The significance of the mineralogical and surface characteristics of gold grains in the recovery process

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SYNOPSIS

A description is given of the nature and occurrence of gold at various stages in the process of its recovery from Witwatersrand and related ores. Electron microprobe investigations show that the surface of gold grains in the ore is already coated. During metallurgical processing, further coatings, mainly hydrated iron oxides, accumulate on the grains. Theories are advanced for the formation of these coatings, and the adverse effects on metallurgical operations are discussed.

SINOPSIS

'n Beskrywing word gegee van die aard en voorkoms van goud op verskeie stadiums in die prosesse van herwinning van Witwatersrand en verwante ertse. Elektronemikrobuis ondersoeke het aan die lig gebring dat die oppervlaktes van goud greintjies in die erts alreeds aangepak is. Gedurende metallurgiese bewerking versamel meer aanpaksels, veral gehidreerde ysterhidroksiede, op die greintjies. Teorieë vir die ontwikkeling van hierdie aanpaksels word voorgelê en die ongunstige invloede op metallurgiese prosesse word bespreek.

INTRODUCTION

Several suites of plant products and numerous individual samples were received from Anglo American Corporation gold mines, notably Western Deep Levels, the Vaal Reefs mines, Western Holdings, and Freddies. These samples were examined in an attempt to find out more about the degree of liberation of the gold, its mode of occurrence and associations, size distribution, and other features that could influence the efficiency of gold recovery.

A number of reef samples were also studied in detail to obtain information on the characteristics of the original gold particles before their exposure to plant conditions.

Heavy concentrates were prepared from the various plant products, and these, together with the light fractions, were examined by ore microscopy and other mineralogical techniques supplemented where necessary by electron-microprobe analysis of selected grains. The relative abundance of the various kinds of gold-bearing grains present in the samples was expressed in terms of mass percentages, the masses being calculated from the sizes of the gold particles. It must be stressed that, owing to the comparatively small number of gold grains exposed in most of the polished sections, the results are approximate and give only a rough indication of the relative amounts.

Gold particles that, although attached to or partially occluded by gangue constituents, are sufficiently exposed to permit ready dissolution (or amalgamation) are, for the present purpose, classified as "free gold" — see, for example, photomicrograph 1, Plate I.

RESIDUES

In an investigation of this nature the most logical place to start is at the tail-end of the plant — the residue dumps. A knowledge of the appearance and mode of occurrence of the gold still present in residues could well provide important clues to why this gold had not been recovered in the plant.

We have studied residue samples from several localities and have found that certain features are common to all.

One of the main gold carriers in all residue samples (in calcine leach residues, frequently the only gold carrier) is thucholite, that enigmatic hydrocarbon loaded with occlusions of uraninite and, usually, gold. Total precious metals assays on the thucholite concentrates we have prepared gave values ranging from a few hundred to several thousand grams per tonne.

Thucholite is not concentrated in the plant, nor is much of its load of occluded gold released on calcining during sulphuric acid manufacture, as practised in the Group. In thucholite, the property of lightness is combined with extreme refractoriness, and it is not surprising that this constituent is such a common cause of losses in gold-plant residues.

The problem of recovering and treating thucholite is still being examined, and in this paper only casual reference will be made to this important material.

Apart from thucholite, sulphide grains occurring in residue samples were seen to occlude small specks or veinlets of gold. More rarely, gold occlusions were noted in quartz, in poorly preserved uraninite, skutterudite, leucoxene, limonitic material, and a variety of other gangue constituents.

An occasional grain of free gold was seen in most of the residue samples, and, in spite of its scarcity, this form of gold usually accounts for almost the entire gold content of the sample (excluding gold associated with thucholite), as reference to Table I will show. These grains range in size from less than 0,075 mm to over 0,075 mm, and the majority have the following features in common:

(i) The grains are enveloped in a distinct coating of hydrated iron oxide.

(ii) The grains are frequently flattened or otherwise distorted, and extraneous mineral matter may have been pressed into the grains.

It is understandable that small specks of gold occluded in gangue

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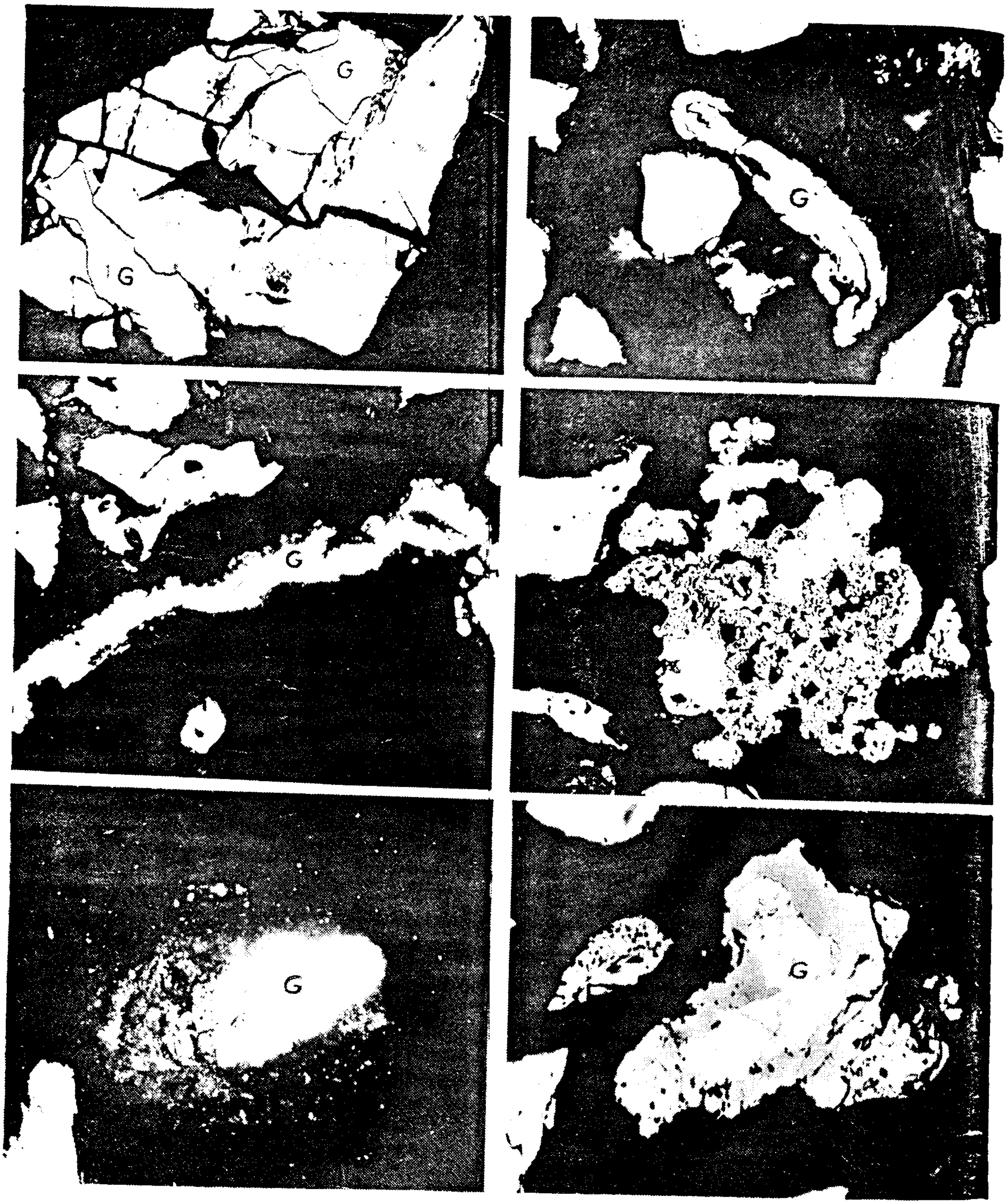

Description of Photomicrographs

PLATE I

Photomicrographs

1	2
3	4
5	6

Photomicrograph 1

Fractured aggregate of pyrite (grey) and gold (white). In spite of the gold being attached to pyrite and partly occluded by it, it is sufficiently exposed for ready dissolution. Freddies: Minus 3/4″ Dry crusher product. X 620.

Photomicrograph 2

Distorted gold grain (G). Western Holdings: Feed to Cleaner Tables Nos. 1 and 2 banks. X 600.

Photomicrograph 3

Flattened gold grain (G). The flake is intersected at right angles by the surface of the polished section. Freddies: Secondary cyclone underflow. X 620.

Photomicrograph 4

Partially amalgamated gold. The porous zone of the grain is pale in appearance, the colour gradually deepening to normal golden yellow towards the solid, unamalgamated portions. Western Holdings: Johnson Concentrator Tails No. 3 Bank. X 600.

Photomicrograph 5

Gold grain enveloped in transparent amorphous material. Western Holdings: Mine Sludge. X 600.

Photomicrograph 6

Gold (white) encrusted by hydrated iron oxide (grey). Sallies Dump. X 6[illegible]

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...d in transparent ... Western Hold... 600.

...sted by hydrated ...lies Dump. X 600.

...stituents may find their way into ...e residue, but the loss of the free ...ns is probably related to the ...y tarnish on the grains and to ...e effects of excessive milling, which ...nges the properties of the gold ...ns. In some of the residue ...mples, gelatinous materials remini...nt of settling agents were seen. ...s material may envelop mineral ...ns and could conceivably have ...vented the dissolution of some ...the gold grains.

The question that now arises is, ...en and how did the grains of free ...d acquire the properties that ...evented their recovery in the ...nt? Later in this paper the mech...sm of coating the grains and the plant conditions that contribute to the formation of a coating will be examined in some detail.

Also, the fact that occluded gold (again excluding gold associated with thucholite) constitutes such a very subordinate proportion of the gold in most of the residues examined indicates that gold has been liberated adequately in the plant — as a matter of fact, the flattened appearance of so many of the grains suggests gross over-milling.

As a next step we shall examine the occurrence of gold in the various plant products; but, before doing so, let us consider the gold occurring in the mine sludge, before it even reaches the plant.

MINE SLUDGE

The appearance of the sludge differs from mine to mine, and depends largely on the particular procedure adopted to separate the sludge from the mined ore. In the mine sludge from Western Holdings, for example, the gold grains are considerably coarser grained than those in the Western Deep Levels sludges. (See Tables III and IV.) However, there are certain significant features in common with all the sludge samples examined. These are:

(i) Auriferous thucholite is abundant.

(ii) Almost all of the remainder of the gold is liberated, the common practice of drilling and blasting

TABLE I
FREDDIES CONSOLIDATED MINES LIMITED
SUMMARY OF MINERALOGICAL DATA

Designation of sample	Size analysis µm	Wt. %	Precious metals assay Gold	Silver	Gold occurrence (Mass %) µm	Free	Locked*
...y crusher product ...nus ¾" from Symons ...reen	+600	94	7,9	1,7	+150	—	10
	+150	3	Insufficient		+ 75	78	
	—150	3	Insufficient		— 75	12	
...usher rake ...assifier ...derflow	+600	82	12,7	1,6	+150	—	8
	+150	16	12,0	1,7	+ 75	76	
	—150	2	Insufficient		— 75	16	
...usher rake ...assifier ...verflow	+600	<1	5,8	1,3	+150	—	2
	+150	6			+ 75	83	
	—150	94			— 75	15	
...ll mill feed	+600	85	3,8	0,7	+150	—	<1
	+150	12	19,7	2,2	+ 75	95	
	—150	3	40,3	4,9	— 75	5	
...ll mill ...yclone ...nderflow	+600	64	141,6	13,0	+150	53	<1
	+150	19			+ 75	45	
	—150	17			— 75	2	
...ll mill ...yclone ...verflow	+600	21	14,7	2,0	+150	—	1
	+150	27			+ 75	79	
	—150	52			— 75	20	
...ube mill ...scharge	+600	7	161,9	13,5	+150	53	<1
	+150	33			+ 75	46	
	—150	60			— 75	1	
...econdary cyclone ...nderflow	+600	14	190,1	14,8	+150	47	<1
	+150	39			+ 75	48	
	—150	47			— 75	5	
...econdary cyclone ...verflow	+600	1	18,1	2,4	+150	62	1
	+150	5			+ 75	31	
	—150	94			— 75	6	
...ombined residue ...ashed	+600	<1	0,5	0,6	+150	—	8
	+150	3			+ 75	—	
	—150	97			— 75	92	
...reddies washed ...esidue (incompletely ...ssolved)	+600	<1	0,4	0,4	+150	insufficient	
	+150	4			+ 75		
	—150	96			— 75		

*Excluding gold locked in thucholite

TABLE II

VAAL REEFS WEST GOLD MINE
SUMMARY OF MINERALOGICAL DATA

Designation of sample	Size analysis µm	Size analysis Wt. %	Precious metals assay Gold	Precious metals assay Silver	Gold occurrence (Mass %) µm	Gold occurrence (Mass %) Free	Locked*
Washing plant Overflow	+150 —150	8 92	22,0 24,4	1,6 1,7	+150 + 75 — 75	— — 99	1
Washing plant Underflow Rake return	+150 —150	91 9	31,8 131,8	0,8 6,5	+150 + 75 — 75	 78 21	1
Waste washing plant Waste sludge			18,3		+150 —150	89 11	<1
Waste washing plant Reef sludge and stock pile fines	+1 mm +300 +150 —150		1,1 1,9 5,3 6,9		+150—300 —150	88 12	<1
Low grade Primary mill discharge	+150 —150	61 39	9,2 18,3	0,8 1,5	+150 + 75 — 75	— — 95	5
Low grade Primary cyclone Overflow	+150 —150	55 45	9,9 17,0	0,8 1,2	+150 + 75 — 75	— 61 38	1
Low grade Primary cyclone Underflow	+150 —150	84 16	12,4 57,6	1,0 3,6	+150 + 75 — 75	— 69 30	1
Low grade Secondary tube Mill discharge	+150 —150	56 44	23,0 171,7	2,7 9,3	+150 + 75 — 75	17 68 15	<1
Low grade Secondary cyclone Overflow	+150 —150	18 82	3,7 8,8	0,2 0,8	+150 + 75 — 75	— 80 20	<1
Low grade Secondary cyclone Underflow	+150 —150	81 19	20,5 289,0	1,9 13,3	+150 + 75 — 75	— 78 18	4
Low grade Pulp head or Slimes original					+150 + 75 — 75	— 71 28	<1
Low grade Unwashed Residue					+150 + 75 — 75	— 74 22	4
High grade Primary mill Discharge	+150 —150	66 34	13,7 22,3	1,1 1,8	+150 + 75 — 75	— 89 11	<1
High grade Primary cyclone Overflow	+150 —150	57 43	7,6 15,4	0,7 1,2	+150 + 75 — 75	— 81 18	1
High grade Primary cyclone Underflow	+150 —150	81 19	14,5 55,2	1,0 3,2	+150 + 75 — 75	— 39 60	1
High grade Secondary tube Mill discharge	+150 —150	68 32	14,9 164,2	1,2 8,3	+150 + 75 — 75	— 65 35	<1
High grade Secondary cyclone Overflow	+150 —150	15 85	3,1 11,8	0,1 0,8	+150 + 75 + 75	— — 97	3
High grade Secondary cyclone Underflow	+150 —150	75 25	8,4 97,2	0,8 5,8	+150 + 75 — 75	— 80 20	<1
High grade Pulp head or Slimes original					+150 + 75 — 75	— 65 33	2
High grade Unwashed residue					+150 + 75 — 75	— 33 62	5
Flotation plant tails					+150 + 75 — 75	— 83 17	<1

*Excluding gold locked in thucholite

TABLE III
WESTERN DEEP LEVELS GOLD MINE
SUMMARY OF MINERALOGICAL DATA

Designation of sample	Size analysis µm	Size analysis Wt. %	Precious metals assay Gold	Precious metals assay Silver	Gold occurrence (Mass %) µm	Free	Locked*
ge from 3 shaft	Not determined				+150 + 75 + 75	— 89 11	1
ge from 2 shaft	Not determined				+150 + 75 — 75	— 69 30	1
w grade ry screening nus 3"	+2,4 mm +1 mm +400 +200 +150 —150	56 18 11 7 3 5	2 13 10 10 12 19	21 2 1 1 2 2	+200—400 +150 —150	75 19 6	>1
w grade l mill ed	+2,4 mm +1 mm +400 +200 +150 —150	70 12 7 6 3 2	7 14 13 15 26 62	— 1 2 2 4 8	+200—400 +150 —150	77 20 3	>1
ow grade kins classifier verflow	+150 —150	54 46	11	1	+150 + 75 — 75	66 18 15	>1
ow grade be mill scharge	+150 —150	30 70	41	6	+150 + 75 — 75	44 48 8	>1
ow grade econdary yclone feed	+150 —150	49 51	80	9	+150 + 75 — 75	83 15 2	>1
ow grade econdary cyclone verflow	+150 —150	3 97	10	2	+150 + 75 — 75	65 28 7	>1
ow grade econdary cyclone nderflow	+150 —150	54 46	56	7	+150 + 75 — 75	51 40 9	>1
ow grade ertiary cyclone verflow	+150 —150	30 70	45	6	+150 + 75 — 75	53 43 4	>1
ow grade ertiary cyclone Underflow	+150 —150	43 57	80	10	+150 + 75 — 75	62 33 5	>1
ow grade ohnson tails	+150 —150	17 83	100	13	+150 + 75 — 75	23 64 13	<1
igh grade ube mill ischarge	+150 —150	8 92	119	15	+150 + 75 — 75	77 17 6	<1
igh grade econdary cyclone eed	+150 —150	32 68	60	7	+150 + 75 — 75	66 28 6	<1
gh grade econdary cyclone verflow	+150 —150	— 100	27	4	+150 + 75 — 75	55 28 17	<1
gh grade econdary cyclone nderflow	+150 —150	33 77	143	18	+150 + 75 — 75	32 50 17	<1
igh grade ertiary cyclone verflow	+150 —150	4 96	58	8	+150 + 75 — 75	38 35 27	<1
igh grade ertiary cyclone nderflow	+150 —150	31 69	240	34	+150 + 75 — 75	43 40 16	1
igh grade ohnson Tails	+150 —150	29 71	334	42	+150 + 75 — 75	57 31 12	<1

TABLE III (Continued)

Designation of sample	Size analysis µm	Size analysis Wt. %	Precious metals assay Gold	Precious metals assay Silver	Gold occurrence (Mass %) µm	Gold occurrence (Mass %) Free	Locked*
Belt concentrator Feed	+150 —150	41 59	2 324	269	+150 + 75 — 75	52 38 10	1
Belt concentrates	+150 —150	25 75	75**	9**	+150 + 75 — 75	53 35 12	<1
Belt tails	+150 —150	31 69	1 293	216	+150 + 75 — 75	53 35 12	<1

*Excluding gold locked in thucholite
**Kg/tonne

TABLE IV
WESTERN HOLDINGS
SUMMARY OF MINERALOGICAL DATA

Designation of sample	Size analysis µm	Size analysis Wt. %	Precious metals assay Gold	Precious metals assay Silver	Gold occurrence (Mass %) µm	Gold occurrence (Mass %) Free	Locked*
Mine sludge	Not determined				+200 +150 + 75 — 75	41 27 31 1	<1
No's 1 and 2 Shaft sludge	+300 +150 + 75 — 75	1 23 53 23	18,0		+150 + 75 — 75	Inadequate Sample	
No. 3 shaft sludge	+300 +150 + 75 — 75	1 34 41 24	9,0		+150 + 75 — 75	Inadequate Sample	
Composite rake Classifier overflow	+300 +150 + 75 — 75	4 25 34 37	41,8		+150 + 75 — 75	64 25 10	1
Composite rake Classifier return	+6 mm +3 mm +300 +150 + 75 — 75	4 40 44 9 2 1	41,2		+150—300 + 75 — 75	80 15 2	3
Composite washing Plant cyclone Underflow	+300 +150 + 75 — 75	35 42 16 7	63,0		+150 + 75 — 75	67 23 7	3
Composite dewatering Cyclone underflow	+300 +150 + 75 — 75	18 37 31 14	350,3		+150 + 75 — 75	48 43 7	2
Composite ball Mill feed	+13 mm +6 mm +3 mm +300 +150 + 75 — 75	3 18 29 40	21,3		+150—300 + 75 — 75	68 28 2	2
Composite ball mill Cyclone overflow	+300 +150 + 75 — 75	28 24 18 30	17,7		+150 + 75 — 75	66 24 2	8
Composite secondary Tube outlet	+300 +150 + 75 — 75	2 21 45 32	50,2		+150 + 75 — 75	— — 99	1
Composite secondary Cyclone underflow	+300 +150 + 75 — 75	19 34 38 9	52,1		+150 + 75 — 75	46 45 9	<1

Designation of samp

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..mposite cleaner ..ble tailings No. 3 ..nk

*Excluding gold locked in thu..

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to the ready libera..
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a few it may even b..
as heavy. Photomi..
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oxide, probably dep..
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) Particles of rusty tra..
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TABLE IV (Continued)

Designation of sample	Size analysis µm	Size analysis Wt. %	Precious metals assay Gold	Precious metals assay Silver	Gold occurrence (Mass %) µm	Gold occurrence (Mass %) Free	Locked*
…posite kreb …ary cyclone …erflow	+300 +150 + 75 — 75	17 32 35 16	426,4		+150 + 75 — 75	47 39 13	1
…posite tertiary …e outlet	+300 +150 + 75 — 75	3 24 39 34	349,8		+150 + 75 — 75	70 22 7	1
…posite tertiary …one overflow	+300 +150 + 75 — 75	2 21 45 32	40,6		+150 + 75 — 75	41 47 7	5
…posite Johnson …centrator tails No. 1 and 2 …s	+300 +150 + 75 — 75	10 35 36 19	212,5		+150 + 75 — 75	76 22 2	< 1
…posite Johnson …centrator tails No. 3 …k	+300 +150 + 75 — 75	8 34 33 25	179,5		+150 + 75 — 75	24 67 9	< 1
…mposite feed to …aner tables Nos. …d 2 banks	+300 +150 + 75 — 75	6 26 45 23	2 559,2		+150 + 75 — 75	58 26 5	11
…mposite feed to No. 3 cleaner bank	+300 +150 + 75 — 75	7 25 46 22	2 862,8		+150 + 75 — 75	77 20 3	< 1
…mposite cleaner …ble tailings Nos. …nd 2 banks	+300 +150 + 75 — 75	6 24 49 21	1 244,9		+150 + 75 — 75	92 6 2	< 1
…mposite cleaner …ble tailings No. 3 …k	+300 +150 + 75 — 75	7 27 39 27	179,5		+150 + 75 — 75	58 40 2	< 1

*Excluding gold locked in thucholite

in the reef probably contributing to the ready liberation of the metal (see Tables III and IV). Most of the gold particles already show a thin iron oxide coating, and on some of the grains this coating is distinct. On a few it may even be described as heavy. Photomicrograph 4, Plate II depicts a grain of gold surrounded by hydrated iron oxide, probably deposited from a suspension of colloidal materials.

ii) Particles of rusty tramp iron are common, and most probably constitute the main source of the secondary iron compounds coating the gold. However, the bulk of the secondary hydrated iron oxide in the sludge occurs as fragments of massive, colloform or banded deposits that do not occlude other mineral particles, and have evidently been precipitated from a comparatively clear, colloidal suspension. In view of evidence of copious supplies of secondary, hydrated iron oxide, it appears anomalous that mineral aggregates cemented together by iron oxide are so rare in mine sludge. In the plant, such aggregates can be seen to form very readily, frequently encrusting the walls of, for example, sumps and launders, and one would expect similar deposits underground in gullies, depressions, and channels. These ferruginous agregates are frequently very rich in gold, and the possibility of some of the metal being permanently lost underground is at present being examined.

In the sludge samples examined, the presence of materials resembling gelatinous settling agents is very much in evidence. In photomicrograph 5, Plate I, for example, a grain of gold enveloped in hardened, resinous material is illustrated. Such material must undoubtedly play an inhibiting role in the cyanidation of the gold. Mine sludges have also been found to contain various unexpected constituents, usually of no more than passing interest. Almost all of the sludges examined to date contain, sometimes in fair amounts, pulverulent or scaly zincite (ZnO) probably derived from the decomposition of galvanized materials, such as ventilation pipes.

We shall now consider the behaviour of the gold during its passage through the reduction plant.

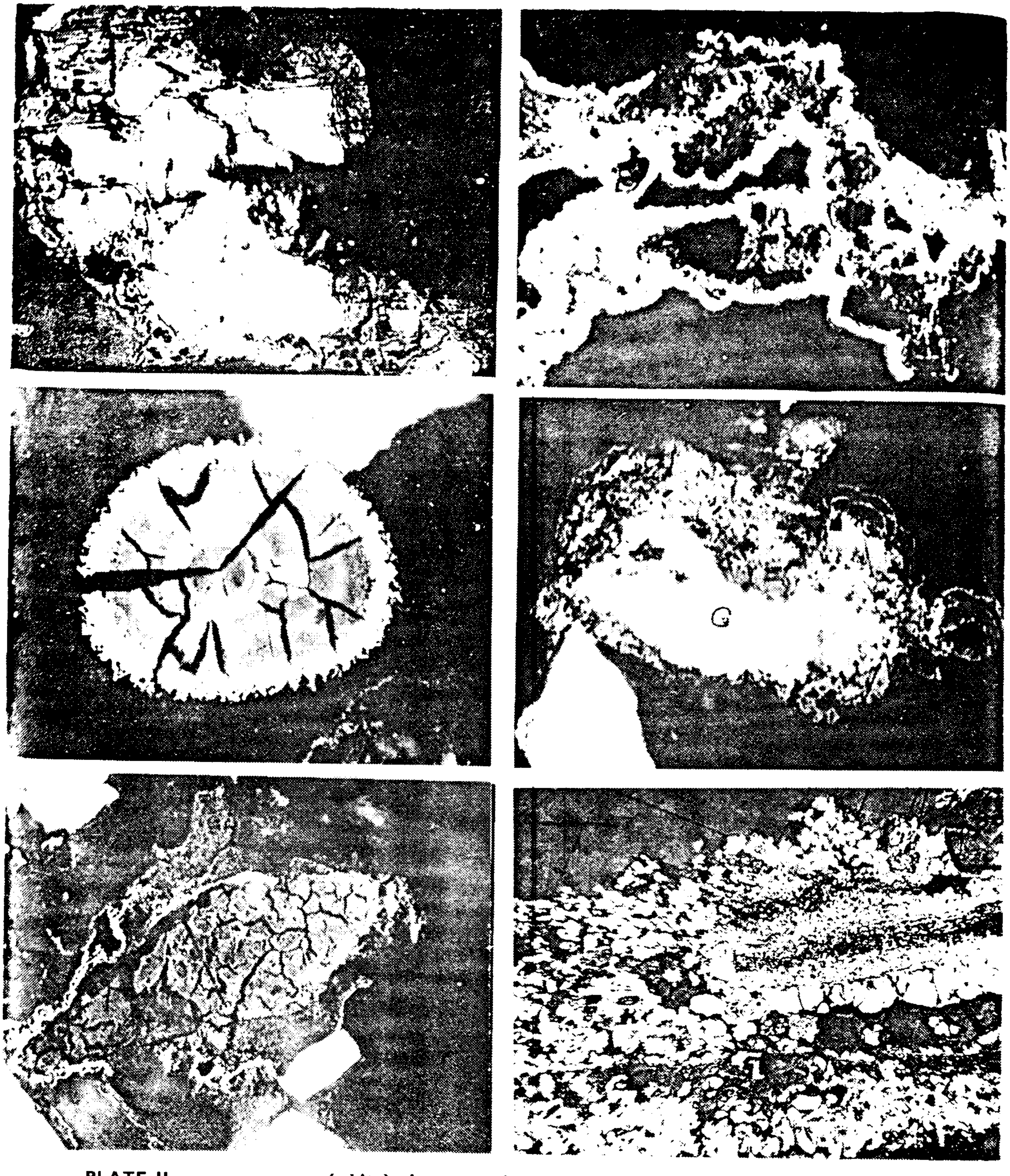


PLATE II

1	2
3	4
5	6

ᵒᵗomicrographs

ᵒᵗomicrograph 1

Pyrite (white) partially altered to ...ated iron oxide (dark grey). Sal... Screening Plant Minus 1/2″ Fract... X 600.

ᵒᵗomicrograph 2

Deposit of hydrated iron oxide (white) incorporating a variety of mineral fragments (black and grey). Sallies: Screening Plant Minus 1/2″ Fraction. X 600.

Photomicrograph 3

Newly formed limonitic nodule showing concentric build and typical shrinkage cracks. Sallies: Screening Plant Minus 1/2″ Fraction. X 600.

Photomicrograph 4

Gold (white) encrusted by colloform hydrated iron oxide. Western Holdings: Mine Sludge. X 600.

Photomicrograph 5

Completely rusted grain of tra... iron. Attached are grains of pyri... (white) and quartz (dark grey). We... ern Deep Levels: Belt feed. X 600.

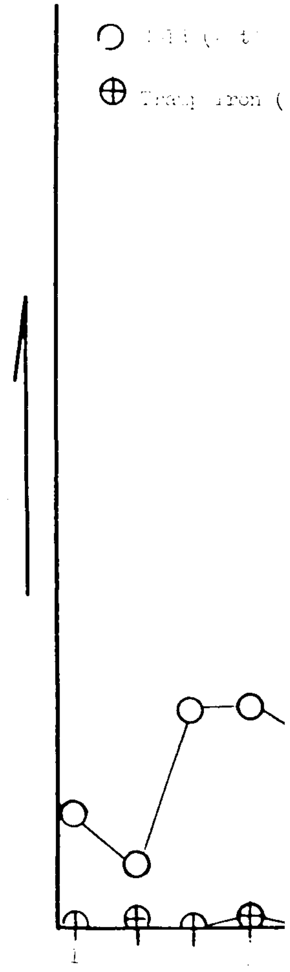
Photomicrograph 6

Auriferous scale. The mineral grai... (mainly pyrite, gold and quartz) a... cemented together by hydrated ir... oxide. The ratio of gold to pyrite (bo... appear white on the photomicrograp... is about 1:100. Western Deep Leve... X 35.

(Photomicrographs by M. Seda.)

GOLD RECOVERY P...

Reference to the tables ... the mineralogical da... ...at in most cases almost ... ...ld in the minus 600 μm f... ...e plant feed and the c... ...lling circuit materials ... ...erated. Furthermore, t... ...erated preferentially: alt... ...erated gold occurs in ... ...nstituting only, say, 10 ... ...ent of the feed, it repres... ... per cent of the total gol... ...ese gold grains display th...



Sympathetic relatic...

DESCRIPTION OF SA...

...mple No.	Designation
1.	Nos. 1 and 2 shaft slud...
2.	No. 3 shaft sludge
3.	Rake classifier O flow
4.	Rake classifier return
5.	Washing plant cyclone
6.	Washing plant U flow

raph 5

' rusted grain of tram ed are grains of pyr quartz (dark grey). Wes els: Belt feed. X 600.

raph 6

scale. The mineral grain e, gold and quartz) are gether by hydrated iron tio of gold to pyrite (both on the photomicrograph 0. Western Deep Levels

hs by M. Seda.)

GOLD RECOVERY PLANT

Reference to the tables summariz- g the mineralogical data reveals at in most cases almost all of the ld in the minus 600 μm fractions of e plant feed and the other pre- lling circuit materials is already erated. Furthermore, the gold is erated preferentially: although the erated gold occurs in a fraction nstituting only, say, 10 to 20 per nt of the feed, it represents some per cent of the total gold content. ese gold grains display their natural shapes, and very few show signs of mechanical distortion. All of the grains are tarnished.

After ball-milling, 90 per cent and more of the gold is usually liberated as free, tarnished grains frequently showing evidence of flattening and distortion. (See photomicrographs 2 and 3, Plate I.) Even if part of the tarnish of an occasional gold particle is momentarily scraped off, it is immediately replaced. Secondly, during ball-milling, copious quantities of finely divided tramp iron are produced — sometimes as much as one kg per ton of ore milled, i.e. an amount 50 times higher than the amount of gold in the ore. From here onwards, the tramp iron plays its deleterious role in the circuit.

Examination of polished sections reveals that much of the tramp iron is heavily oxidized, the grains becoming surrounded by a thick crust of hydrated oxide. Tramp iron that has been circulating in the plant for some time may be completely rusted away, or only a small remnant of the

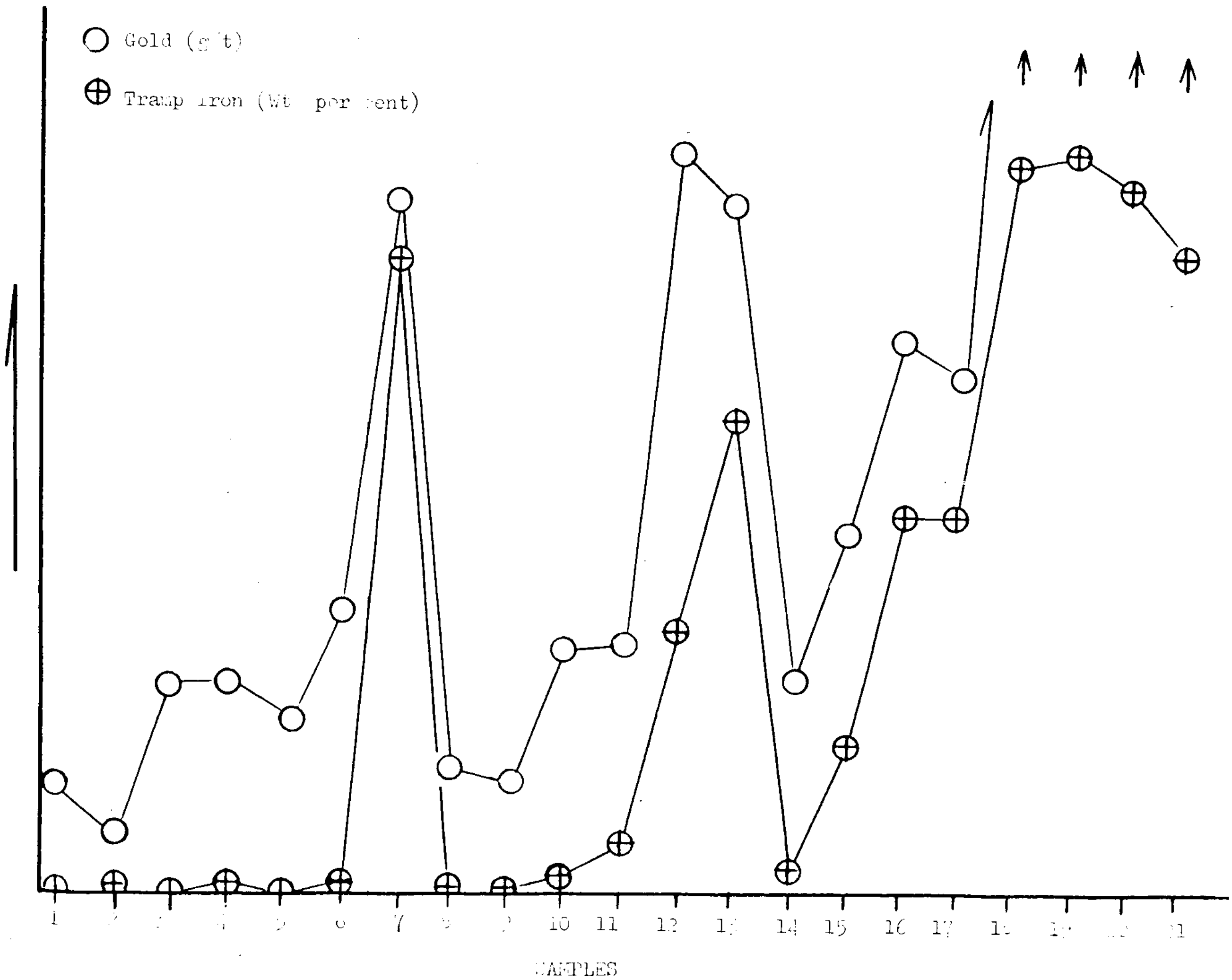


FIGURE 1

Sympathetic relationship between the abundance of gold and tramp iron in a suite of samples from Western Holdings Gold Mine.

DESCRIPTION OF SAMPLES

Sample No.	*Designation*
1.	Nos. 1 and 2 shaft sludge
2.	No. 3 shaft sludge
3.	Rake classifier O/flow
4.	Rake classifier return
5.	Washing plant cyclone O/flow
6.	Washing plant U/flow
7.	Dewatering cyclone U/flow
8.	Ball mill feed
9.	Ball mill cyclone O/flow
10.	Secondary tube outlet
11.	Secondary cyclone U/flow
12.	Kreb tertiary cyclone U/flow
13.	Tertiary tube outlet
14.	Tertiary cyclone O/flow
15.	Spargo tertiary cyclone U/flow
16.	Johnson concentrator tails, nos. 1 and 2 banks
17.	Johnson concentrator tails, no. 3 bank
18.	Feed to cleaner tables, nos. 1 and 2 banks
19.	Feed to cleaner table, no. 3 bank
20.	Cleaner table tailings, nos. 1 and 2 banks
21.	Cleaner table tailings, no. 3 bank

original metallic iron may remain in the core of the pseudomorph of alteration products. (See photomicrograph 5, Plate II.)

Unfortunately, the particles of free gold and tramp iron have by now acquired very similar properties: both are covered by hydrated iron oxide, and both are of high specific gravity. It is not surprising, therefore, that the free gold and tramp iron show a similar concentration behaviour during passage through the plant. This relationship is illustrated in Fig. 1, which reveals that, by and large, the relative abundance of gold and tramp iron fluctuates sympathetically from sample to sample.

One unfortunate aspect of the similar concentration behaviour of the gold and tramp iron is the very real possibility that a proportion of the gold may literally be "crowded out" of a concentration circuit by the superabundant tramp iron. A second result of the tendency of these two constituents to concentrate together is that the iron, which is in a state of rapid oxidation, is strategically placed to contribute to the coating of the gold particles, and to cause the formation of firmly cemented aggregates of gold and other heavy-mineral constituents. The common nature of the coatings on gold and tramp iron most probably assists substantially in joining the particles together.

Examples of mineral aggregates cemented by hydrated iron oxide are common. Possibly the most significant is the scale deposited on the concrete walls of sumps and launders, and on the walls of cyclones and, presumably, other equipment. In photomicrograph 6, Plate II, a cross section of gold-bearing scale from a sump at Western Deep Levels is shown. Strangely, gold seems to be preferentially attracted to such scales, which may assay several kg per tonne of total precious metals.

It is also interesting that the aggregates cemented with hydrated iron oxide must be capable of forming very rapidly, as evidenced by the build-up of a thick deposit of gold-rich scale on the walls of the cyclone used to fill the amalgam barrel at Western Deep Levels. The gold and other mineral grains show a distinct preferred orientation, and are arranged in cyclic layers, thus indicating formation of the scale during operation of the cyclone.

At this juncture, mention should also be made of the deleterious effects of stockpiling ore for any length of time. As one could imagine, the coating on the gold grains soon becomes so pronounced that prior treatment is needed before efficient gold recovery is possible. Bleeding the untreated material into the recovery circuit invariably leads to noticeable increases in the residue values.

The same problem, only in an intensified form, applies to the recovery of gold from old dumps. In such dumps, the sulphides are in a process of decomposition (see photomicrograph 1, Plate II), thus providing copious additional quantities of secondary iron colloids, firmly cementing aggregates of mineral fragments (including gold), and heavily encrusting free gold (see photomicrographs 4 and 6, Plate II). Photomicrographs 2 and 3, Plate II illustrate the deposits of nodular, hydrated iron oxide formed typically in this environment.

In the gold recovery plant, the overflow and underflow figures relating to the various cyclones (see Tables I to IV) reveal the interesting fact that the grain size of the gold in the overflow fraction is consistently very similar to that in the underflow, and, which is more important, reveal that in both fractions the proportion of locked gold is almost negligible. The comparatively coarse grain size of the gold in the overflow fraction is most probably due to the flattish shape of the grains. Thucholite also collects in the overflow, and is sent from here, via the cyanidation plant, to the residue dump. Recycling any of the cyclone products for remilling seems to serve no useful purpose, but could result in further deformation of the gold particles and their contamination by mineral matter pressed into them. These mutilated grains reporting in the tertiary cyclone underflow eventually collect in the concentrator tailings and are almost invariably returned for yet another dose of milling. The circulating load thus created can only result in the loss of gold particles that have lost all of their original properties. Very obviously, it would be beneficial rather to remove the gold from the circuit as soon as it is liberated.

It testifies to the efficiency of the current cyanidation and amalgamation processes that such a high proportion of the tarnished, overmilled gold grains is still being recovered. The tarnish is probably of a porous nature. In a successful attempt at increasing the recovery efficiencies, concentrates were treated with hydrochloric acid to reduce the effect of the iron oxide coating. This treatment has, for example, contributed to the remarkable amalgamation efficiencies (99,46 per cent) achieved by Western Deep Levels.

The gold in amalgam-barrel residues consists essentially of free tarnished or incompletely amalgamated grains (see photomicrograph 4, Plate I), and the current practice at some mines of recycling these to the milling circuit can only result in gold losses.

The locked gold in amalgam-barrel residues constitutes a minor proportion of the total gold. Most of this gold occurs as minute specks (less than 10 microns in size) and veinlets in uraninite. Gold occlusions also occur in sulphide, skutterudite, silicate minerals, hydrated iron oxides, titanium compounds, and a variety of other minerals. In all of these, the gold occlusions are so minute that no amount of additional milling will ensure their complete liberation. We shall now consider the mechanism of the development of hydrated iron oxide tarnish on the gold grains.

THE NATURE AND ORIGIN OF THE COATING ON GOLD

By means of the electron microprobe, sectioned Witwatersrand gold grains in unprocessed Carbon Leader, Basal and Vaal Reefs were found to contain a more or less constant few per cent of silver, together with traces of copper and nickel.

The samples of ore were crushed to fragments approximately one inch in diameter, thereby providing fresh exposures of gold grains for examination. The surface of fragments selected for examination were cleaned in an ultrasonic cleaner bath using acetone, alcohol, and methyl ethyl ketone successively. The spec-

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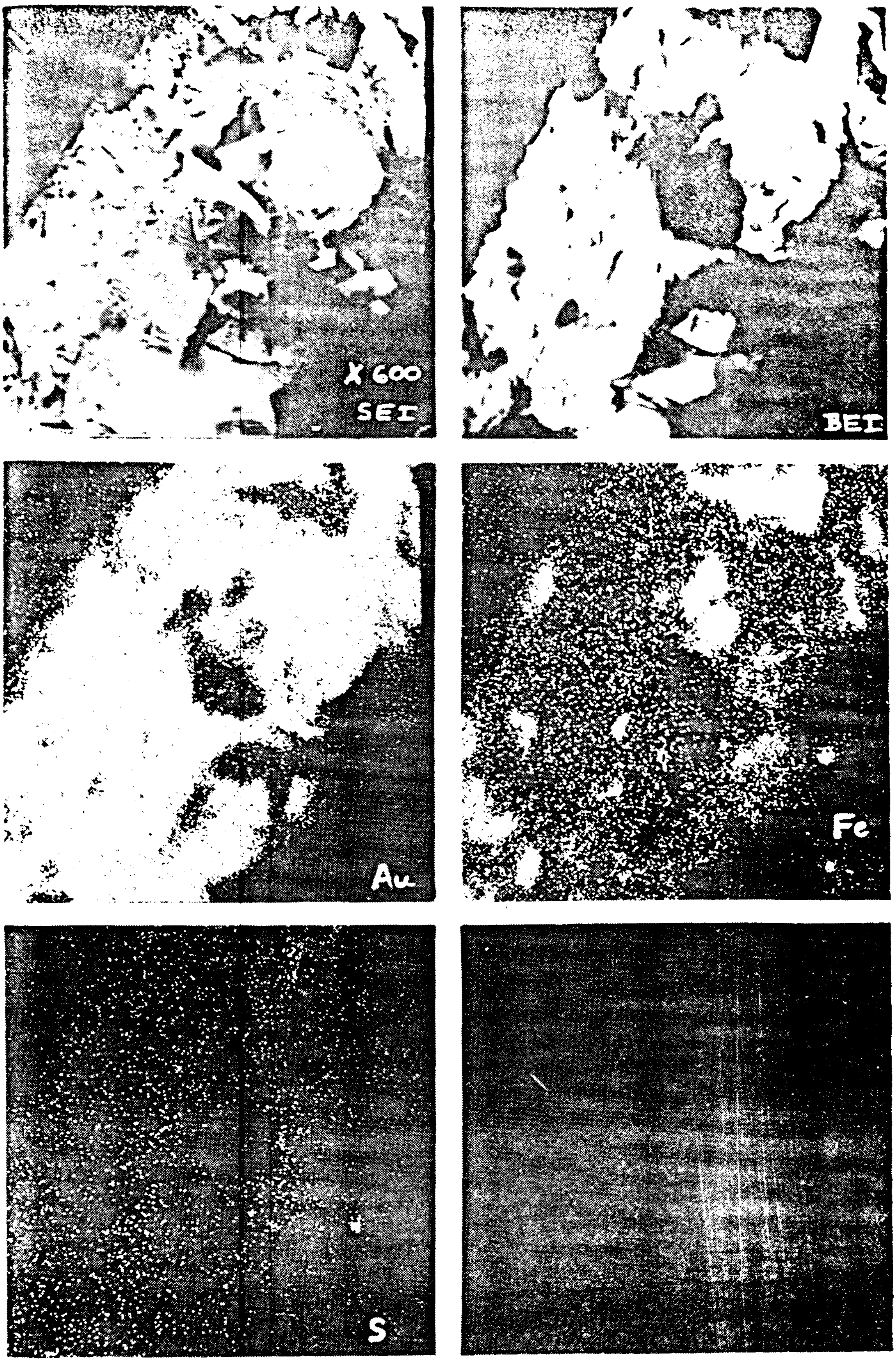

Electron Microprobe CRT Images

PLATE III

Figures

1	2
3	4
5	

Linear magnification: X 600
Scale: 10 microns = 6 mm.

Figure 1

Secondary electron image of a gold grain in Basal Reef, showing delicate surface textures giving rise to a large surface area. The grain is coated with a very thin layer of iron sulphide.

Figure 2

Compositional back-scattered electron image of the same are.a

Figure 3

Distribution of gold.

Figure 4

Distribution of iron, in the surface coating and in iron oxide crystals attached to the surface of the gold grain

Figure 5

Distribution of sulphur (in the surface coating).

mens were thereafter flash-coated with a conductive layer of pure carbon and examined in the electron microprobe.

Without exception, the outer surfaces of the gold grains examined were found to possess a thin layer of iron sulphide or iron oxide (Plate III) or both. Where the sulphide coating was thicker than average, the iron and sulphur were found to be present in constant proportions, probably as pyrrhotite or pyrite.

On some grains the alloy was seen to be coated so thickly with iron oxide as to be almost completely concealed from detection by the microprobe. It is likely that many grains were so thickly coated as to have escaped detection altogether.

Where gold-alloy grains were found in the proximity of zinc sulphide (sphalerite), the surface coating on the alloy grains was found to contain zinc in addition to sulphur and iron. Lead sulphide may coat the alloy grains when galena is abundant and in close proximity to the alloy grains.

Laboratory experiments were carried out with pure gold, pure silver, and gold/silver alloy concentrated from the Witwatersrand Reefs. The metals were treated with Fe^{2+}, S^{2-}, H^{+}, and SO_4^{2-} ions in dilute aqueous solution at 40°C.

After twelve hours the silver was heavily coated with a layer of silver sulphide containing minor concentrations of iron, the pure gold had not reacted at all, and a readily detectable sulphide coating formed on the gold/silver alloy.

It thus appears that the silver in solution in the alloy becomes available for reaction with sulphide ions in solution, thereby forming a silver sulphide surface deposit.

HYPOTHESIS FOR THE FORMATION OF REFRACTORY COATED GOLD IN WITWATERSRAND GOLD ORE

Studies of the conglomerate reefs of the Witwatersrand have indicated that the age of the system is in the region of 2 600 million years. There is abundant evidence that, during the vast expanse of time following its formation, it has been subjected to metamorphic processes; and it may be concluded that, at least during the metamorphic history of the reef, free sulphide ions were available, and sulphides were formed readily.

In the laboratory experiments described earlier, it was demonstrated that silver-bearing gold is easily attacked by sulphide ions, whereas pure gold is inert. It is concluded that similar reactions have taken place in the reefs.

The hypothesis advanced is that, in nature, silver atoms in the peripheral regions of gold/silver alloy grains are able to combine with the available sulphur. Once sulphur atoms have been bonded to the alloy surface by this means, the alloy grains become excellent seeds for the growth of yet more sulphide, especially iron sulphides. To at least some extent such coatings have been observed on all the Witwatersrand gold grains studied.

By subsequent oxidation, the iron sulphide coatings have become capable of seeding further growth of iron oxides. In the course of mining and plant operations, the process initiated in nature can be continued with extraordinary rapidity owing to the abundance of introduced metallic iron and the prevailing highly oxidizing conditions.

The chemical and galvanic decomposition of tramp iron and the precipitation of ferric hydroxides in the alkaline milling and processing circuits are readily observable. In a similar manner the introduction of calcium into the surface coatings, by the addition of calcium hydroxide to the pulp, has also been demonstrated.

It is interesting also to note that dilute nitric acid is found to be better than dilute hydrochloric acid for removing the coating from the gold/silver alloy prior to mercury amalgamation on the gold plants. Silver in the surface of the alloy grains will react with the acids, and with hydrochloric acid only, forms a very thin coating of insoluble silver chloride on the surface of the alloy grains. With nitric acid, no tarnish forms.

Coated gold, and its adverse effects in plant operations, was known in the U.S.A. as early as 1934[1]. Head[2] states, "These coatings may encase the gold particles entirely, or they may exist as films or tarnishes whose presence is rendered perceptible only by comparison with normal clean gold". Using microchemical tests, he established that iron was the essential constituent of the coatings, but offered no explanation for its presence. He observed that coated gold was prevalent in pyritic deposits, and noted that the coating renders the gold refractory to amalgamation and other recovery processes.

As early as 1889, reference was made to "rebellious gold" that resists recovery[3], but this property was not specifically correlated with the presence of an iron oxide coati... Even earlier, Stetefeldt[4] came ve... close to the truth when he spoke ... refractory gold as "rusty gold".

CONCLUSIONS

Great benefit should result fro... removing the gold from the circu... as soon as it is liberated. Not only unnecessary milling a wasteful opera... tion, but it contributes substantia... to gold losses.

Tramp iron is a most deleterio... constituent in the plant circuit. ... results in the formation of copio... quantities of colloidal iron com... pounds, which add to the hydrate... iron oxide coating on individual go... grains, and contributes to the fo... mation of rusty mineral aggregate... As a result of the iron oxide coa... ings and encrustations, gold re... covery becomes more difficult an... occasionally, impossible.

Removal of tramp iron from th... circuit (and separate treatment t... recover entrained gold) should clea... ly have a beneficial effect on go... recoveries in general.

ACKNOWLEDGEMENTS

It is a pleasure to express o... appreciation for the assistance a... co-operation received from the Hea... Office Metallurgical Department, t... various Group mines concerned, a... our colleagues at Anglo-Americ... Research Laboratories.

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