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The current limited impact of Witwatersrand gold-mine residues on water pollution in the Vaal River system

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SYNOPSIS

This paper discusses the concentrations of sulphides and total sulphur in widely spread regions around mine residue deposits, from which rain-water run-off can enter the Vaal River system. Analyses of borehole samples from several deposits are used to establish typical sulphur head grades.

It is shown that a high percentage of all the oxidizable, and hence leachable and pollution-causing, sulphur has already been removed. When the residues were fresh, water that came from the deposits was highly polluted, but the dissolved solids from these residues are today of very minor significance.

The data are supported by analyses of the drainage streams.

SAMEVATTING

Hierdie referaat bespreek die sulfied- en totale swaelkonsentrasie in wydverspreide gebiede om mynresiduafsettings vanwaar afloopreënwater in die Vaalrivierstelsel kan beland. Ontledings van boorgatmonsters van verskeie afsettings word gebruik om tipiese toevoergrade vir swael te bepaal.

Daar word getoon dat 'n hoë persentasie van al die oksideerbare en dus uitloogbare swael wat besoedeling veroorsaak, reeds verwyder is. Toe die residu's vars was, was die water wat van die afsettings gekom het, erg besoedel, maar die opgeloste vaste stowwe afkomstig van hierdie residu's is tans van baie min belang.

Die data word gestaaf deur ontledings van die dreineerstrome.

Introduction

As mining activity on the Witwatersrand increased from the turn of the century, so did the contamination by dissolved solids, largely calcium sulphate, in the effluent entering the Vaal River above the Barrage. Part of this increase came from the expanding population as sewerage-plant effluent, and another part as industrial effluent. As the mines developed, increasing quantities of sulphate-contaminated water were pumped from underground. A portion of this flow passed into streams that entered the Vaal. Solutions from metallurgical circuits that were high in sulphate were periodically released into these streams up to 1964[1]. Additional sulphates derived from the pyrite near the surface of sand deposits and, to a limited extent, from slime residues oxidized slowly to sulphates. In the rainy season, portions of these sulphates became leached out and eventually entered the barrage system. In recent years, effluent from retreatment plants such as that at ERGO have contributed to the solids load.

In the past twenty to thirty years, mining activity on the Witwatersrand has decreased substantially. Because of this and because of pollution-control measures, the dissolved solids in the streams arising from the mines has fallen. Data on the pollution load for the 1982–1983 summer-rainfall season have been provided by Funke[2].

In 1952 and 1953, the Council for Scientific and Industrial Research undertook an extensive survey of the Witwatersrand catchment area of the Vaal River. The final report, by Stander *et al.*[3], concluded: 'The principal pollutants are mineral and acid accretions from various sources *together with sand which accumulates on river beds*'. Thomas[4], Verster[5], and Henzen *et al.*[6] expanded on this theme, viz that mine sand and slime in water courses were a major cause of pollution of the Vaal system.

A computer survey of the mineral load discharged into the Vaal at the Barrage, which was undertaken by Stewart, Sviridov and Oliver over a two-year period, gave the following results:

	August 1977 to August 1978 %	September 1978 to October 1979 %
Mine pumpage	25	30
Municipal and industrial	17	23
Unknown diffuse sources	58	47
Total mass, kt	547	273

It will be noted that the load in the more recent year was half that for the previous year, showing how variable the calculated pollutant load can be. The load arising from diffuse sources is frequently misquoted as emanating from mine residues, and the higher, although earlier, value is usually quoted.

In 1983, having assumed the post of Chamber of Mines Environmental Protection Officer, the writer examined

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the condition of many of the slime deposits and sand dumps on the Witwatersrand and of the adjacent vlei- and water-courses containing washed-off residues. It was noted that most of the regions where wash-off had settled were adequately to profusely vegetated. At two sites, sections of the walls of slime-residue deposits had previously collapsed, resulting in considerable flows of unoxidized slime into the veld. These sites were also well vegetated.

Active oxidation of pyrite results in low pH values in the wash-off—normally pH 2 to 3 or less[7]. Grass will not grow well where pH values are less than 4 and it was therefore apparent that the concentration of oxidizible pyrite available at the many sites visited could not be high. It was thus unlikely that much of the mineral load from the diffuse sources noted in the computer survey consisted of mine residues. To confirm this supposition, a sampling programme of the washed-off material was initiated. Subsequently, for comparative purposes, the adjacent residue deposits were sampled. The sulphide content of the upper layers was found to be so low that these sites were examined in greater detail. Samples were obtained from auger holes drilled in the vlei regions down to 2 m or to the deposit bottom, whichever was the lesser, and to 3 m in the deposit from which the settled material had mainly originated. This paper gives the results obtained. Also tabulated are the borehole analyses provided by East Rand Gold & Uranium Company Limited, Rand Mines Milling & Mining Company Limited, and Randfontein Estates Gold Mining Company Limited. Sulphide sulphur values obtained from other sources are also included.

It must continually be borne in mind that the Witwatersrand residue deposits collectively contain millions of tons of pyritic sulphur—over 13 Mt was the figure given for the South African gold-mining industry in 1966. This total must now have increased substantially. Should all the sulphur suddenly oxidize to sulphate and then become leached out and pollute the run-off, the pollution problem would be insurmountable. However, in practice little oxidation is occurring.

Determination of Analytical Accuracy

The Leco procedure was used for the determination of sulphide sulphur, and the modified ISO coal procedure for sulphate. The procedures were tested initially and produced very consistent results.

The forerunner of the Leco procedure—the Strauhlein furnace method for the rapid determination of sulphur in steels—has been in use for many years. In 1957, Mendelowitz[8] reported using the procedure for pyrite, as did Webb and Munro[9]. Consequently, when borehole sampling of residue deposits was undertaken, mainly in 1974 and 1975, gas evolution would have been the technique employed. Thus, the borehole values given in Tables XIII to XV and the Addendum should also be reliable. Further, since pyrite was the sulphur mineral of economic importance being determined, it follows that the values, although reported as 'sulphur content', actually refer to the pyritic or sulphide sulphur present.

Sulphur Content of Gold Ores

Table I lists the pyrite (sulphide) sulphur content, mainly run-of-mill average values, for the year 1966, compiled from information available in the records of the Chamber of Mines of South Africa. Additional values presented in 1970 at the Symposium on the Recovery of Pyrite[10] are also included.

TABLE I
SULPHUR CONTENT OF GOLD ORES

	Sulphide sulphur, %		
	Reported	Average value	
Mine	source	1966	1970
Witwatersrand Nigel	Run of mill (Main Reef Leader)	1,34	
Spaarwater	Run of mill	1,26	
Vogelstruisbult	Primary mill product		1,0
East Rand Proprietary Mines	Run of mill	0,96	
City Deep	Run of mill	1,07	
Crown Mines	Run of mill	0,85	
Consolidated Main Reef	Run of mill	1,33	
Rand Leases	Mainly Monarch Reef	1,07	
Durban Roodepoort Deep	High in Kimberley Reef		2,3
West Rand Consolidated	Bird Reef	0,99	
Venterspost	Run of mill		1,05*
Blyvooruitzicht	Carbon Leader	0,85	
Buffelsfontein	Vaal Reef	1,94	
Hartebeesfontein	Vaal Reef	1,60	
Stilfontein	Vaal Reef	1,60	
Zandpan	Vaal Reef	1,17	
Lorraine	Elsburg Reef	1,44	1,42
	Elsburg Reef		0,85*
	Bird Reef		0,74*
Virginia	Basal Reef	1,28	
	Leached uranium ore		1,55
Harmony	Basal Reef	1,24	

* Spot samples of mill feed

Table II, also from the records of the Chamber, gives the estimated distribution of pyrite in the surface residues of mines in 1966.

Most of the reported sulphur grades in Table I lie in the range 0,85 to 1,60 per cent, but Durban Deep gave 2,3 per cent, stating that the ore contained a high proportion of material from the Kimberley Reef. At the Symposium it was reported that the slime deposit at the Government Gold Mining Areas had a sulphide sulphur content of 3,9 per cent, part of this high value arising from the mining of the Black Reef and part from the partial removal of sand from the circuit, leaving the pyritic fraction to enrich the remaining fines.

Sulphide and sulphate concentrations are reported in the present paper, the reduction of the sulphide value below the estimated head grade giving the amount of oxidation to sulphate that has occurred. As the ore is virtually sulphate free, if oxidation has taken place and only a low concentration of sulphate remains, the balance has been leached away.

TABLE II

ESTIMATED DISTRIBUTION OF PYRITIC SULPHUR IN MINE SURFACE DEPOSITS, 1966

Sulphur grade, %								
0–0,27	0,27–0,53	0,53–0,80	0,80–1,07	1,07–1,33	1,33–1,60	1,60–1,87	1,87–2,13	2,13
Percentages of total								
13,5*	9,3*	18,4	27,7	12,1	9,2	1,6	5,7	2,5

* The relatively high percentage of the total sulphur distribution present in this residue is consistent with it being the residue left after extraction of the pyrite from a flotation concentrate

Age of Residue Deposits

As the investigation described in this paper progressed, low sulphide values were reported, showing that, in the first 2 m of depth, most of the pyritic sulphur originally present had oxidized. An attempt was then made to determine the age of the deposits and thus obtain an indication of the rate of oxidation. The only information found was in the Residue Deposit Index of the Chamber of Mines, which was published in 1963. Fortuitously, this revealed that most of the sites sampled had been abandoned by 1963, i.e. in 1983 they had been at least twenty years old, although some could be considerably older. Those still in use on which borehole data were available were East Geduld 6L/13†, Geduld 6L/12, Government Gold Mining Areas 5L/28, and South African Lands 5L/32.

The investigation described in this report was undertaken from 1983 to 1984. Most of the borehole analyses recorded in the Addendum were conducted about 1975. At that date the deposits were at least twelve years old, and some could have been far older.

Results for the Slime Deposits

The results obtained for the individual slime deposits, as well as for their washed-off residues, are given in Tables III to VII. Tables VIII to XII provide results for the settled wash-off, which generally comes from more than one deposit. The results provided by Rand Mines Milling & Mining Company Limited are given in Tables XIII to XV.

All these results are summarized in Tables XVI and XVII, which include brief interpretations of the information from each site. To assist in the clarification of these interpretations, the situation at several sites is discussed in more detail below.

Modderfontein B, Deposit 5L/26

The western end of this deposit has eroded appreciably through the years. Borehole 3 (Table A-VI) was drilled near this region in about 1975. In 1983/1984, samples were taken in the vicinity on top of the lower terrace. Samples of the adjacent 'washed-off' material were also gathered.

The results given in Table III show that, on the terrace at depths of 2 and 3 m, the total sulphur values are of the same order as those obtained nine years earlier for the deposit average and for borehole No. 3, i.e. little of the total sulphur had been lost in the period that had elapsed. Table III also shows that, at the 2 m horizon, the sulphide sulphur is low, i.e. most of the original pyrite has oxidized to sulphate. However, at the 3 m horizon, the sulphur is still present as sulphide, except in hole 1, where oxidation has occurred. These results mean that the pyritic (sulphide) sulphur has oxidized to a depth of between 2 and 3 m—slightly deeper in hole 1, i.e. the oxidation interface lies between the 2 and 3 m horizons. However, as stated above, the total sulphur content has not fallen materially; therefore, despite oxidation to the relatively soluble sulphate, little has leached away.

That oxidation has occurred means that both air and water have penetrated, but the absence of leaching implies that the quantity of leachant rain water has been insignificant. The recorded pH values of 3,6 show that sulphide oxidation potentials exist but, since virtually no leached has occurred, the polluting rate must be low.

The 3 m sample taken from hole 2 in January 1984 has a pH value of 7,2, which implies that this material is inert—probably because no oxygen is reaching the site. This situation is confirmed by the fact that the values for sulphides and total sulphur are virtually identifical, viz 0,52 and 0,53 per cent.

Two holes were sunk into the eroded material that had settled on the flat, dry vlei ground adjacent to the northwest face, and the results are recorded in the final two sections of Table III. It can be seen that the sulphide still present amounts to between 0,02 and 0,045 per cent, and the total sulphur to between 0,1 and 0,2 per cent.

The important implication of the low sulphur content of these vlei samples is that, even if the sulphur eventually leaches away, the resulting water pollution will be negligible. Similarly, although the material at depths of 2 and 3 m in the original deposit contains sulphate, the rate of leaching is relatively so low that the rate of pollution of any adjacent water source will be insignificant. It is suggested later in this paper that some of the 0,1 to 0,2 per cent sulphur present in the vlei is, in fact, non-soluble sulphur, which makes the ultimate pollution potential even lower.

New Van Ryn 5L/14 and Witwatersrand Deep 4L/24

The pH values of the majority of the samples taken in the project were well below 7, indicating that the acidity and sulphide oxidation potential were low but present. The hole samples from New Van Ryn (Table VI) differ. With a pH value of close to 7, the sulphide is either inert

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† These are the numbers allotted in the 'Index of Sand and Slime Deposits of the Witwatersrand', which was published by the Chamber of Mines of South Africa.

TABLE III

SULPHUR VALUES, MODDERFONTEIN B 5/L26 DEPOSIT, LOWER TERRACE ADJACENT TO ERODED WESTERN END OF NORTH SLOPE
(Average sulphide sulphur value for whole deposit is 0,65%)

Location	Depth of sample m	Date	pH value	Sulphide sulphur %	Sulphate as S %	Total sulphur %
Hole 1						
5 m from edge, 4 m west of upper terrace	0,1	6/83	5,6	0,026	–	–
	0,5		5,2	0,016	–	–
	1,0		3,2	0,017	–	–
	1,5		2,8	0,019	–	–
	2,0		2,2	0,02	–	–
Re-sampled adjacent to Hole 1	2,0	1/84	2,95	0,02	0,52	0,54
	3,0		2,9	0,04 0,043	0,37	0,41
	Surface	2/84	–	–	–	0,41
Hole 2						
5 m from edge, 15 m west of Hole 1	0,1	6/83	3,6	0,023	–	–
	0,5		3,4	0,022	–	–
	1,0		2,8	0,023	–	–
	1,5		2,3	0,025	–	–
	2,0		3,3	0,38	–	–
Re-sampled adjacent to Hole 2	2,0	1/84	2,6	0,02	0,86	0,88
	3,0		7,2	0,52	0,01	0,53
Re-sampled again next to Hole 2	2,0	2/84	–	–	–	0,29
	3,0		–	–	–	0,46
Hole 3						
5 m from edge, 15 m west of Hole 2	0,1	6/83	3,3	0,043	–	–
	0,5		2,9	0,032	–	–
	1,0		3,1	0,049	–	–
	1,5		2,9	0,042	–	–
	2,0		2,4	0,041	–	–
Re-sampled adjacent to Hole 3	2,0	1/84	3,1	0,03	0,70	0,73
	3,0		3,1	0,44	0,89	1,03
	3,0	2/84	–	–	–	0,48
Hole 3A						
10 m behind Hole 3, 15 m from edge	3,0	12/84	–	0,5	0,24	–
Hole 4						
Behind Hole 1, approximately 60 m from edge	3,0	12/84	–	0,50		0,74
Washed down adjacent to north slope						
Run-off, 70 m north of west corner	0,1	6/83	3,65	0,021	0,11	0,13
	Bottom 0,4		3,55	0,030	0,18	0,21
Run-off, 140 m north of west corner	Bottom 0,15	6/83	3,60	0,047	0,023	0,07

– No analysis was undertaken

TABLE IV

SULPHUR VALUES, GOVERNMENT GOLD MINING AREAS 5L/27 DEPOSIT

Location	Depth of sample m	Date	pH value	Sulphide sulphur %	Sulphate as S %	Total sulphur %
Terrace						
Top north-west corner, 25 m from wash-away site	2,0	6/83	3,6	0,025	0,24	0,27
Run-off						
60 m north-east of north-west corner	Bottom 0,15	6/83	4,2	0,025	0,047	0,072

TABLE V

SULPHUR VALUES, NEW VAN RYN 5L/22 DEPOSIT

(This is a very shallow deposit)

Location	Depth of sample m	Date	pH value	Sulphide sulphur %	Sulphate as S %	Total sulphur %
Top north side						
200 m from north-west corner and 30 m from north edge	0,1	4/83	5,80	0,055	0,12	0,18
	0,5		4,85	0,037	0,13	0,17
	1,0		4,10	0,039	0,14	0,18
	1,5		3,45	0,034	0,12	0,15
	Bottom 1,7		3,75	0,049	0,12	0,17
Top centre						
200 m south of previous hole	0,1	4/83	3,75	0,060	0,15	0,21
	0,5		3,70	0,061	0,14	0,20
Wash-off						
50 m east of south-east corner, deposit only 10 to 20 mm thick	Surface	4/83	3,6	0,064	0,13	0,19
	Re-sampled surface		4,4	0,12	0,03	0,15
New Van Ryn 5L/21, adjacent to but west of 5L/22						
Wash-off						
In stream bed, 30 m south of south-east corner	0,01	4/83	4,75	0,030	0,15	0,18
	Bottom 0,65		3,85	0,084	0,18	0,26

and stable, or the sulphide is all encapsulated, which is most unlikely, in a totally impermeable matrix or film. The sulphate concentration, which is the difference between the total and the sulphide sulphur, reveals that, even at a depth of 3 m, the concentration is low. The sulphide residuals are also low, showing that oxidation and leaching have taken place to at least that depth. The overall picture is that, down to a depth of 3 m, little sulphide or sulphate remains and, with a pH value of 7, the residual is inert so that the pollution potential is now very low.

By comparison, the hole samples at Wit Deep (Table VII) at 2 m and lower, except for one 2 m sample, have relatively high sulphide contents and low pH values, meaning that the sulphide is actively oxidizing. The free-sulphate values are higher than at New Van Ryn, and it appears that, at this site, less of the sulphate has been leached away. Taken together, the highish sulphide values, the lack of leaching even at a depth of 2 m, and the fact that the site is at least 20 years old indicate that the deposit is relatively impermeable. Consequently, although there is an ultimate pollution potential, the current rate of pollution is very low.

The reason why oxidation and leaching have extended beyond the normal 2 m limit in deposit 5L/14 is shown clearly from the size analyses given in Table XVIII. Whereas the fineness of the slime sampled in deposit 4L/24 is normal for older deposits—about 70 per cent passing 0,038 mm (200 mesh)—that in New Van Ryn is far coarser, i.e. only 35 to 40 per cent passing 0,038 mm. Because of this greater coarseness, the deposit will be far more permeable. Consequently, oxidation and subsequent leaching will occur to a greater than normal depth.

Material Washed into Vleis

As stated previously, although the analyses given in Tables XIII to XV are reported as sulphur, the constituent is actually present in the form of sulphide. The pH values are not on record for these analyses, so it is now impossible to determine whether active sulphide oxidation was occurring. However, the age of the deposits and the regularity of the residuals found in the vlei deposits, which are 1 to 2 m thick, are consistent with the presence of much inactive, non-oxidizable sulphide having values normally between 0,1 and 0,2 per cent.

The most recent persistent period of heavy rain that caused major wash-down of residue deposits occurred between 1972 and 1974. Thus, most of the deposits in vleis, etc. are over ten years old, although much of the material, particularly in the lower layers, is far older.

Pyrite Oxidation in the Slime Deposits

James and Mrost[7] stated in 1965 that their examination of core samples had shown that pyrite (sulphide) oxidation is confined to a surface layer of about 2 m in depth. Five years later, Mrost and Lloyd[11] added that this statement had been based on studies of core samples taken from ten residue deposits at least five years after they had been abandoned.

After further investigations, Mrost[12] stated three years later that oxidation is limited to the depth to which oxygen can gain access and that the air in the pores of the deposit is stagnant, except for expansion and contraction due to changes in temperature or pressure. He also stated that, from the surface to a depth of 0,1 m, complete oxidation occurs in one month, after which the rate of oxidation diminishes rapidly with depth, taking two to three years to completely oxidize the 1 m horizon.

In the current investigation, twenty years after Mrost's first pronouncement, sulphide oxidation at Modder B 5L/26 was, with the exception of one test hole, far from complete at a depth of 3 m. At Wit Deep 4L/24, it was

TABLE VI

SULPHUR VALUES, NEW VAN RYN 5L/14 DEPOSIT ADJACENT TO BADLY ERODED SOUTH-EAST SLOPE

(Average sulphide sulphur value for deposit 5L/1 (just east of 5L/14) 0,90%)

Location	Depth of sample m	Date	pH value	Sulphide sulphur %	Sulphate as S %	Total sulphur %
Hole 1						
40 m south-west of sand dump: top	0,1	7/85	6,0	0,01	0,12	0,13
	0,5	7/85	6,0	0,04	0,19	0,23
	1,0	7/85	5,0	0,07	0,16	0,23
	2,0	6/83	7,1	0,37		–
Re-sampled adjacent to old hole	2,0	1/84	6,75	0,31	0,02	0,33
	3,0		7,10	0,21	0,00	0,19
Hole 2						
Approximately 30 m south of hole 1	2,0	6/83	7,4	0,24	–	–
Re-sampled adjacent to old hole	2,0	1/84	6,7	0,18	0,04	0,22
	3,0		7,0	0,14	0,06	0,20
Hole 3						
Approximately 30 m south-west of hole 2 and 15 m from upper (SW) terrace	0,1	7/85	6,5	0,01	0,15	0,16
	0,5	7/85	6,0	0,04	0,19	0,23
	1,0	7/85	5,0	0,02	0,22	0,24
	2,0	6/83	7,5	0,20	–	0,24
Re-sampled adjacent to old hole	2,0	1/84	7,0	0,15	0,07	0,22
	3,0		6,8	0,16	0,15	0,31
Re-sampled adjacent old hole	Surface	2/84	–	–	–	0,17
Wash-down						
Wall built from south-east corner	0,1	4/83	5,95	0,042	0,19	0,23
	0,5		5,65	0,036	0,17	0,21
Run-off residue	1,2		5,10	0,037	0,18	0,22
Wash-down						
Wall built from north-east corner	0,1	4/83	5,35	0,051	0,17	0,22
	0,5		5,85	0,032	0,15	0,18
Run-off residue	1,2		4,80	0,036	0,15	0,19
New Van Ryn vlei						
	0,1 Slightly damp	4/83	3,35	0,039	0,03	0,068
Opposite downstream south-east end of 5A/6 (and 5L/14 and 5L/1)	0,5		3,10	0,042	0,13	0,17
	1,0		3,40	0,024	0,03	0,057
	1,25 Very damp					
	1,5		3,45	0,19	0,11	0,30
	2,0 wet		4,40	0,17	0,04	0,21
New Van Ryn vlei						
200 m further downstream	0,1	4/83	3,35	0,046	0,02	0,069
	0,5		3,25	0,034	0,09	0,12
	1,0		3,40	0,17	0,04	0,21
	1,5		3,55	0,14	0,24	0,38
	2,0		5,15	0,51	0,05	0,56

found that, even at the 2 m horizon, oxidation was generally poor. At a third site, New Van Ryn 5L/14, oxidation and leaching had reached 3 m, the limit of depth tested. The reason for this apparent anomaly has already been discussed.

It is evident from the results of the present investigation that Mrost's original statement, made in 1965, is still substantially correct, i.e. that the limiting depth of oxidation is about 2 m. Mrost may not have tested a deposit as coarse as that at New Van Ryn and, to be conservative, Mrost's original statement is probably best amended to 'oxygen penetration and hence pyrite oxidation in a slime deposit is limited to between 2 and 3 m in depth'.

It is therefore valid to assume that, below that horizon, the 1975 borehole analyses were still applicable in 1983/1984, when the analyses for the present investigation were made.

Sulphate Remaining in the Slime Deposits

The findings in the present study indicate (Table XVI) that, although oxidation may have proceeded to a depth of 2 m, or even 3 m, considerable amounts of the sulphate

TABLE VII
SULPHUR VALUES, WIT DEEP 4L/24 DEPOSIT ADJACENT TO EAST FACE SLIP ZONE:
(Average sulphide sulphur value for whole deposit 0,73%)

Location	Depth of sample m	Date	pH value	Sulphide sulphur %	Sulphate as S %	Total sulphur %
Hole 1						
30 m south of northern edge of slip zone (east side terrace)	0,1	7/85	6,0	0,02	0,25	0,27
	0,5	7/85	6,0	0,02	0,25	0,27
	1,0	7/85	4,5	0,04	0,37	0,41
	2,0	6/83	2,6	0,56	–	–
Re-sampled adjacent to old hole	2,0	1/84	3,1	0,15	0,27	0,42
	3,0		3,2	0,65	0,40	1,05
Hole 2						
90 m south of Hole 1	2,0	6/83	2,8	0,67	–	–
Re-sampled adjacent to old hole	2,0	1/84	3,3	0,58	0,47	1,05
	3,0		3,1	0,78	0,64	1,42
Re-sampled adjacent to old hole	Surface	2/84	–	–	–	0,41
	3,0		–	–	–	0,91
Re-sampled adjacent to old hole	3,0	12/84	–	ca 0,55	ca 0,35	ca 0,9
Hole 3						
90 m south of Hole 2 above south edge of slip zone	0,1	7/85	6,0	0,03	0,36	0,39
	0,5	7/85	6,0	0,02	0,33	0,35
	1,0	7/85	5,5	0,05	0,35	0,40
	2,0	6/83	2,9	0,06	–	–
Re-sampled adjacent to old hole	2,0	1/84	3,2	0,18	0,44	0,62
	3,0		3,3	0,28	0,75	1,03
Re-sampled adjacent to old hole	3,0	2/84	–	–	–	1,03
Hole 4						
10 m north of access road, near bottom of slip between Holes 2 and 3	1,5	12/84	–	0,72	0,08	ca 0,8
Break-away						
250 m out from slip face	0,1	4/83	3,35	0,075	0,09	0,17
	Bottom 0,65		3,20	0,061	0,13	0,19

TABLE VIII
SULPHUR VALUES, WIT DEEP 4L/40 DEPOSIT

Location	Depth of sample m	Date	pH value	Sulphide sulphur %	Sulphate as S %	Total sulphur %
Run-off						
60 m away from north-east corner base	0,1	4/83	3,20	0,061	0,13	0,19
	0,5		3,30	0,11	0,24	0,35
	Bottom 1,0		3,20	0,13	0,17	0,30

then produced are still present in the deposit. This, in turn, means that the rate of leaching of the sulphate is low, and consequently the rate of pollution. That the sulphate is still present implies that the site is only marginally permeable to rain.

Pollution Potential

The typical sulphur grades of South African gold ores given in Table I indicate that most of these ores have a sulphide sulphur content of between 0,85 and 1,6 per cent. If there is a residual value of 0,26 per cent in a sample, the maximum pollution potential remaining if this can oxidize and leach completely will be between 15 and 30 per cent of the original value. Similarly, from a residual value of 0,1 per cent, the potential will be 6 to 12 per cent of the original value, and lower residual values will result in proportionately lower pollution potentials.

It is probable that the true pollution potential of the residual sulphide is even lower than outlined above for, as shown later, a fraction of the sulphide present does not oxidize.

From the remarks above and Table XVII, it is evident

TABLE IX
SULPHUR VALUES, NEW CANADA VLEI DEPOSIT

Location	Depth of sample m	Date	pH value	Sulphide sulphur %	Sulphate as S %	Total sulphur %
Vlei deposit						
0,7 km south of Main Reef Road. Also drains Western Langlaagte Estates	0,5	4/83	4,85	0,23	0,02	0,25
	1,0		5,05	0,23	0,03	0,26
	1,5		5,55	0,23	0,03	0,26
	2,0		6,50	0,25	0,03	0,28
Vlei deposit						
30 m downstream of New Canada dam	Bottom—mainly slimes 0,3	4/83	5,5	0,16	0,01	0,17
Vlei deposit						
80 m west of New Canada dam, east side of vlei draining 2L/2–2L/3 and 2L/4. Upstream from previous sample	0,1	4/83	3,15	0,11	0,15	0,26
	0,5		3,00	0,13	0,16	0,29
	1,0		3,25	0,11	0,22	0,33
	1,5		3,50	0,50	0,16	0,66
	2,0		3,55	0,54	0,17	0,71
Vlei deposit						
380 m west of New Canada dam, draining 2L/2, 2L/3, and 2L/4, 0,3 km upstream from preceding samples	0,1	4/83	2,20	0,13	0,41	0,54
	0,5		2,80	0,65*	–	0,23*
	1,0		3,75	0,49	0,15	0,64
			Repeat analysis	0,25	0,19	0,44
	1,5		5,15	1,18	0,15	1,33
	Bottom 1,7		4,00	0,54	0,21	0,75
Re-sampled adjacent to previous hole	0,1	5/83	2,6	0,12	0,55	0,67
	0,5		3,1	0,075	0,01	0,086
	1,0		3,7	0,36	0,01	0,37
	1,5		4,7	1,04	0,02	1,06
Wash-off						
At east end of 2L/3	0,1	4/83	2,90	0,19	0,22	0,41
	0,5		2,70	0,18	0,20	0,38
	Bottom 0,9		2,75	0,16	0,23	0,39
Wash-off						
At west end of 2L/3	0,1	4/83	2,60	0,22	0,38	0,60
	Repeat analysis		2,90	0,18	0,12	0,30
	Bottom 0,45		2,50	0,21	0,24	0,45

* One of these values is incorrect, probably that for the sulphide, which cannot be higher than the total sulphur

TABLE X
SULPHUR VALUES IN WEST KLIPSPRUIT, VLEI DEPOSIT

Location	Depth of sample m	Date	pH value	Sulphide sulphur %	Sulphate as S %	Total sulphur %
Vlei deposit						
0,5 km north of Roodepoort–Randfontein road	0,1	4/83	2,85	0,062	0,04	0,10
	0,5		3,15	0,12	0,06	0,18
	Bottom, wet 0,75		3,65	0,065	0,01	0,078
Vlei deposit						
2,5 km south of Roodepoort–Randfontein road	0,1	4/83	3,3	0,12	0,03	0,15
	Bottom 0,3		3,6	0,15	0,03	0,18
Vlei deposit						
10 km south of Roodepoort–Randfontein road	0,1	4/83	3,4	0,10	0,31	0,41
	Repeat analysis		3,6	0,10	0,40	0,50
	Bottom 0,6		2,05	0,16	–	–
	Repeat analysis		2,0	0,15	0,17	0,32
Re-sampled adjacent to previous hole	0,1	5/83	2,5	0,44	0,63	1,07
	0,6		2,2	0,60	1,00	1,60

TABLE XI

SULPHUR VALUES IN DAM BREAK-AWAY, SOUTH OF SOUTH ROODEPOORT 2L/34, 2L/35, 2L/36 DEPOSITS

Location	Depth of sample m	Date	pH value	Sulphide sulphur %	Sulphate as S %	Total sulphur %
Dry run-off from deposit break						
0,4 km south of deposits	0,1	4/83	4,30	0,12	0,14	0,26
	Bottom 0,3		3,35	0,16	0,20	0,36
Dry run-off						
0,75 km south of deposits	0,1	4/83	4,35	0,17	0,17	0,34
	0,5		5,5	0,18	0,16	0,34
Dry run-off						
0,9 km south of deposit	Bottom 0,15	4/83	3,35	0,19	0,21	0,40
Re-sampled adjacent to previous hole	Bottom 0,3	5/83	3,50	0,59	0,19	0,78

TABLE XII

SULPHUR VALUES, WONDERFONTEINSPRUIT VLEI DEPOSIT

(Vlei lies south of Krugersdorp)

Location	Depth of sample m	Date	pH value	Sulphide sulphur %	Sulphate as S %	Total sulphur %
Vlei deposit						
Beside Wonderfonteinspruit, 0,1 km	(Some humus) 0,1	4/83	5,65	0,28	0,04	0,32
south of Roodepoort–Randfontein road	0,5		4,55	0,047	0,05	0,093
	1,0		4,50	0,048	0,04	0,084
	1,5		5,35	0,17	0,34	0,51
Vlei deposit				0,12		0,62
0,5 km south of Roodepoort–Randfontein	0,1	4/83	6,75 6,90	0,12	0,53	0,68
road	0,5		4,95	0,17	0,04	0,21
	1,0		4,90	0,070	0,00	0,074
	1,5		5,10	0,043	0,00	0,081
Vlei deposit						
At Zuurbekom–Randfontein road, 10 km downstream from previous sampling point	Bottom 1,0	4/83	2,8	1,27	0,21	1,48
Vlei deposit						
1,0 km south of Zuurbekom–Randfontein road	0,1	4/83	4,1	0,15	0,49	0,64
Vlei deposit						
0,5 km south of Zuurbekom–Randfontein	0,1	4/83	7,2	1,59	0,01	1,60
road	0,3		7,1	0,67	0,02	0,69

that pollution by the dissolved solids emanating from sites on the eastern Witwatersrand is small, and the rate very low. It is reasonable to assume the same for the western section; that is, for the whole of the Witwatersrand section of the Vaal basin, *the mass of pollutants and the polluting rate are today very low.* This conclusion is in accord with the contention by Funke[2] that the residues are responsible for 2 per cent or less of the polluting load entering the Witwatersrand catchment area of the Vaal system.

It is pertinent to stress again that the residue deposits contain tens of millions of tons of sulphur, which, should it suddenly oxidize, would have catastrophic consequences. However, in practice, the rate of oxidation and pollution from the old deposits is low owing to the inability of oxygen to penetrate more than 2 to 3 m into a deposit.

Evaporation Gradient

At the end of winter, it is sometimes noted that thin cluster deposits of small crystals form on the slopes of slime deposits. Analyses have confirmed that these crystals are essentially calcium sulphate. The inside of a slime deposit normally has a moisture content of 20 to 30 per cent, whereas the relative humidity of the air outside the deposit is very low in winter. It is postulated that capillary movement of some of the moisture to the outer surface occurs as a result of what can be referred to as an 'evaporation gradient'. The moisture evaporates at the surface, depositing crystals of calcium sulphate in the process.

The occurrence is frequent, but the crystal layer is thin and disappears with the first rain. Consequently, the mass involved is small. In any event, when the sulphate has been redissolved, it flows into the catchment areas at the

TABLE XIII
SULPHUR VALUES IN RESIDUES WASHED INTO VLEI

Location of vlei	Grid line 1		Grid line 2		Grid line 3		Grid line 4	
	Depth m	Sulphur %	Depth m	Sulphur %	Depth m	Sulphur %	Depth m	Sulphur %
Crown Mines	1,15	0,17	1,00	0,15	0,77	0,05	1,00	0,11
South of 3A/6	1,07	0,24	1,18	0,20	1,00	0,27	1,00	0,14
Length 1300 m			0,98	0,08	1,00	0,17	1,00	0,17
Width 100 to 500 m	2,12	0,23	1,00	0,09	1,00	0,14		
			1,00	0,15	1,00	0,19		
	Grid line 5		1,75	0,25	0,79	0,15		
						0,34		
	1,23	0,19						
	1,00	0,18						
	1,90	0,20						
	2,21	0,16						
	Deposit average 0,18%							

Location of vlei	Grid line 1		Grid line 2		Grid line 3		Grid line 4	
	Depth m	Sulphur %	Depth m	Sulphur %	Depth m	Sulphur %	Depth m	Sulphur %
Crown Mines	1,45	0,11	1,13	0,16	0,83	0,10	1,00	0,1
South-west of 3A/6	1,50	0,19	1,31	0,13	1,12	0,07		
South of 3L/12	1,50	0,28	1,12	0,13	0,60	0,02		
Length 1225 m	1,50	0,41	1,18	0,13	0,50	0,04		
Width 200 m	1,50	0,29	1,28	0,19	0,50	0,06		
	1,55	0,26	1,30	0,21	0,60	0,09		
	2,00	0,26	1,28	0,09	0,80	0,13		
	2,10	0,37	1,35	0,13	1,00	0,18		
			1,35	0,15	1,00	0,23		
			1,30	0,20				
	Deposit average 0,21%							

TABLE XIV
SULPHUR VALUES, RESIDUES WASHED INTO VLEIS

Site of vlei	Length and width sampled, m	No. of samples	Depth of hole, m		Sulphur %
			Min.	Max.	
Rosherville Dam	1300 × 100–500	48	1,23	1,80	0,26
Crown Mines					
South-east of 3A/6	280 × 175	16	0,63	3,03	0,16
South of 3A/6	1300 × 100–500	26	0,77	2,20	0,18
South-west of 3A/6	1225 × 200	23	0,80	2,10	0,21

TABLE XV
SULPHUR VALUES, RESIDUES WASHED INTO VLEIS

Site of vlei	Length and width sampled, m	No. of samples	Depth of hole, m		Sulphur %
			Min.	Max.	
New Canada					
North of Main Reef road	595 × 60	10	1,80	1,80	0,10
South of Main Reef road	450 × 150	25	1,65	1,80	0,22

TABLE XVI
SUMMARY OF SULPHUR VALUES WITHIN 3 m OF RESIDUE-DEPOSIT SURFACE

Site	Table no.*	Depth m	No. of samples	Sulphur, %			Remarks
				Sulphide as S	No. of samples	Sulphate as S†	
Modder B 5L/26 Head value 1975 0,65% sulphide, use ceased prior to 1963	III	0–2	17‡	0,015–0,05	4	0,3–0,85	Compared with the 0,65% head value, pyrite (sulphide) oxidation is almost complete to 2 m, while little has occurred at 3 m depth. Relatively little sulphate has leached away at either depth. *Conclusion*: As practically no leaching has occurred from the over-20-year-old deposit, the pollution potential is very low. Oxidation of the pyrite has generally occurred to an interface at about 2 m.
		3	4§	0,45–0,55	4	0,25–0,6	
			5∮				
G.G.M.A. 5L/27 Use ceased prior to 1963	IV	2	1	0,025	1	0,25	Almost all the original sulphide has oxidized, and most of the sulphate has leached away. According to Westwood[16], the original sulphide probably exceeded 2%. Its oxidation and removal caused pollution in the past, but to 2 m depth the residue is now almost inert.
New Van Ryn 5L/22 Use ceased prior to 1963	V	1,7 (Bottom)	7	0,035–0,06	7	0,15–0,20	Except for a small residual, complete oxidation of sulphide has occurred. Most of the sulphate has leached away. *Conclusion*: The remaining pollution potential is very low.
New Van Ryn 5L/14 Use ceased prior to 1963	VI	0–1	6	0,01–0,07	6	0,12–0,22	Relatively little free sulphate remains, and leaching has occurred down to the 3 m level. The sulphide sulphur is low, and pH values are almost all 6,0 or greater. The material is inert and the oxidation potential is almost nil. *Conclusion*: The pollution potential at all near-surface depths is negligible. The pH values are given in Table VI.
		2–3	9	0,14–0,37	7	<0,15	
Wit. Deep 4L/24 Head value about 1975 0,73% sulphide, use ceased prior to 1963	VII	0,1	6	0,02–0,05	6	0,12–0,22	Compared with the 0,73% sulphur head value, most of the sulphur is still present at 2 m depth (as sulphide plus sulphate), i.e. little leaching has occurred. The sulphide values fluctuate. At two 2 m sites, they are below 0,2%, and considerable oxidation has occurred there. The oxidation interface is generally between the 2 m and 3 m horizons. *Conclusion*: At 2 m depth and below, little sulphate has leached away in over 20 years. Hence, the annual pollution potential is very low. Judged from this fact and the surface analysis of 0,41% sulphur, the deposit is relatively impermeable.
		2	6	0,06–0,62	3	0,25–0,45	
		3	4	0,28–0,78	4	0,35–0,75	
		Surface	6**		1	Total 0,41	

Notes

* Tables giving pH values and individual sample details

† Sulphate (reported here as sulphur) has been taken as the difference between the total sulphur and the sulphide sulphur reported in Tables III to XII

‡ An 18th sample gave 0,38%. Sulphide oxidation was relatively poor in this sample

§ A 5th sample gave 0,04% so that oxidation at this site was virtually complete at 3 m

∮ These values exclude one 3 m sample, where the pH value 7 indicated no oxidation activity. Either sulphate has never formed or, and this is unlikely, it has leached away completely

** Hole 4 is in a wettish lower-slope region, where pyrite oxidation has been limited and there is little free sulphate

TABLE XVII
SUMMARY OF SULPHUR VALUES IN MATERIAL DISPLACED FROM RESIDUE DEPOSITS

				Sulphur, %			
Site	Table no.*	Depth m	No. of samples	Sulphide as S	No. of samples	Sulphate as S†	Remarks
Modder B 5L/26							
Use ceased prior to 1963 70 m and 140 m from side	III	0–0,4 (Bottom)	3	0,02–0,045	3	0,02–0,2	A very low, but positive sulphide value persists. The total sulphur content is very low. *Conclusion*: The pollution potential is negligible.
G.G.M.A. 5L/27							
Use ceased prior to 1963 60 m from 5L/27 side	IV	Bottom 0,15	1	0,025	1	0,05	Very low, but positive sulphide and total-sulphur values persist. *Conclusion*: Pollution potential is negligible.
New Van Ryn 5L/21 and 22							
Use ceased prior to 1963, 50 m from 5L/22 side		Only 10–20 mm thick	2	0,06–0,12	2	0,03–0,13	Despite the extreme thinness of this displaced residue, a low sulphide content persists. Total sulphur and pollution potential virtually nil.
30 m from 5L/21 side		0–0,65 (Bottom)	2	0,03–0,08	2	0,15–0,18	A very low sulphide content is present. Total sulphur and pollution potential is very limited.
New Van Ryn 5L/14							
Use ceased prior to 1963	VI	Walls built from run-off	6	0,03–0,05	6	0,15–0,19	A very low, positive sulphide content. Total sulphur and pollution potential very limited.
New Van Ryn Vlei							
SE of 5A/5	VI	0–1,0	3	0,025–0,04	3	0,03–0,13	Down to 0,5 m very low but positive sulphide. At 1,5 m: low sulphide (one sample). At 2 m: low to moderate sulphide. Only 2 samples (in 10) contain more than 0,10% sulphur as sulphate (one being 0,24%). *Conclusion*: Pollution potential down to 1,5 m is very limited.
		1,5–2	2	0,18	2	0,04–0,11	
200 m further down stream	VI	0–0,5	2	0,035–0,045	2	0,02–0,09	From 2 m down sulphide is present but, probably owing to lack of oxygen, little has oxidized (pH 5,15 confirms this). *Conclusion*: Pollution potential also low.
		1,0–1,5	2	0,15–0,17	2	0,04–0,24	
		2	1	0,5	1	0,05	
Wit Deep 4L/24 and 4L/40							
Use ceased prior to 1963 Break-away at 4L/24 occurred in 1972 (or possibly earlier)	VII	0–1,0 (Bottom)	5	0,06–0,13	5	0,10–0,24	Low, positive sulphide value persists, although deposit thin and 11 years old. Low sulphate sulphur present. *Conclusion*: Pollution potential low, and negligible on an annual basis.
Rosherville Dam	XIV	0–1,8	48	0,26 Average			Sulphate values are not available. Head sulphur value at Crown Mines was 0,85% in 1966. (Table II 3A/6 was abandoned before 1963.) *Conclusion*: About 75% of the original sulphur has leached away. Hence remaining pollution is limited and rate of pollution must be low.
Crown Mines							
Vlei SE of 3A/6	XIV	0–3,0	16	0,16 Average			
Vlei S of 3A/6	XIV	0–2,2	20	0,18 Average			
Vlei SW of 3A/6	XIV	0–2,1	23	0,21 Average			
New Canada Vlei							
North of Main Reef Road	XV	0–1,8	10	0,10 Average			
South of Main Reef Road	XV	0–1,8	25	0,22 Average			

TABLE XVII
(continued)

Site	Table no.*	Depth m	No. of samples	Sulphur, %			Remarks
				Sulphide as S	No. of samples	Sulphate as S†	
New Canada Vlei	IX	0–0,5	8	0,10–0,25	7	0,01–0,16	Head values of sulphide sulphur in the vicinity have been given as 1,33% and 0,89%. Compared with these, about 75% of the sulphide has oxidized to 0,5 m depth and 75% to nil at 1 to 2 m. With one exception, most of the sulphate that formed has leached away. *Conclusion*: In the top metre, little sulphur remains to be oxidized. Below this, little sulphate is present—possibly leached as the deposit formed. The presence of highish values show the rate of oxidation is low, hence also the rate of pollution. Ultimate total pollution potential if oxidation does occur is moderate to low. Rate negligible.
					1	0,6	
		1–2	3	0,11–0,25	7	0,16–0,25	
			4	0,36–0,55			
			2	1,05–1,20	2	0,02–1,20	
Run-off C.M.R. 2L/3							
East End	IX	0–0,9 (Bottom)	3	0,16–0,19	3	0,20–0,23	At the same head values as for New Canada, over 75% of the total sulphide has oxidized and leached. *Conclusion*: Remaining pollution potential is low. Pollution rate is very low.
West End		0–0,45 (Bottom)	3	0,18–0,22	2	0,12–0,24	
					1	0,38	
West Klipspruit Vlei							
4 samples drilled over 10,5 km distance	X	0–0,75 (Bottom)	9	0,06–0,16	6	0,01–0,17	A total of 4 holes drilled. At 3 holes, the sulphide and sulphate values are low and therefore the pollution potential is also low. At the other hole, which is adjacent to one of the others, relatively little oxidation or leaching has occurred. *Conclusion*: A pollution potential exists, but the rate of leaching is almost negligible at this hole. (At others, the pollution potential is negligible.)
					2	0,30–0,40	
		0–0,6 (Bottom)	2	0,45–0,60	2	0,63–1,0	
Break-away from S. Roodepoort deposits							
Break-away occurred 1972, 4 holes drilled over 0,5 km	XI	0–0,5 (Bottom)	5	0,12–0,19	5	0,14–0,21	Deposit 11 years old. Low but positive sulphide sulphur persists. Low sulphate sulphur. *Conclusion*: Pollution potential is low, and on an annual basis negligible.
		0,3 (Bottom)	1	0,59	1	0,20	
Wonderfontein Spruit Vlei							
5 holes drilled over 11 km distance							
3 holes	XII	0–1,5 (Bottom)	9	0,04–0,28	6	0,04–0,05	Low positive sulphide. Sulphate virtually completely leached from 6 samples, being moderate in others. Pollution potential is low to negligible.
					3	0,35–0,5	
2 holes		0–0,3 (Bottom)	3	0,67–1,59	3	0,01–0,21	Relatively little sulphide oxidation. Little sulphate present. As the pH of 2 samples was 7, there is little oxidation potential. Humic material may be causing reducing conditions.

* Tables giving pH values and details of individual samples

† Sulphate (here reported as sulphur) has been taken as the difference between the sulphide and the total sulphur reported in Tables III to XII

TABLE XVIII

SIEVE ANALYSES FOR SAMPLES TAKEN FROM SURFACE TO A DEPTH OF 2 m

Site*	Borehole no.	Percentage passing sieve size, mm							
		4,760	2,362	1,190	0,590	0,297	0,147	0,074	0,038
New Van Ryn 5L/14	1		100	99,8	99,0	93,9	72,9	49,3	35,7
	3	100	99,9	99,4	98,6	94,7	78,7	56,3	41,0
Wit. Deep 4L/24	1		100	99,7	99,5	99,4	99,0	88,5	70,2
	3	100	99,7	99,5	99,3	99,1	98,9	92,7	77,4

* The borehole sites are the same as those given in Tables VI and VII

base of the residue deposits. Provided it evaporates there, it does not contaminate streams.

Material Washed off Residue Deposits

Table XVII gives a summary of the sulphur values in the residues that have been washed into vleis or that remain adjacent to the sides of the deposits. The sulphides in the first metre have a sulphur content of 0,26 per cent or lower, and many contain less than 0,1 per cent sulphur. The residuals in the second metre are not much higher, with the exception of 8 samples from vleis. These vlei samples are mainly from the bottoms of the West Klipspruit (i.e. New Canada vlei), Wonderfonteinspruit, and South Roodepoort vlei. It is assumed that the access of oxygen to these parts of the vlei has been both low and slow.

In summary, Table XVII shows that 212 samples have sulphide concentrations amounting to between 0,02 and 0,26 per cent sulphur, and 11 vlei samples have values exceeding 0,35 per cent sulphur. It is evident that the pollution potential of all except the vlei samples has been reduced to between 6 and 30 per cent of the original value in the ore, and most samples in the more leachable first-metre depth are at the lower end of that range. The primary consideration with the 9 vlei samples is that the displaced deposits, particularly in the lower layers, have existed for many years, so that their rate of oxidation and pollution is very low.

No sulphate analyses are available for the results given in Tables XIII to XV. As these deposits are shallow, the values should be low. Of the remainder summarized in Table XVII, 72 samples have sulphate concentrations expressed as sulphur of 0,25 per cent or less, 6 lie between 0,3 and 0,5 per cent, and only 2 have higher values. Therefore, it is evident that most of the sulphate that formed has been leached away, particularly from the upper metre of the deposit. Where there is still an appreciable residue of sulphate, the leaching rate, and hence the pollution rate, must be low.

It is abundantly evident that, not only is the total mass of the remaining sulphide and sulphate that could be released from the sites to pollute low, but the rate at which this is occurring is very low. If this were not true, all the sulphur would have been eliminated from these areas by now.

The sites sampled were chosen from among the worst areas of mine residues on the Witwatersrand in which the most extensive run-off occurs. It therefore follows that, on average, the conditions elsewhere throughout the Witwatersrand Basin should be better.

Although, when fresh and high in pyrite, the sites were major polluting sources, they now give rise to very little pollution. This is confirmed by the presence of vegetation on most of the sites: nothing would grow if active, acid-causing, oxidation conditions were present.

Pyrite Oxidation in the Sand Deposits

Mrost[13] reported that rain water penetrated sand deposits, leaving the surface relatively free of acid, and that the depth to which acid is generated[12] was about 5 m. The limiting factors were the difficulty of air penetration and the large physical volume of air needed for sulphide oxidation. Later in this paper it is shown that, after an interval of more than twenty years, the limit of penetration and oxidation is now about 10 m.

In an undisturbed sand deposit, the pyrite in the upper layers will have oxidized and been removed. Thus, even when rain water percolates deeply, there can be virtually no sulphate leaching. Consequently, the mass of sulphate pollutant now forming is vastly less than when the deposits were being built or had just been abandoned.

That there is still slight oxidation activity is evident in the acid seepage from the bases of sand deposits in the rainy season. It is probable that, along the inclined sides within 10 m of the surface, air and water percolating down oxidize the pyrite residuals. A further contribution may be the oxygen content of the rain water, even although this is very low. These seepages tend to evaporate and concentrate as they reach the deposit edges. Retaining walls have been built round these sites to trap and evaporate the seepage solutions.

An additional factor to be considered relative to sulphate pollution is that the areas covered by sand deposits constitutes only about 15 per cent of the total area covered by residue deposits. In 1967, Clausen[14] gave the areas of residue deposits as 1215, 5670, and 1160 ha respectively for sand deposits, the tops of slime deposits, and the (projected) sides of slime deposits—a total of 80 km^2 of residues. It follows that, although the amount of pollution caused per unit mass of sand deposit is greater than for slime deposits, the mass percentage of the total pollution load from sand dumps is still small. It is interesting that Cook[15] gave the number of sand and slime deposits in 1971 as 95 and 247 respectively.

Presence of Non-oxidizable Sulphide

Several of the deposits listed in Table XVII are thin and do not occur in the form of vleis. The penetration of oxygen and the removal of sulphide should therefore be complete. However, this is not the case. These sites

TABLE XIX
THIN NON-VLEI DEPOSITS

Site	Thickness of deposit m	Sulphide S %	Age years
G.G.M.A.	0,15	0,025	At least 2–3
New Van Ryn 5L/22	0,01–0,02	0,06 and 0,12	At least 2–3
Wit Deep breakout	Up to 0,65	0,06–0,08	11–12
South Roodepoort break-out	0,1–0,15	0,12–0,19	11–12

are listed in Table XIX.

It will have been noted that, whenever sulphide sulphur was determined in the study described here, a positive residual of at least 0,015 per cent was found. As stated earlier, a much higher, apparently inert residual was found in the samples from New Van Ryn (Table VI). It has already been mentioned that the analytical technique used is considered adequate. Mrost and Lloyd[17] reported that oxidation proceeds until the remaining sulphur amounts to about 0,1 per cent. Westwood[16] reported that a residue of approximately 0,2 per cent sulphur in the form of sulphate persisted in a weathered deposit at Government Gold Mining Areas. It is inconceivable that, in all ores, a finite amount of pyrite is completely encapsulated and thus non-oxidizible. The alternative hypothesis is that a small fraction, 0,02 per cent or more, of the sulphur is not present as pyrite or other readily oxidizible sulphide. Mrost and Lloyd[17] reported the presence of small quantities of several other sulphides in 1970.

Contamination of Streams

The data presented so far have related the pyrite (sulphide sulphur) and sulphate residuals in gold-mine residues to their pollution potential, and have shown that the potential is now far lower than when the deposits were fresh.

Another positive approach to the determination of the current pollution hazard involves the assessment of the extent to which the pollution load entering individual streams from the mines is decreasing.

In 1951 the Rand Water Board started routine monitoring of the pollution load entering the Vaal at the Barrage, and in 1972 they increased the number of measuring sites. The component pollution sources at these sites cannot be isolated, and could include the discharges from municipalities, industries, and mines, as well as large balances from dispersed unidentified sources.

To eliminate the difficulty, it was decided that a study should be made of the Wonderfonteinspruit, which is a stream flowing southwards into the Mooi River. So in 1954 the Chamber of Mines undertook an extensive stream survey to determine the pollution loads arising. This stream drained run-off from several mines in the northern sector of its basin, which contained few houses or industries that bypassed effluent-treatment plants. Consequently, the pollution found would have arisen primarily from the mines. The sampling site chosen was just north of the Roodepoort–Randfontein road. At the termination of the survey in 1956, systematic monitoring of the stream ceased until it was started again in September 1977 by the Department of Water Affairs.

The sampling in the Chamber study was made at approximately weekly intervals, and the Department increased the intervals to quarterly. The results obtained in the original survey at approximately three-monthly intervals and since 1977 at about annual intervals are given in Table XX.

Because the pollution load arising from surplus-solution dams at a uranium-extraction plant, an acid plant, and several metallurgical plants was still discharging into the spruit in 1977[18], it is not feasible to isolate the portion of the pollution load arising from mine residues at that time. A second set of results that does not have this complication was therefore examined. These relate to the adjacent Witpoortjie stream, which flows southwards from the East Champ d'Or drainage region into the West Klipspruit. Its basin also has large areas of residue deposits near its northern rim, and in 1972, like Wonderfonteinspruit in 1954, there were few houses or industries to provide effluent that bypassed effluent treatment plants and entered the stream. The monthly data from the Rand Water Board at their sampling site K 14 along the Roodepoort–Randfontein road were converted to a yearly basis and are presented in Table XXI.

Results for Wonderfonteinspruit

In 1954, about 200 ha of slime and 105 ha of sand deposits lay within the rim of the stream basin. By 1963, a further 120 ha of slime had been added and, when the sampling restarted in 1977, the area must have been even greater since two of the mines were still operational. As already stated, it was considered in 1954 that the pollution load in this stream arose essentially from the mines. Contributing to the load at this period was surplus solution loaded with calcium sulphate that was discharged from the metallurgical plants during rainy periods. This practice was supposed to have ceased in 1964, but, as indicated earlier, it actually continued for many years after that time.

Table XX shows the following:

(1) Throughout the sampling period until approximately a year after the uranium plant had closed, the solids were consistently in the range 2400 to 3100 mg/l (with corresponding electrical conductivities, in millisiemens per metre, that were 9,1- to 11,4-fold lower).

(2) By far the major constituent of the pollution load was calcium sulphate.

(3) Owing to rain in the catchment area the flow was approximately three times the normal flow on 4th October, 1955, but the concentration of total dissolved solids did not drop. However, the results could have been influenced by discharge from a metallurgical plant.

(4) It appears from the conductivity data recorded that the concentration of dissolved solids did not decrease significantly until 1985. However, the flowrate decreased from 10- to 20-fold between 1982 and 1985. Consequently, the pollution load also decreased considerably. The fact that the adjacent mines stopped discharging solutions at this time had a major in-

TABLE XX

CHEMICAL ANALYSES OF WONDERFONTEINSPRUIT AT BRIDGE ON ROODEPOORT–RANDFONTEIN ROAD

Date of sampling	pH value	Total dissolved solids mg/l	Electrical conductivity mS/m	Flow-rate m^3/h	Sulphate as SO_4 mg/l	Chloride as Cl mg/l	Calcium as Ca mg/l	Manganese as Mn mg/l	Total dissolved solids t/d	Ratio of total dissolved solids to conductivity
6/1/54	7,3	3079	280		1600	43	595	Not done		11,0
7/4/54	5,0	2647	250		1684	37	596	Not done		10,6
7/7/54	5,1	2278	220		1393	17	499	Trace		10,4
19/10/54	8,6	2651	260		1680	46	685	3		10,2
11/1/55	4,8	2512	220		1663	40	570	11		11,4
5/4/55	5,8	2728	240	*	2125		630			11,4
5/7/55	4,2	2769	250	874	1845		580		58,7	11,1
4/10/55	9,3	3156	300	2916†	2000		690		221,0	10,5
3/1/56	3,5	3010	280	1150	1920		632		83,1	10,8
4/4/56	8,4	2825	260	704	1880		650		47,7	10,8
23/9/77	2,8	2450		V. large						
5/4/78	6,0	3440		V. large	2050					
1/2/79	7,3	3190		120	1850				9,2	
14/5/80	7,5	3060	295	1380	1840				101,3	10,37
26/2/81	6,6	2645	279	140	1560			7,5	8,9	9,48
4/6/81	6,8	3040	318	60	2040			72,0	4,4	9,56
8/12/81	7,3	2415	265	200	1450			10,0	11,6	9,11
17/2/82	6,4		286	150‡	1720			5,4	9,9	9,63∮
23/3/83	8,4		271	80	1600			0,6	5,0§	9,63
3/11/83	7,2		259	60	1600	46	550	1,8	3,6§	9,63
14/8/84	6,7		279	20	1560	47			1,3§	9,63
28/2/85	5,9		233	40	1280	42		7,5	2,2§	9,63
20/8/85	5,6		125	20	468‡	35		3,7	0,6§	9,63
29/11/85	6,4		97		390	32		4,6		

* The normal flow was first measured in 1955 and found to be 700 to 1000 m^3/d

† 12 mm of rain that day

‡ Flows from metallurgical circuits in the northern and western sections of the basin were finally eliminated about 1982[18]

§ Calculated from the data on electrical conductivity

∮ Ratio of 9,63 taken, which is the average of the 1980–1981 ratios

TABLE XXI

ANNUAL CHEMICAL ANALYSES OF WITPOORTJIE STREAM AT RAND WATER BOARD SAMPLING SITE K 14

Year	pH value*	Approximate total dissolved solids† mg/l	Electrical conductivity mS/m	Flow-rate* m^3/h	Sulphate as SO_4 mg/l	Chloride as Cl mg/l	Calcium as Ca mg/l	Manganese as Mn mg/l	Total dissolved solids t/d
Jan 72–Sep 72	3,0	403‡	41	144	313‡	14	39		1,39
Oct 72–Sep 73	3,0	718	99	432	546	13	88	1,2	7,44
Oct 73–Sep 74	3,3	439	73	62	323	9	47	1,1	0,65
Oct 74–Sep 75	3,6	253	48	121	185	6	29	1,0	0,73
Oct 75–Sep 76	3,6	177	32	626	127	5	22	0,8	2,66
Oct 76–Sep 77	3,5	135	32		102	6‡	15	0,6	
Oct 77–Sep 78	3,6	132	32		92	6	22	0,5	
Oct 78–Sep 79	4,0	157	29	168	102	10	20	0,5	0,63
Oct 79–Sep 80	5,0	114	23	450	74	7	13	0,4	1,23
Oct 80–Sep 81	5,2	119	25	355	71	10	14	0,4	1,01
Oct 81–Sep 82	6,0	109	22		59	14	14	0,3	
Oct 82–Sep 83	6,0	225	46		151	30	22	0,7	
Oct 83–Sep 84	4,8	134	23		66	19	15	0,5	
Oct 84–Sep 85	5,1	78	23		60	10	14	0,4	

* Where the flowrate is recorded, the analysis values given are weighted averages; where no flowrate is given, they are arithmetic means. All the pH and conductivity values are arithmetic means

† These values do *not* include silica, which normally amounts to between 5 and 10 mg/l

‡ In these instances, only one value was recorded during the year

fluence, but the drought during this period may have been a contributory factor to the decreased flow. Thus, a final conclusion as to the true reason for the reduction in pollution load cannot be drawn until the rainfall returns to normal. However, it will be surprising if it is not found that there has been a very substantial improvement since the pre-1982 data were obtained.

Results for Witpoortjiespruit

In 1963, the northern part of the basin contained 109 ha of slime and 79 ha of sand deposits. Mining operations had ceased, or would cease shortly after, so the area covered by residue deposits would have been similar to that in 1972, when sampling had commenced. The results in Table XXI show that very little pollution of the stream has occurred, particularly since 1975. As with the Wonderfonteinspruit, most of the dissolved solids consist of calcium sulphate. The low pollution load carried by the stream strongly supports the other evidence presented in this paper that old residue deposits are no longer significant pollution hazards and that oxidation of their pyrite contents has virtually ceased.

Dissolved Solids Reporting at Rand Water Board Monitoring Weirs

Although not completely conclusive, there is strong support for the inference that few pollutants from the sites are entering the Vaal. This is the fact that no diminution in the pollution load has been noted in the past two years[17]. During the past twenty-five years, the Vegetation Unit of the Chamber of Mines and others have built retaining walls and toe paddocks wherever they have operated. In the past two years, a total of 38 residue deposits on the Witwatersrand have had water-retaining walls and toe dams built round them, or existing walls have been completely renovated. Had polluted water previously been flowing from these sites into water courses, the walls and dams would have stopped this. However, no diminution in pollution has been noted in the Vaal system.

Pollution of Ground Water

Rock-waste Deposits

Since the rock in rock-waste deposits emanates from off-reef regions, it contains little pyrite and can be only a minor polluting source. An earlier comment, that oxidation of any pyrite accessible to the air should have occurred in the past and the products should have been removed by now, is equally applicable to rock dumps.

Sand Deposits

Where the ground below the deposit is permeable, there will be some pollution from percolation, but since, as stated earlier, the mass of sulphate pollutant is far less than it was twenty years ago, the amount of ground-water contamination will also be proportionately less.

Old Slime Deposits

Mrost[12] and James[7] found, and the present paper confirms the finding, that sulphide pollution products form in slime deposits to a maximum depth of 2 and 3 m. Tables XVI and XVII show that the pollution potential of the original deposits, in vleis, etc. is now low. Taken together, these facts show that, even if rain water percolates to the base of older, undisturbed deposits, any pollutants transported into the ground water below will be minimal. An exception would be rain water draining from the sides of deposits above the phreatic line, or in recently formed sink holes or cracks. As these sites permit air to penetrate and pyrite to oxidize, polluted water can flow from such regions. However, in relation to the total volume of residues, these sites are small.

In support of the contention that there is little contamination of ground water below a slime deposit, the data given in Table XXII were obtained from the soils of recently removed deposits[17].

TABLE XXII
DATA FROM THE SOILS BELOW RECENTLY REMOVED DEPOSITS

Blyvooruitzicht No. 6 slimes dam

Soil depth m	pH value	Conductivity† mS/m
0–0,12	3,2*	513
0,12–0,4	4,9	438
Below 0,4	6,7	300

Springs Mines 6L/8

Location and depth m	pH value	
	4 samples	1 sample
Surface	5	3
0,15	5	4
0,3	6	5

New State Areas 6L/4

Depth m	pH (water)	Conductivity†
0–0,1	4,1	1485
0,1–0,2	4,3	1340
0,2–0,3	4,9	890
0,3–0,4	5,2	570
0,4–0,5	5,5	430
0,5–0,6	5,8	323
0,6–0,7	5,8	390

* Contains some slime
† Typical soil conductivities do not often exceed 200 mS/m. Plants will grow at 200 to 400 mS/m but under stress

At one or two sites other than those mentioned in Table XXII, the bed formation below the deposit has allowed pollution of the adjacent ground water to occur. The polluting mechanism at these sites is being investigated. A contributory factor could be oxidation in cracks or along the sides of the deposit, as discussed previously. If the bed below is at all permeable in this region, possibly in dolomitic areas, sulphates could percolate into the ground water.

At one site, where the return-water dam—return water is always high in dissolved solids—was at ground level, some seepage occurred. The problem was eliminated when the dam was lined with plastic sheeting.

Although there may be other unknown transportation mechanisms, it is considered that these exceptions do not in any way invalidate the well-substantiated conclusion that the formation of (potentially polluting) sulphate is limited to the layer within the first 2 to 3 m from the surface of a deposit, nor the finding that, in the old Witwatersrand deposits, the major portion of the sulphate has leached away so that the pollution potential is now far less than originally.

Current Slime Deposits

Some of the fresh material in the slime deposits currently being built up will become oxidized and will pollute the process water in contact with it. However, retaining dams are erected round these sites to collect rain water and seepage water, and to prevent the escape of this polluted flow. Should solutions percolate from these retaining dams into the ground, the quantity of percolated solution should be minimal since current residue sites are located on impermeable ground or are equipped with collecting underdrains.

Underground Drainage from Residue Deposits

As already mentioned, the building and repair of many drainage catchment dams have not resulted in any noted diminution of the pollution load entering the Vaal system. Failure to note any change supports the contention that the load entering from either surface or underground flows is not high, although, because of the large area of the system, the connection is tenuous.

Tables XX and XXI show the surface load from dispersed sources to be low, and the mass of pollutants entering any ground water must also be low.

Maintenance of Old Residue Deposits

It was stated earlier that freshly exposed pyrite oxidizes rapidly, and oxidation extends to between 2 and 3 m from the surface in slime deposits, and to greater depths in sand deposits. It follows that the erosion of old surfaces, as well as the exposure of fresh material in other ways, should be avoided. Consequently, the erection of berms and dams to prevent run-off, and the grassing of residue deposits to stabilize their surfaces, will help to minimize future pollution. Tests indicate that significant erosion of the sides of ungrassed slime deposits may be occurring. It is known that this erosion can be substantially reduced if the sides are vegetated.

Analyses of Borehole Cores

Borehole analyses for 4 sand and 7 slime deposits are given in Tables A–I to A–X in the Addendum. This type of information is not normally available and several aspects are discussed below.

Slime Deposits

The slime deposits are widely distributed, one being in the west at Randfontein, one in the central Rand, and five on the East Rand. These five are in two lines running east to west, the one being north of the other. Government Areas and S.A. Lands are taken as constituting the southern line. Of the northern sites, it is to be noted that the sulphur grades at Modderfontein B are exceptionally low. In the central Rand, concentrations at Consolidated Main Reef are reasonably similar to the averages for the Rand, and those at Randfontein are slightly higher.

In general, the grades conform to those given in Table I and to the statement made earlier that the sulphide concentrations of Witwatersrand gold ores are normally in the range of 0,85 to 1,6 per cent sulphur.

Sand Deposits

Two of the sand deposits are situated on the East Rand, one in the central Rand, and the other on the Near West Rand.

A comparison of the sulphur concentrations in the upper layers of the deposits with the values immediately below gives the depth of air penetration and sulphide oxidation. It is evident that the penetration in sand deposits varies appreciably, possibly owing to differing particle and void sizes and to differing ages of exposure. At Government Areas, it is not clear whether air (oxygen) has penetrated almost completely and/or whether most of the head grades were low, possibly because of partial removal of pyrite in a flotation plant, as mentioned by Westwood[16]. At Brakpan Mines, penetration appears to be complete in the shallower holes, and to 18 and 6 m in holes 2 and 4 respectively. At Consolidated Main Reef, oxidation has consistently reached a depth of 5 to 9 m (±4). At Crown Mines 4A/6, penetration has generally occurred to between 5 and 9 m, extending to about 13 m in borehole 4.

A suite of samples taken at an adjacent deposit, No. 3A/8, in 1984 while the deposit was being recycled gave unexpected results[19]. Samples were obtained from just above ground level across the freshly exposed face, which was being removed at a rate of about 10 m per month. The values obtained are shown in Table XXIII.

TABLE XXIII
RESULTS FOR DEPOSIT 3A/8, 1984

Approximate distance from side m	Colour of sample	Total sulphur as S %
Centre (120)	Blue grey	1,93
40	Blue grey	1,11
30	Blue grey	1,87
30	Grey with orange streak	1,66
30	Orange-yellow	0,16
25	Light grey-white	0,13
20	Orange-yellow	0,19
4	Orange-yellow	0,14
Repeat at centre (6 months later)	Blue-grey	1,22

Discussion

Mrost[11] gave a limit of 5 m for the penetration of air—and oxidation of sulphide—in a sand deposit. The data in Tables A–I to A–III indicate that a slightly higher value, of 10 m, would be more appropriate, although, as already stated, a variation in the value because of differing parameters would not be unreasonable. However, the air penetration of about 30 m in deposit 3A/8 is exceptional. The reason for this is unknown.

The analyses of slime deposits show no significantly lowered sulphide values below the 0 to 3 m (or 0 to 4 m) horizon. This fact is in accord with current observations. At S.A. Lands (Table A–VIII) and Randfontein Estates (Table A–X), no near-surface oxidation is evident. This is because the deposits were still in use or had just been abandoned when the sampling was undertaken, in 1975 and 1981 respectively. Consequently, the deposits had high moisture contents, which severely limited the penetration of air. The situation at Geduld could be similar.

The oxidation maxima noted above agree well with the values given from a sampling programme undertaken by Rand Mines in the central Witwatersrand, where the maximum depths were normally 10 m in sand deposits and 3 m in slime residues[20]. In that programme, 13 sand and 30 slime deposits were sampled by drilling.

Conclusions and Summary

The following conclusions can be drawn:

(a) The sulphide in Witwatersrand ores is normally 0,85 to 1,6 per cent.

(b) Residue material displaced into vleis and adjacent to deposits, and in the original deposits, now has sulphide concentrations in the upper metre of from 0,05 to a maximum of 0,25 per cent, and they are not much higher in the next metre. Where the values are higher, little or no leaching is occurring.

(c) The amount of sulphide that oxidizes at present and causes water pollution is very low. The fact that the residuals persist at all in these regions, which are at least ten years old (most of them being over twenty years old), confirms that the current pollution rate, if pollution occurs at all, is low.

The sites and data examined extend across most of the geographical region from which pollutants arising from mine-residue deposits could flow into the Vaal Barrage system. Consequently, the above conclusions are applicable to the Barrage system as a whole, viz that the amount of pollution by dissolved solids arising from mine-residue deposits is now only a small fraction of that when the deposits were fresh.

These results strongly support Funke's contention[2] that pollutants from Witwatersrand mine-residue deposits—and displaced residue deposits—now constitute 2 per cent or less of the pollution load entering the Vaal River system.

In an intensive investigation on pyrite oxidation in residue deposits, Mrost and his co-workers at the Chamber of Mines Research Organization established in the early 1950s that the oxidation products were a considerable source of water pollution. It was found that oxidation did not proceed below a depth of 2 m in slime and about 5 m in sand. The data reported in the present paper on deposits that are at least twenty years old indicates a depth of 2 to 3 m in slime and about 10 m in sand deposits.

There is evidence that at least a part of the sulphide remaining is not pyritic sulphide but a non-oxidizible form. This means that the pollution potential of the small residual remaining in near-surface, oxidizable regions is lower than their analyses suggest.

Little water percolates into the soil below slime deposits, and what does percolate contains practically no pollutants. Water percolates through sand residues, but the pollution arising from old, undisturbed deposits is far less than in earlier years. The fact that grass and other vegetation grow at many sites is proof that oxidation activity and leachable sulphate production are virtually absent.

The study confirms the soundness of the concept of erecting compacted walls round and at the tops of residue deposits to contain and prevent the run-off of water and erosion. Also sound is the practice of vegetating to stabilize the surfaces of deposits.

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Addendum

Sulphur Values of Mine Residue Deposits

TABLE A-I
SAND DEPOSITS, GOVERNMENT GOLD MINING AREAS 5A/10 AND BRAKPAN MINES 5A/2

Government Gold Mining Areas 5A/10					Brakpan Mines 5A/2				
Borehole depth m	Sulphur content, %				Borehole depth m	Sulphur content, %			
	Hole number					Hole number			
	1	2	3	4		1	2	3	4
0–3	0,54	0,21	0,31	0,19	0–3	0,15	0,03	0,14	0,39
3–6	0,48	0,56	0,23	0,18	3–6	0,11	0,11	0,59	0,29
6–9	0,95	0,56	0,16	0,25	6–9	0,17	0,01	1,13	1,30
9–12	0,79	0,38	0,18	0,21	9–12	0,10	0,10	0,15	1,50
12–15	0,63	0,99	0,24	0,31	12–15		0,01		0,48
15–18		0,43	0,16	0,23	15–18		0,01		1,49
18–21		0,39	0,24	0,25	18–21		0,92		1,48
21–24		0,42	0,16	0,22	21–24		0,83		1,76
24–27		0,32	0,26	0,17	24–27		1,17		0,46
27–30		0,17	0,32	0,25	27–30		1,38		
30–33		0,25	0,16	0,27	30–33		0,95		
33–36		0,34	0,32	0,60					
36–39		0,17	0,57	0,64					
39–42		0,50	0,64	1,40					
42–45		0,44	0,50	1,56					
45–48		0,57	0,28	1,55					
Average	0,68	0,42	0,30	0,50	Average	0,13	0,50	0,51	1,02

TABLE A-II
SAND DEPOSIT, CROWN MINES 3A/6

Borehole depth m	Sulphur content, %							
	Hole number							
	1	2	3	4	5	6	7	8
0–4,3	0,10	0,17	0,05	0,05	0,31	0,09	0,09	0,09
4,3–8,8	0,25	0,69	0,12	0,07	0,17	0,07	0,05	0,62
8,8–13,4	1,48	1,37	1,51	0,14	0,86	0,78	0,78	1,40
13,4–18,0	1,60	1,57	1,25	0,91	0,88	Lost	1,26	1,33
18,0–22,6	1,38	1,35	1,09	0,21	0,90	1,27	1,33	1,27
22,6–27,1	1,25	1,16	1,41	0,21	1,39	1,22	1,17	1,24
27,1–31,7	1,21	1,13	1,41	1,32	1,17	1,20	0,91	1,03
31,7–36,3	1,06	1,11	1,47	1,21	1,31	1,32	1,36	1,31
36,3–40,8	1,18	1,16	1,29	1,30	1,43	1,13	1,74	1,36
40,8–45,4	1,11	1,18	1,24	1,25	1,33			1,29
45,4–50,0	1,08	1,23	1,09	1,11	1,58			1,14‡
50,0–54,6	1,15	1,27	0,39	1,06	1,37			
54,6–59,1	1,11	1,18	0,71	1,05	1,20			
59,1–63,7	1,04*	1,15		1,18				
63,6–68,3		1,21		1,15†				
68,3–71,3		1,05						
Average	1,08	1,13	1,01	0,81	1,07	0,91	0,97	1,10
Deposit average	1,03%							

* To 62,2 m
† To 66,8 m
‡ To 46,6 m

TABLE A-III
SAND DEPOSIT, CONSOLIDATED MAIN REEF 3A/1

Borehole depth m	Sulphur content, %							
	Hole number							
	1B	2	3	4	5	6	7	8
0–4,3	0,14	0,30	0,47	0,12	0,14	0,14	0,09	0,17
4,3–8,8	0,09	0,94	2,11	1,58	0,93	0,55	0,87	0,15
8,8–13,4	0,02*	1,73	2,13	1,63	1,51	1,06	1,19	0,14
13,4–18,0		1,52	1,92	1,68	1,32	1,18	0,43	0,41
18,0–22,6		0,96	1,88	1,68	1,12	1,08	0,77	0,91
22,6–27,1		1,45	1,78	1,26	1,20	1,04	0,82	0,95
27,1–31,7		1,38	1,55	1,34	0,96	0,97	0,89	1,03
31,7–36,3		1,47	1,56	1,39	0,72	0,89	0,92	1,15
36,3–40,8		Lost	1,24	1,18	1,05	0,95	0,89	1,13
40,8–45,4		1,31	1,21	0,47	1,19	1,20	0,87	1,03
45,4–50,0		1,24	1,19	1,65	0,99	1,21	0,80	0,58
50,0–54,5		0,25	1,07	0,96	0,65	0,38	0,55	0,83
54,5–59,1		0,49	0,97	0,66	1,19	0,83	0,82	
59,1–63,7		1,48	0,25	1,64	0,90	0,85	0,73	
63,7–68,3		1,27	0,87	0,79	1,01	0,95	0,91	
68,3–72,8		0,86	1,60	1,30	0,93	0,97	0,48	
72,8–78,0		0,80†	1,21	0,98‡			0,15§	
Average	0,09	1,11	1,36	1,20	0,99	0,89	0,74	0,71
Deposit average	0,98							

* To 12,2 m
† To 74,7 m
‡ To 76,2 m
§ To 75,0 m

TABLE A-IV
SLIME DEPOSIT, EAST GEDULD 6L/13

Borehole depth m	Sulphur content, %																	
	Hole number*																	
	1	2	3	4	5	8	9	12	13	16	17	18	19	20	21	22	23	24
0–3	0,37	0,33	0,38	1,28	0,61	0,48	0,67	0,85	0,59	0,63	0,66	0,53	0,64	0,50	0,53	0,54	0,40	0,45
3–6	0,65	0,78	0,89	1,32	0,72	0,61	0,64	0,68	0,73	0,56	0,92	1,03	0,78	0,99	0,76	0,79	0,75	0,61
6–9	0,76	0,70	0,97	1,24	0,67	0,91	0,64	0,72	0,78	0,67	0,82	0,93	0,78	0,76	0,66	0,85	0,61	0,70
9–12	0,71	0,70	1,19	1,01	0,64	0,71	0,71	0,72	0,63	0,72	0,83	0,76	0,75	0,77	0,83	0,87	0,70	0,76
12–15	0,83	0,83	1,32	1,39	0,84	0,83	0,68	1,04	0,85	0,75	0,88	0,83	0,81	1,03	1,20	0,92	0,63	0,66
15–18	0,96	0,92	1,42	1,46	0,92	1,00	0,98	1,10	0,98	0,99	0,80	0,82	0,80	1,04	0,85	0,71	0,96	0,72
18–21	1,19	1,13	1,49	1,65	1,01	0,93	0,97	0,97	0,97	1,04	0,98	0,70		0,95	0,89	0,86	1,16	0,93
21–24	0,40	0,33	2,12	1,23	0,49	1,07		0,96		0,52	1,00			1,12	0,84	0,85	1,01	0,79
24–27						0,99		1,01		0,97	0,36				0,35	0,48	0,45	0,38
27–30						0,43		0,44										
Average	0,76	0,74	1,23	1,33	0,75	0,82	0,76	0,85	0,78	0,75	0,81	0,80	0,76	0,89	0,77	0,76	0,74	0,67

* Hole nos. 6, 7, 10, 11, 14, and 15 were not drilled

TABLE A–V
SLIME DEPOSIT, GEDULD G L/12

Borehole depth m	Sulphur content, %													
	Hole number													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
0–3	0,76	0,82	1,17	1,23	1,07	1,37	0,26	0,69	3,05	1,09	1,44	1,51	1,04	2,21
3–6	1,01	1,29	1,22	1,28	0,82	0,85	0,25	0,96	1,44	1,09	0,85	0,91	0,97	1,04
6–9	0,81	0,77	0,67	0,78	0,78	0,80	0,82	0,82	1,15	0,84	0,82	0,84	0,74	0,86
9–12	0,74	0,69	0,58	0,78	0,69	0,89	0,68	0,86	0,77	0,63	0,79	0,88	0,77	0,85
12–15	1,04	1,02	1,08	0,77	0,86	0,94	1,30	0,75	0,80	0,77	0,34	0,77	0,80	0,92
15–18	0,37	1,03	0,90	0,98	0,90		1,06	0,67	1,02	0,81		0,96	0,93	1,09
18–21			0,75	0,24	0,52			0,76	0,69	0,83				0,87
21–24			0,47							0,26				0,49
Average	0,79	0,93	0,86	0,87	0,81	0,95	0,71	0,79	1,27	0,79	0,85	0,97	0,88	1,04

	15	16	17	18	19	20	21	22	23	24	25	26	27	28
0–3	2,11	0,74	2,69	1,82	1,57	1,77	1,72	1,58	1,22	1,55	1,77	1,73	0,86	1,17
3–6	1,72	0,70	2,47	2,06	1,66	1,50	1,34	1,58	1,89	1,27	1,83	1,76	0,91	0,84
6–9	0,81	0,83	1,66	1,06	1,38	0,78	0,97	0,77	1,21	0,86	1,20	0,96	0,69	0,70
9–12	0,72		0,81	0,15 *0,07	0,78	0,29	0,78	0,92	0,78	0,78	0,92	0,76	0,83	0,81
12–15	0,80		0,95	0,94	0,87		0,74	0,30 0,81	0,76	0,82	0,49	0,88	0,80	0,84
15–18	0,74			0,87	1,58		0,89	1,67	0,89	0,76		0,31	0,36	0,47
18–21	2,07				0,39		0,79	1,27	0,29					
21–24							0,43	1,10						
Average	1,28	0,76	1,70	1,15	1,28	1,09	1,96	1,14	1,01	1,01	1,24	1,07	0,74	0,81

TABLE A–VI
SLIME DEPOSIT, MODDERFONTEIN B 5L/26

Borehole depth m	Sulphur content, %															
	Hole number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0–4,3	0,57	1,06	0,59	0,42	0,65	1,44	0,33	0,46	0,35	0,37	0,38	0,33	0,39	0,24	0,39	0,39
4,3–8,6	0,66	0,54	0,82	0,41	0,85	0,49	0,76	0,48	0,74	0,39	0,32	0,37	0,49	0,41	0,38	0,39
8,6–12,9	0,61	0,80	0,79	0,79	0,51	0,48	0,40	0,40	0,50	0,68	0,36	0,43	0,41	0,40	0,28	0,44
12,9–17,9	0,71	0,96	0,82	0,95	0,63	0,56	0,56	0,67	0,62	0,58	0,54	0,52	0,44	0,40	0,49	0,44
17,9–21,5	0,70	0,90	0,90	0,56	0,63	0,82	0,56	0,75	0,55	0,63	0,64	0,43	0,49	0,50	0,69	0,39
21,5–25,8	0,47	0,61	0,60		0,66	0,76	0,39	0,74	0,88	0,67	0,54	0,70	0,47	0,48	0,50	0,36
25,8–30,1					0,64	0,58		0,37	0,36	0,47	0,32		0,40	0,50		
Average	0,64	0,84	0,73	0,61	0,66	0,73	0,52	0,56	0,56	0,55	0,46	0,42	0,45	0,40	0,42	0,41

TABLE A-VII
SLIME DEPOSIT, GOVERNMENT GOLD MINING AREAS 5L/28

Borehole depth m	Sulphur content, %								
	Hole number								
	1	2	3	4	5	6	7	8	9
0-3	0,42	0,39	0,31	0,75	0,40	0,78	0,42	0,57	0,70
3-6	0,85	0,73	0,60	0,81	0,77	0,93	0,75	0,72	0,53
6- 9	0,97	0,63	0,73	0,51	0,89	0,72	0,79	0,81	0,66
9-12	1,53	1,51	1,18	0,68	0,75	0,77	0,82	0,90	0,85
12-15	1,12	1,09	0,82	1,11	0,72	0,97	0,73	0,91	0,85
15-18	0,43	0,96	0,84	1,06	0,88	1,04	1,09	1,07	0,87
18-21		0,97	0,95		1,31	0,55	1,33	1,10	1,33
21-24			0,36		1,05		1,07	1,25	1,48
24-27							1,33		0,94
Average	0,89	0,89	0,72	0,82	0,85	0,82	0,93	0,91	0,91

TABLE A-VIII
SLIME DEPOSIT, S.A. LANDS 5L/32

Borehole depth m	Sulphur content, %											
	Hole number											
	1	2	3	4	5	6	7	8	9	10	11	12
0-3	1,02	1,13	1,09	1,42	1,36	0,62	1,07	0,79	1,15	1,35	0,84	1,19
3-6	1,15	1,03	1,07	1,23	1,42	1,40	1,38	1,31	1,43	1,28	0,90	1,33
6-9	0,97	1,03	1,10	1,29	1,41	1,10	1,10	1,04	1,38	1,04	1,24	1,21
9-12	1,32	1,08	1,14	1,48	1,46	1,11	1,18	1,07	1,28	0,70	1,24	1,21
12-15	1,27	1,05	0,37	1,31	1,21	1,15	1,30	1,18	1,19	1,18	1,43	1,48
15-18	0,46	0,54		1,31		1,22	0,98	0,71	0,62	0,61	1,37	1,19
18-21											0,75	0,69
Average	1,03	0,98	0,95	1,34	1,37	1,17	1,17	1,02	1,18	1,03	1,11	1,19

TABLE A-IX
SLIME DEPOSIT, CONSOLIDATED MAIN REEF 2L/3

Borehole depth m	Sulphur content*, %							
	Hole number							
	1	2	3	4	5	6	7	8
0-4,27	0,40	0,42	0,84	0,59	0,41	0,68	0,55	0,93
4,27-8,84	1,03	0,94	0,86	1,03	0,70	1,00	1,07	0,98
8,84-13,41	0,73	0,91	1,03	0,91	0,82[†4]	0,86	0,70	1,05
13,41-17,98	1,19	0,63	0,84	1,32		0,91[†5]	0,91	0,87
17,98-22,55	1,22	0,99	1,47	0,93			0,86	0,89
22,55-27,12	1,38[†1]	1,26	1,10	0,93			0,71	0,89
27,12-31,69		0,94[†2]	1,12	1,34			0,73[†6]	0,84
31,69-36,26			0,93[†3]	0,91				0,86[†7]
Average	0,99	0,87	1,02	1,00	0,64	0,86	0,79	0,91
Deposit average	0,89							

* The sulphur values of adjacent deposits 2L/2 and 2L/4 are very similar

† The depths of the holes were as follows:

1 27,12 m 3 34,74 m 5 17,98 m 7 32,60 m
2 31,39 m 4 11,58 m 6 30,17 m

TABLE A-X

SLIME DEPOSIT, RANDFONTEIN ESTATES 1L/39 (ANALYSED 1981)

Average sulphur concentration in boreholes, %					Sulphur concentration in randomly selected boreholes, %				
Gridline no.					Borehole depth m	Hole V*	Hole W*	Hole X*	Hole Y*
1	2	3	4	5					
1,01	1,34	1,57	1,31	0,96	0–1	1,36	0,42	1,25	1,10
2,11	1,14	1,21	1,40	0,64	1–2	1,30	1,23	1,53	0,60
1,74	1,00	1,25	–	0,69	2–3	1,55	1,37	1,40	1,12
1,30	1,06	1,19	–	1,05	3–4	1,53	1,31	1,31	2,58
0,92	1,44	1,20	0,96	0,82	4–5	1,51	2,19	1,00	1,89
1,48	1,01	1,78	1,04	0,96	5–6	1,32	1,86	1,09	0,95
1,28	0,97	1,39	0,90	0,73	6–7	1,37	2,00	1,35	1,35
1,05	1,19	0,97	1,04	1,55	7–8	1,34	1,88	1,39	1,51
1,42	0,87	1,33	1,06		8–9	0,66	1,91	1,38	1,50
1,24	1,19	1,40	–	–	9–10	0,58	1,65	1,29	1,69
1,42	1,66	1,43	–	–	10–11	1,09	1,76	1,38	1,71
1,58	1,25	1,41	–	–	11–12	1,20	1,59	1,73	1,55
1,57					12–13	1,58	1,55	1,82	1,54
1,69					13–14	1,18	1,35	0,30	1,59
2,08					14–15	1,14	1,48	0,36	1,52
Deposit average 1,12%					Average	1,25	1,57	1,34	1,48

* Exact location of holes unknown

Mintek wins premier award

The National Award of the Associated Scientific and Technical Societies of South Africa is the premier South African award for outstanding achievement in the fields of science and engineering. In 1986 this recognition is accorded to the Council for Mineral Technology for its contribution to the understanding and development of the carbon-in-pulp (CIP) process. The Award, in the form of a plaque, was presented at the Resources of Southern Africa II Conference banquet on 13th November, 1986, which was held at the Johannesburg College of Education, St Andrew's Road, Parktown.

The Council for Mineral Technology (Mintek) and the South African gold-mining industry undertook a major research-and-development programme on the development of a CIP process for local ores and tailings that could be operated on a large scale. The successful achievements of this programme included the following:

(a) fundamental studies of the chemistry involved in the adsorption of gold onto carbon and its elution, and in the electrowinning of the gold from the eluate;
(b) an examination of the nature and structure of activated carbon to serve as a sound foundation for the further development of the CIP process;
(c) improved screening of large volumes of fine feed material;
(d) development of novel interstage screening devices;
(e) development of a novel electrowinning cell;
(f) optimization of the thermal reactivation of carbon;
(g) development of specific instrumentation applicable to the CIP process; and
(h) scale-up of the process in nine years from laboratory scale, via several stages of pilot-plant work, to a full-scale operation of 50 000 tons per day.

The reports and papers that were published represent a significant advance on the total knowledge of the process throughout the world, and this has contributed to the overseas reputation of South African research and the concomitant transfer of the technology to industry.

Since the commissioning of the first CIP plant, no conventional plant has been built in South Africa for the recovery of gold from newly mined ore or from tailings. By 1986, this collaborative programme of research and development had led to the construction of more than 20 plants with an annual capacity in excess of 50 million tons. Apart from its lower capital and operating costs, CIP can achieve higher gold recoveries than those attained in the conventional process. A conservative estimate of the average additional gold that can be recovered by the CIP circuits already installed is 1620 kilograms per annum and is worth more than R40 million at present-day gold prices.

It is obvious that, in such a major industry-wide programme, all the scientific and technical contributions could not emanate from one source, and the overall success of the process must be ascribed to the synergistic ongoing collaboration between Mintek and the gold-mining industry.