the second alternative may also contain some truth. If, for example, it could be shown that most gold is deposited, in epithermal deposits, in an environment which favours also the separation of sulphides, whereas in hypothermal deposits most of it normally separates only after the chemical environment has changed, with the deposition of non-sulphide minerals, then the low fineness of epithermal gold could be attributed to the same factors which cause early-deposited hypothermal gold to contain appreciable amounts of silver.

Fundamental differences between conditions prevailing at the time of deposition of the gold in the epithermal deposits and other deposits are suggested by Lindgren (1937, p.364) who wrote: "In the epithermal deposits the sulphides are crowded within a shorter vertical distance; they are 'telescoped', using Spurr's expression ....." and "In the mesothermal and hypothermal classes the sulphides are spread over a larger interval and zoning is more apparent."

Equally suggestive is a comparison of the paragenetic relationships established by Lowell (1942) for ore deposits in south-western Oregon. This brings out the significant fact that here the position of gold in the paragenesis does in fact vary in the manner which was suggested above. In the hypothermal and mesothermal deposits gold continued to crystallize until the last stages of mineralization. In the epithermal deposits of this region, however, chalcopyrite, tetrahedrite, tennanite and bornite continued to separate after gold. It could be inferred that here the chemical environment in which gold was precipitated differed fundamentally in hypothermal and epithermal deposits.

This particular aspect does, perhaps, merit further investigation, especially in view of the fact that the epithermal deposits may be considered to include deposits formed at elevated temperatures as well as low temperatures (Buddington, 1935; Schmitt, 1950).

CHAPTER VII

GENERAL SUMMARY OF CONCLUSIONS

In the following brief summary, the more important conclusions which have emerged from the work described on foregoing pages are listed. Discussions of the different conclusions have been omitted entirely in order to present the findings in as concise a manner as possible. The list of conclusions includes both statements of findings and the inferences which have been drawn from them.

(1) Gold fineness in any hydrothermal deposit is seldom a rigid value characteristic of that deposit. Variations of the order of 100-150 parts per thousand are by no means uncommon.

(2) Average gold fineness may, in different ore shoots lying within the same ore body, show considerable differences.

(3) Production data indicate, in many cases, that the average fineness of an ore body varies only slightly but closer examination may reveal that the composition of the constituent gold grains is very variable. This feature is due to a process of 'averaging-out' of fineness values which takes place during the recovery of an output from substantial tonnages of ore, while such averaging-out is less effective in the case of small specimens of ore.

(4) Microscopic examination reveals that the silver content of gold grains varies widely in some deposits, in grains of gold which may lie less than 1 mm apart.

(5) In the hypothermal ores which have been studied, there is little definite evidence to suggest that gold grains have a zonal structure. Each gold grain appears to be uniform in composition. It is probable that, at the time of deposition,

a zonal structure existed, but that this has been destroyed by diffusion taking place over a long period of time. Accordingly, adjacent grains may now contain different proportions of silver, although each is homogeneous.

(6) An examination of a typical gold belt in Southern Rhodesia failed to reveal any zonal distribution of fineness values in the area. No evidence was found to suggest that the nature of the country rock in which a deposit occurs, or the distance of a deposit from the contact between the schist belt and the intrusive granite, have any influence on the fineness of the gold deposited. It does appear, however, that where the deposits in any particular group are very similar with regard to the type of mineralization, the fineness of the gold contained in them varies far less than in groups of deposits where the diversity of mineral species is great.

(7) In most of the deposits which have been studied, there exists a definite relationship between the fineness of recovered gold and the grade of the ore. Where the grade of the ore is high, the fineness of the gold tends to be high, and where the gold fineness is low, the grade of the ore tends to be low. This relationship is best demonstrated by the production statistics where the average grade and the average fineness vary between wide limits, but it may also be demonstrated by the assaying of samples of the ore. Sampling may establish the presence of small pockets of ore containing gold of exceptional purity, although the value of the sample might not necessarily be high. The examination of samples of concentrates from the ores indicates that, in these Southern Rhodesian deposits, the variations in apparent fineness, determined by assaying, are due primar~~e~~ily to the variations in the composition of the constituent gold grains rather than to gold or silver occurring in other mineralogical forms.

(8) Apparent fineness values vary sharply, in these ores, over distances of only a few feet, and the variations are neither regular nor predictable.

(9) Although hypothermal deposits are normally characterized by the presence of gold with a relatively low silver content, some contain gold which is relatively rich in silver, although the mineral assemblage indicates deposition at high temperatures. It is concluded that temperature is not the most important factor controlling the fineness of the gold deposited. The fact that many epithermal deposits, in which there is no paucity of silver, may contain gold of moderately high fineness supports this view.

(10) While the average fineness of the gold particles may increase with increasing depth in some deposits, it may decrease in others. There is no general rule.

(11) While the fineness of gold increases with particle size in some deposits, it may decrease in others. There is no general rule, although it has been found, in all the cases which the writer has studied, that coarse-grained gold tends to be silver-rich and fine-grained gold, in the same deposit, is purer.

(12) The detailed study of textural relationships shown between gold and other minerals indicates that it may crystallize in company with a number of other ore minerals i.e., it is not confined to any one stage in the paragenesis of ore minerals. The evidence indicates that that gold which crystallizes early in the paragenetic sequence contains more silver than that which crystallizes in the final stages of ore deposition. It was found that in those deposits where the gold fineness is most variable, the crystallization of the gold extended from early in the paragenesis to late, whereas in those deposits where gold fineness tends to be almost constant, the period of crystallization of gold, relative to other ore minerals, is very

short and the mineralogy of the ore is likely to be simple. Similarly, 'free' gold in ores tends to be purer than gold entrapped within sulphides, for gold of the latter type is frequently of relatively early crystallization.

(13) While detailed mineragraphic work on some Southern Rhodesian deposits has indicated a relationship between the purity of gold grains and their age, as indicated above, a survey of available literature indicates that, in general, gold which is closely associated with minerals such as pyrrhotite, chalcopyrite and sphalerite, which separate fairly early in the sequence of crystallization, is very commonly rich in silver. Gold which is intimately associated with late minerals such as tellurides, native metals or oxides, is very commonly exceedingly pure. Gold which occurs intergrown with galena, which lies between these two groups of minerals in the paragenesis, may be either silver-rich or silver-poor.

(14) From what literature is available on the subject, it appears that similar relationships between the fineness of gold, the tenor of the ore body and the position in the paragenesis, of gold, exist in deposits in other countries.

(15) In the hypothermal deposits which have here been studied, the increase in the gold fineness with the progress of ore deposition is held to be due to an increase in the solubility of silver in the ore-depositing fluids in the late stages. It is believed that while gold continues to be precipitated until the very latest stages of metallization, silver shows an increasing tendency to remain in solution and to be swept further from the ultimate source in the latest stages. As a result, 'late' gold is constrained to increase in purity. This is probably one of the chief reasons why gold in hypothermal ores is of high fineness, for the bulk of hypothermal gold is generally precipitated after most other ore minerals have

ceased to crystallize. The evidence which has been gathered suggests, further, that where hypothermal deposits contain gold which is alloyed with a relatively high proportion of silver, an uncommonly large amount of gold was precipitated at a relatively early stage. That is, the bulk of the gold may be found to be of the same age as pyrrhotite, chalcopyrite, sphalerite or even galena.

(16) The downward increase in average gold fineness in some deposits, and the downward decrease in others is held to be due to slight changes in the age of the gold, relative to other ore minerals, at different levels. Acceptance of this principle makes it unnecessary to invoke complex and improbable variations in temperature at different levels to account for the inconsistent variation in fineness in different deposits.

(17) The relationship which exists between fineness and tenor in ore bodies is, in all probability, the result of variations in the permeability of the ore channel during deposition of the ore. Where the ore channel became filled with gangue and ore minerals at a relatively early stage, fluids would have been prevented from circulating during the late stages, and the bulk of the gold in these sections would be 'early' gold, and, according to the conclusions which have been drawn, it would be relatively rich in silver. Where, however, deposition of gold continued unhindered to a late stage, by virtue of the presence of openings in the ore channel, or as a result of brecciation or fracturing, gold would be deposited in greatest amount, and, a large proportion of it being 'late' gold, its silver content would be low. As a result, rich ore shoots should contain gold which has less silver than that which occurs in medium- or low-grade ore. On a smaller scale, the variability of fineness and apparent fineness at closely spaced points along the strike of the ore body can be ascribed to the same mechanism.

(18) As a final conclusion, it may be inferred that the characteristic differences in gold fineness in the hypothermal, mesothermal and epithermal deposits cannot be attributed wholly to differences in the temperatures at which deposition occurs. While it is possible that temperature is not an unimportant factor, differences in the chemical attributes of the ore-depositing fluids and, in particular, differences in the paragenetic relationships of gold, should be given equal prominence in any attempt to explain the differences in gold fineness.

CHAPTER VIII

APPLICATIONS OF INVESTIGATION

Although this investigation has been one of purely scientific interest, some practical aspects could be turned to advantage. It is suggested that the incorporation of fineness data in mill records would in many cases be of value, and that mine and ore evaluation should take into consideration variations in the character of the gold. Some aspects might be of importance in the controversy regarding the origin of the Witwatersrand gold.

(a) Mill Records

In Chapter IV, the analysis of the Olympus mine mill records illustrated that the fineness of gold varied in different sections of the workings, and that the average fineness of the gold recovered by amalgamation gave an indication of the proportions of gold contributed by each section. Also, fineness was found to be intimately related to the grade of the ore recovered.

Detailed records, for those mines in which these relationships obtain, could be of invaluable assistance for periodic checks on the efficiency of grade-control or of sorting, in that the incorporation of excessive amounts of low-grade or waste ore should be reflected in conspicuously low fineness values for the corresponding period. It is an aspect which could well repay further detailed research.

(b) Mine Evaluation

A problem which continually faces exploration companies engaged in the purchase and development of partially developed deposits is that which concerns the depth-persistence of the ore bodies. Clearly, the purchase price is a function of the anticipated return from exploitation, but there is frequently no guide whatever to assist in assessing possible continuity below levels already developed. While the writer has but little data on which to draw, it does appear that fineness variations might sometimes provide a hint, when often little more than a hint will serve to influence a final decision.

It appears that, in many cases, the bottoming of a rich ore shoot is heralded by a drop in the average fineness of the gold. Thus, in the Lonely mine, the valuable ore body was characterized by rather uniform fineness values for something like 2,000 feet from surface, but, with the appearance of silver in notable quantities, the ore body failed. The Olympus mine was characterized by highly variable fineness values, and did not repay exploitation below the 6th level. The Lone Hand mine, which was sampled on the 10th level, showed great fluctuation in gold fineness. The reef is reported to be less robust in more recent levels which have been opened up below. The Makanga mine failed when the fineness dropped sharply.

Conversely, the Blanket 'A' mine, which can be expected to show persistence to great depth, judging from the dimensions of the ore body exposed in the shallow workings, shows hardly any variation in the silver content of the free gold.

Deductions based on these considerations should be drawn only with the greatest circumspection. Some ore bodies appear to show variations in fineness throughout their entire vertical extent, in which case the arguments do not apply. They apply only where an abrupt change in the average fineness is evident, forecasting zonal change in the character of the mineralization. It should also be remembered that the Southern Rhodesian deposits formed at great depths, and have ~~only~~ been exposed only by prolonged erosion. They do not correspond to deposits which cluster around granite cupolas.

(c) The Occurrence of Gold in Ancient Sediments of the Transvaal

It would not be out of place to conclude with some remarks on the character of the gold in the ancient sediments of the Witwatersrand and Transvaal Systems. While the writer has had but little personal contact with these deposits, it is scarcely a disadvantage in these times when so many accounts by skilled research workers are in print. The more interesting aspects of the variations in the composition of the gold are discussed below.

(i) Average Silver Content

The authoritative account by Prentice (1940) established that the average silver content of Witwatersrand ore is 9.64 per cent of the gold content, but that this value varies from 8.3 to 11.8 per cent. Graton (1930, p.132) considered that the Witwatersrand gold "is fairly pure gold as average placer gold goes". Liebenberg (1955, p.205) considered that "the general low silver-content may thus be an additional feature suggesting a detrital origin for the gold". Davidson (1956, p.118), however, took the opposite view, stating that "the Rand bullion uniformly contains around 10 per cent silver. This is much greater than is commonly found in placer gold ..."

If the Gwanda gold belt, in so far as it is a typical occurrence of Primitive rocks mineralized by Old Granite, be assumed to be similar in character to that source which, under the placer hypothesis, yielded gold to the Witwatersrand sediments, Liebenberg's argument loses some of its force. Compared with the Gwanda gold belt, the average Witwatersrand gold is not silver-poor. 55 per cent of the producers in the Gwanda area have produced gold whose upper limit of fineness is above 930, the upper limit for amalgam gold indicated by Prentice (1940) for the Witwatersrand.

(ii) Grain Size

It seems fairly well established that the purity of gold grains increases with size in the Witwatersrand deposits. Young (1917, p.77) referred to this fact as far back as 1917, and Prentice's work (loc. cit., pp. 27, 33) confirmed the statement.

It does not seem likely that any useful conclusions can be drawn from this fact, for it has been shown on foregoing pages that the purity of hydrothermal gold may either increase or decrease with increasing particle size. It is certain, however, that the increase in purity with the increase in particle size is the reverse of what is normally encountered in placer deposits which have not suffered redistribution of their gold values. (Graton, 1930, p.132; Davidson, 1956, p. 118).

(iii) Fineness in Relation to Grade

Prentice (loc. cit., p.32) demonstrated most convincingly that a correlation exists between the grade of the Witwatersrand reefs and the silver content of the ore. Where the grade recovered is high, the silver content is low; this he attributed to a high content of relatively pure free gold in the high-grade samples. Earlier work by Lawn (1924) suggested the same correlation between fineness and tenor, although Cousins (1956, p.109) has denied that this is the case. Data given by Richardson (1940, p.40) suggest that the same relationship might prevail in the case of the Black Reef deposits, for the percentage of silver in the assay beads varies from 15.9 per cent in low-grade samples to 11.6 per cent in rich samples.

An increase in the fineness of gold in high-grade ore has been shown on previous pages to be characteristic of some hydrothermal deposits, and it is probable that further work will show that it is a common feature. The relationship can logically be explained in the case of hydrothermal deposits, but it would seem that the modified placer hypothesis, as interpreted by Ramdohr, does not fully explain the cause of this relationship in the case of the Witwatersrand and Black Reef sediments. Ramdohr (1958, pp. 34, 46) consider~~s~~ed that the solution and redeposition of the gold did not involve transport over distances greater than fractions of an inch. If this is so, it becomes necessary to explain why the original placer gold should have been of exceptional purity in those sections where it was deposited in particular abundance.

(iv) Black Reef Gold compared with Witwatersrand Gold

From what data are available, the silver content of Black Reef ore appears to be greater than that in the older Witwatersrand ores. Frankel (1939, p.116) stated that free gold, separated from concentrates from the New Machavie mine in the Klerksdorp area, assayed 920 fine, but that 40 per cent of the gold is in the form of rounded and irregular grains and veinlets in the pyrite, which averages 30-35 dwt./ton. Assays of individual specimens showed that even in rich concentrates containing up to 80 ounces of gold to the ton, the value 1000 Au/(Au + Ag) falls as low as 790, and, in low-grade samples, this value approaches 500. Gilfillan (1939, p.127) stated that in Machavie mine ore the average for 12 months' sampling showed a ratio of Au:Ag of 7.55:1 (i.e., apparent fineness of 883); the average ratio in the corduroy concentrates was 8.90:1 (apparent fineness 898) and the mill bullion averaged 8.45:1 (894 fine). Richardson (1940) stated that the Black Reef at Government Gold Mining Areas "contains an appreciably higher percentage of silver than the Main Reef Leader." The average of samples of the Black Reef indicated a silver percentage of 13.2 to 13.9 per cent.

These figures indicate a greater silver content in the Black Reef than in the Witwatersrand ores. If the Black

Reef represents an ancient placer deposit formed by erosion of the Witwatersrand System, as advocated by Jeppe (1940, p. 265), Frankel (1940) and others, rather than a placer deposit on which hydrothermal mineralization has left its mark (Swiegers, 1938, 1939), the facts require explanation.

(v) Silver-rich Gold in Pyrite

The occurrence, as inclusions in pyrite, of gold which is richer in silver than typical Witwatersrand gold, has been commented on by different writers (Prentice, 1940; Liebenberg, 1955, p.160; Ramdohr, 1958, pp. 35, 46). The same feature is exhibited by the Black Reef ores (Frankel, 1939, 1940; Liebenberg, 1955, p.166).

While Ramdohr has used the occurrence of this pale gold in pyrite as contributory evidence in support of the detrital origin of pyrite in the reefs, it should be noted that silver-rich gold may occur in pyrite, and silver-poor gold as discrete grains, in ores whose hydrothermal origin is beyond question.

In conclusion, it may be said that in spite of the wide support which the modified placer hypothesis enjoys, there are certain aspects concerning the composition of the gold which are not yet fully explained. This conclusion need not be interpreted to imply the writer's personal rejection of the placer hypothesis, but rather as a summary of certain weaknesses which call for further attention. This task can best be accomplished by those better acquainted than the writer with the Witwatersrand ores.

APPENDIX I

Notes on the Preparation of Polished Surfaces

The most important aspect of the work leading to this paper was the microscopic study of polished surfaces of ore specimens. As gold is generally present, in all but the richest specimens, in only very minor amounts and then usually as minute grains, it was imperative that the polished surfaces should be good enough to permit the study of gold grains as small as 1-2 microns in diameter. Since most interest centred around the occurrence in the ore of gold, which is a relatively soft mineral, generally occurring embedded in hard minerals such as quartz, pyrite or arsenopyrite, the technique had to be such that a fine degree of polish could be achieved on hard and soft minerals alike without the nature of the contacts between them becoming obscured by excessive relief.

When the work was first started, the surfaces were prepared by grinding first on steel plates with graded carborundum abrasives and finishing on a lap, driven at 1400 revolutions per minute, covered with cloth smeared with 30-minute emery. Final burnishing was effected with jewellers' rouge. Results, using this method, were never entirely satisfactory due to excessive relief between hard and soft minerals and imperfect polish of hard minerals such as pyrite. The discolouration produced by the jewellers' rouge was also found to be objectionable.

With the acquisition of a Cooke, Troughton and Simms Ore Polishing Machine, a great improvement in the quality of the polished surfaces was effected. After experimenting with a number of different methods, the procedure which is described below was adopted.

The ore specimen is cut with a diamond saw so that the surface to be polished is a little less than an inch square. The edges of the specimen are then bevelled at an angle of 45 degrees to a depth of about one-eighth of an inch. All sharp edges on the back and sides of the specimen should also be ground smooth so that there is no possibility of material breaking away from the specimen and falling on to the laps in the later stages. The surface is then ground for as long as necessary (usually 3-4 minutes) on a cast-iron lap rotating at about 300 r.p.m., using a stiff paste of 3F carborundum and a little water. At no stage should the paste be mixed with an excess of water, or excessive relief between hard and soft minerals will be produced at the start. The principles of cutting to a level surface with such an 'abrasive film' have been described by Fuller (1941) and the adoption of this technique cannot be too strongly recommended. When the ground face has taken on a smooth, matt surface, it is thoroughly scrubbed and washed.

The specimen is now ground by hand on a glass plate for 10-15 minutes with levigated alumina mixed, again, with a minimum amount of water. Grinding is continued until all pits and scratches from the previous stages have been removed and the contacts between sulphides and quartz are sharply defined under the microscope. This stage is perhaps more important than any other and the quality of the final surface depends largely on the thoroughness with which this operation is carried out. It has been found that polishing can be started at this stage by holding the glass plate under a running tap for about one second - this washes off the coarser abrasive and leaves only a very fine-grained milky residue - and polishing for a further 5 minutes. The hard minerals like pyrite will take on a partial polish at this stage.

Cutting and polishing is now continued on lead laps rotating at 300 r.p.m. using, firstly, 8-micron diamond paste and sewing-machine oil as a lubricant, and then 3-micron diamond paste. The specimen can be cleaned with small cloth strips soaked in carbon tetrachloride. This stage imparts an almost perfect polish to the hard minerals pyrite and quartz. If the lap is kept in operation for 10-15 minutes without further dressing with fresh abrasive, the diamond particles ultimately become so deeply embedded in the lead and the cutting action so slow that hard and soft minerals alike acquire a brilliant polish, and little further treatment is required. Normally, however, the specimen is given a further burnishing on high-speed laps covered with finest quality poplin, lightly smeared with 2-micron and ½-micron diamond pastes. The duration of polishing in each of the latter stages should be 15-90 seconds. If very soft minerals are also present, a final polishing with magnesium oxide and water is desirable.

In practice, a good surface requires 3-4 hours for preparation by this method. It is possible to prepare a polished surface in about 30 minutes by omitting the lead lapping and polishing only with 8-micron, 2-micron and ½-micron diamond pastes on cloth. However, it is impossible to avoid the development of objectionable relief between minerals such as galena and pyrite by this method.

For the preparation of polished surfaces of mineral concentrates, small cylinders were first prepared by moulding the concentrates, in some suitable cement, in short lengths of ½-inch bore glass tubing. One end of the cylinder is then polished, first on a solid nylon lap smeared with ½-micron diamond abrasive paste, and then on cloth laps. Various cements were tried, such as dental cements, magnesium oxychloride, catalyzed phenol formaldehyde resins, canada balsam and Lakeside 70 resin. None was found to be wholly satisfactory, although the last-named gave the best results.

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