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Heavy Metal Enrichment in Mine Drainage: II. The Witwatersrand Goldfields

G. T. W. Wittmann
Department of Chemistry, University of Pretoria,
Pretoria 0002, South Africa.

U. Förstner
Laboratorium für Sedimentforschung der Universität Heidelberg,
D-69 Heidelberg, West Germany.

Sediment and water samples from mine drainage were analysed. The pelitic sediment fraction of $< 2\mu m$ *showed the highest enrichment for the toxic metals lead and mercury. Acid mine drainage was established and characterized by low* pH *and high sulphate values.*

Sediment- en watermonsters afkomstig van myndreinasie is ontleed. Die pelitiese sedimentfraksie van $<2\mu m$ *het die grootste verryking vir die toksiese metale lood en kwik getoon. Suur myn-dreinasie is rasgestel en word gekenmerk deur lae* pH*- en hoë sulfaatwaardes.*

Ninety years have elapsed since the discovery of the gold-bearing conglomeritic outcrop, some 5 km to the west of the city of Johannesburg. During the following seven decades the gold-bearing reefs, as they are commonly known, were traced and exploited to depths exceeding 3 km and along a strike of over 480 km. This area is in the form of an arc stretching from Evander in the east to Virginia in the south-west. In accordance with historical discoveries and geological distribution patterns the gold mining areas have also been subdivided into seven major goldfields. Today it is acknowledged that these goldfields are situated along the periphery of the Witwatersrand Basin, the largest known sedimentary repository of gold.[1]

This paper deals with the Witwatersrand proper, a belt approximately 120 km long stretching from Randfontein in the west to Nigel in the east. The Witwatersrand area has been traditionally subdivided into the West Rand, the Central Rand and the East Rand[2], as illustrated in Fig. 1, by means of slimes residue dams, sand dumps, streams, rivers, etc.[2,3,6]

The geology of the Witwatersrand goldfields has been described in many handbooks and papers[1,4,5], to which the interested reader is referred. The most important gold-bearing beds – popularly known as conglomerates, banket or reefs – form a part of the Witwatersrand System, which consists of a thick group of sediments varying in maximum thickness between 7500 and 8000 m. Although exploitation began on the Central Rand and was followed by the West and East Rand, during 1972 more than 40% of all the gold produced by the goldfields within the Witwatersrand Basin was obtained from the Central Rand.[4] The mineral wealth of the Witwatersrand sediments is almost entirely confined to the Upper Division of the Witwatersrand System.[1–7]

The bulk of the auriferous Witwatersrand conglomerate consists of well-rounded pebbles of quartz cemented into a compact matrix consisting principally of recrystallized quartz (70–90% by mass) and accompanied by phyllosilicates (10–30%), which consist chiefly of sericite and pyrophylite intergrown with variable amounts of muscovite and chlorite. Pyrite (FeS_2) is the most abundant sulphide ore mineral occurring in the reefs and may exceed more than 90% (estimated percentage by mass) of the ore minerals present, although a typical value for Witwatersrand banket is approximately 3%. Other sulphides such as pyrrhotite, galena, cobaltite, arsenopyrite and chalcopyrite occur to a lesser degree (1–2%). Similarly, various primary minerals such as uranite and chromite are encountered in varying degrees in the reefs.

Treatment of Witwatersrand ores for gold recovery

The gold-bearing ore encountered in South Africa is always intimately associated with a matrix, therefore crushing and grinding to release the bulk of gold particles from the surrounding gangue, is a prerequisite to the recovery of the precious metal.

Gravity concentration is widely used on Witwatersrand gold circuits and is especially beneficial in the case of high-grade ores. Due to the large difference between the specific gravity of gold (19.3) and that of the gangue (2.6 to 2.75) a high degree of concentration in particle size between 600 and 300 μm is effected. Although ore grades vary considerably from mine to mine, and also within different reefs of a given mine, generally more than 50% of the South African gold mines practise one or more methods of gravity concentration.[6] The early recovery of gold from the circuit has been advocated for several reasons, such as possible theft or loss in the milling circuit, the slow dissolution of larger grains in cyanide solution, and, possibly most important of all, the deleterious effect of overgrinding which results in gold particles becoming tarnished by film-forming constituents rendering them partially refractory to amalgamation or cyanidation.[5,6,8,9]

When exploitation of gold was begun on the Central Rand in 1886, stamp-milling was employed to release the gold particles, which were subsequently extracted by amalgamation. This is conceived as a wetting process which causes the surface of the 'wetted' gold to be drawn in by mercury, due to the low surface tension between native gold and mercury. Although the formation of distinct compounds between gold and mercury is known to take place on a small scale, the process of amalgamation is not as yet well understood.[5,10]

Consumption of mercury in the amalgamation process depends on the size of the gold particles and can fluctuate considerably, from 3 to 12 kg per ton of milled concentrate (i.e. 10 to 40 mg Hg per tonne of milled ore).[6] The amalgam is commonly recovered by hydrocycloning or some other form of gravity processing to effect cleaning. Surplus mercury and moisture are removed by filter pressing and the pressed amalgam is subsequently retorted to drive off the mercury.[5] The vapour is condensed and collected for re-use, whereby losses, estimated at below 0.02 g per milled ton, are incurred.[6] The retorted gold is smelted and cast into moulds to form 31 kg (1 000 oz Troy) ingots or bars of bullion – unrefined gold which assays 88% gold and 9% silver on average.[11]

The hydrometallurgical process of cyanidation was introduced in 1890 to supplement amalgamation, which had dropped to a recovery value of less than 60% when sulphide ores were being encountered at lower mining depths. Once the outcrop became exhausted, i.e. the sulphide-containing ores were no longer depleted as a result of weathering processes (as described in the following section), amalgamation was inhibited by sulphides.[5]

Gold, being the most 'noble' of all metals, cannot be oxidized by dissolved oxygen, nor is it attacked by strong acids and

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Part 1 of this series, on the Rustenburg platinum mining area, was published in Vol. 72, pp. 242–246.

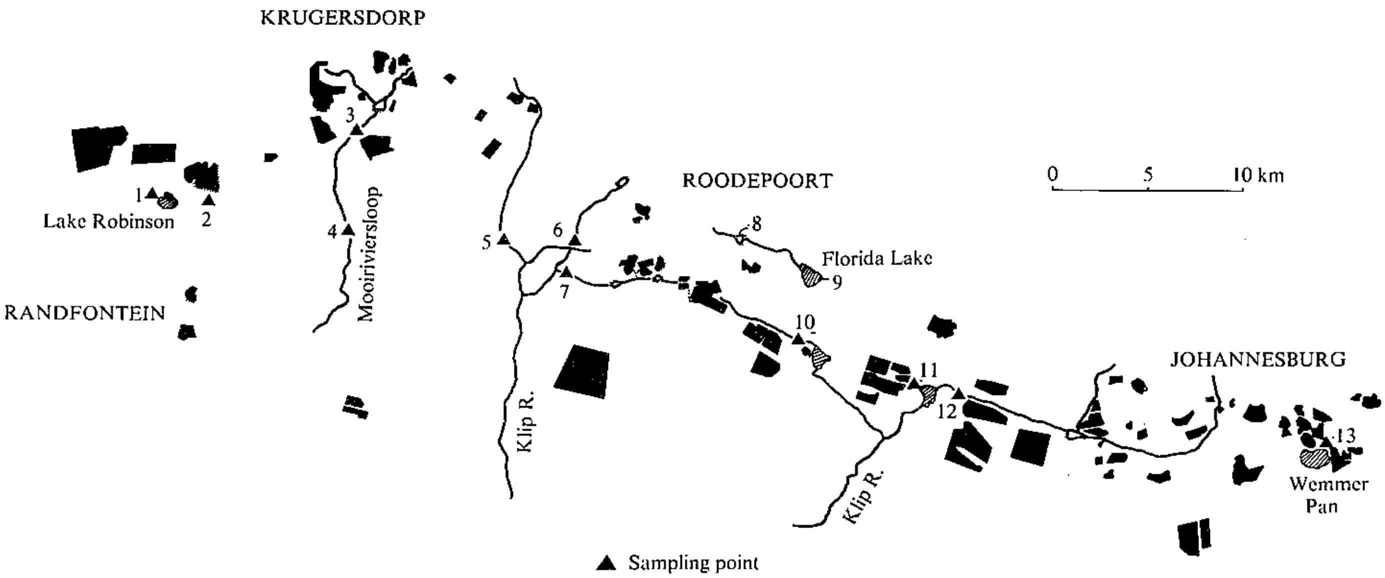


Fig. 1. Map of the Witwatersrand showing the location of mine dumps (solid areas) and sampling points.

alkalis.[12] In the presence of a dilute alkaline solution of cyanide, however, native gold (and silver) is selectively and rapidly oxidized by dissolved oxygen to form the complex $Au(CN)_2^-$ ion, which is stable in aqueous medium. The equation representing the dissolution of gold[5] is usually simply given as:

$$4Au + 8CN^- + O_2 + 2H_2O \longrightarrow 4Au(CN)_2^- + 4OH^-,$$

although it has been concluded[13] that most of the gold dissolves in accordance with the following reaction:

$$2Au + 4CN^- + O_2 + 2H_2O \longrightarrow 2Au(CN)_2^- + H_2O_2 + 2OH^-.$$

The ground ore is agitated in dilute cyanide solution (with a content of approximately 0.025% KCN) and lime is added to provide a protective alkalinity of 0.02% CaO to prevent the loss of cyanide by hydrolysis and the formation of hydrocyanic acid, by acidic constituents of the ore.[5,6] Compressed air is used as a source of oxygen. Generally the common sulphides such as chalcopyrite, arsenopyrite and pyrite are relatively inert in cyanide solution.[5]

Gold (and silver) is precipitated almost invariably by zinc dust from the filtered, pregnant cyanide solution. The addition of 10% lead nitrate solution is thought to enhance the precipitation by forming a zinc-lead couple by a mechanism which is still unclear.[13] Zinc consuption is of the order of 1.5 g per gram of gold, whilst that of lead nitrate is approximately 0.4 g.[6]

Gold slime from the precipitation plant is pumped into wooden acid treatment vats where sulphuric acid is added to dissolve the excess zinc and other impurities. Subsequently, the gold slime is filter-pressed, air-dried and calcined. Smelting of the calcined gold slime leads to the production of gold bullion.

All of the bullion produced in South Africa is treated at a central refinery, the Rand Refinery, at Germiston, which produces the 12.5-kg fine gold bars used mainly for monetary purposes.[6,11]

Although cyanidation was originally introduced to supplement amalgamation, the high degree of extraction efficiency has resulted in the replacement of the latter process on several mines but has offered little scope for the application of flotation methods to the recovery of gold in South Africa. A notable exception is the flotation of pyrite for the production of sulphuric acid, required for the extraction of uraninite.[14] Approximately 43% of the total South African gold output is nevertheless still effected by amalgamation.[6]

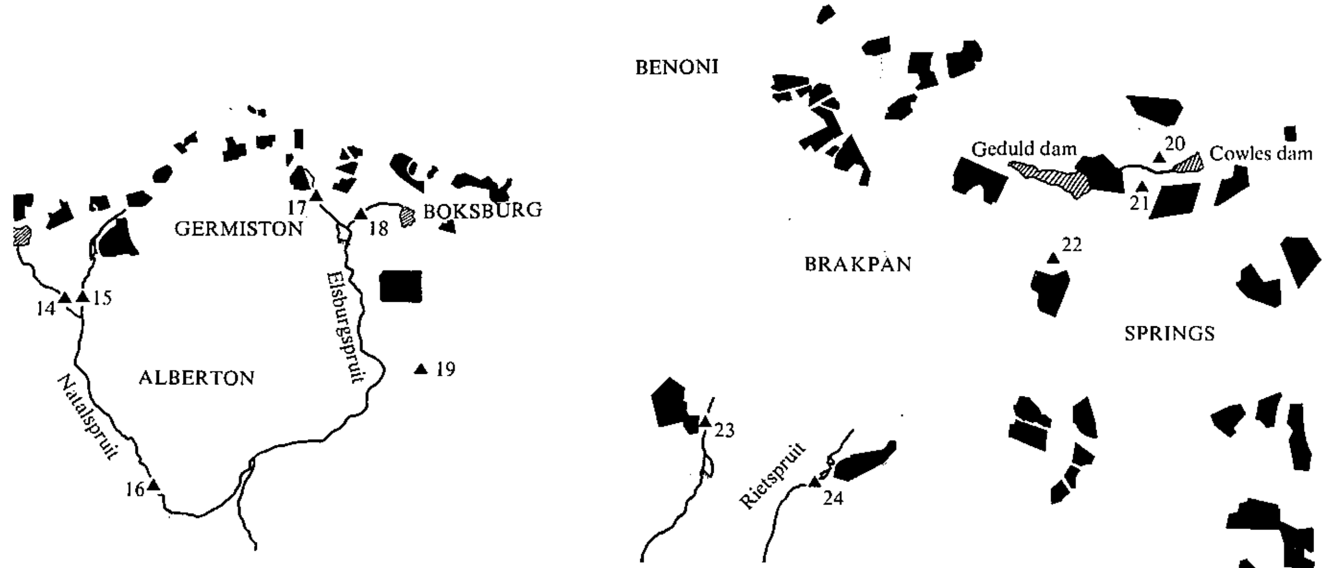
By the end of 1972, a cumulative total of 31 046 625.9 kg gold had been produced from approximately 3 150 000 000 tonnes of auriferous ore milled.[6,15] The main residues from gold-mining operations consist of waste rock, cyanided sand and slimes, and surplus underground water (100 000 t/day).[16] The slimes dams are also used for the disposal of other effluents[17] such as discarded cyanide solutions and sulphuric acid. The disposal of cyanide solution or inadvertent spillage is not regarded as being hazardous due to the low cyanide concentrations (<0.010% KCN) and the rapid decomposition to values below 0.001% within 24–36 h from atmospheric exposure and irradiation by sunlight.[6]

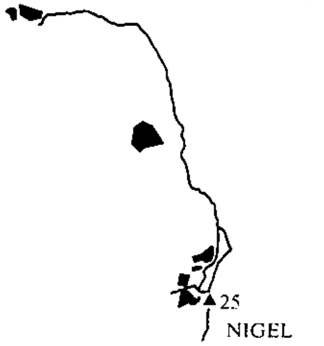
Considerable quantities of water – approximately 100 million m^3/d – originate from the Witwatersrand and are discharged into the streams and rivers which feed the Vaal River.[18]

Ecological problems associated with slimes dams

According to Cook[19], 247 slimes dams and 95 sand heaps are situated between Randfontein and Nigel, some of which are depicted in Figs 2*a* and 2*b*. Apart from their being a source of dust and bleak in appearance, each of these spoil heaps presents an ecological problem to the immediate vicinity and to society at large. The Chamber of Mines Vegetation Unit commenced its voluntary task of combatting air and water pollution during 1960 and has since claimed a considerable degree of success. It would appear that a vegetation cover on defunct sand dumps and slimes dams does solve the dust problem, but our results (see Tables 1 and 2) are not in agreement with either of the following claims: That the problem of preventing pollution of water courses has been successfully overcome[20], and that most slimes dams and sand dumps are still in use, "and being wet, cause little pollution".[19]

Mine drainage not only occurs from the mine itself but also from waste rock dumps and tailings areas. Often the latter two sources contain a high concentration of sulphides and/or sulphosalts which are associated with most ore and coal bodies. The most commonly occurring sulphides are those of iron,





namely the minerals pyrite, pyrrhotite and marcasite.[3]

During coal mining operations pyrite and marcasite are left on the surface after coal has been removed. Exposure to atmospheric oxygen and moisture results in one of the most acidic of all known weathering reactions.[21] The oxidation of FeS_2 and the release of acids into waters draining coal mines had been treated by various authors (see, for example, refs 21–25). Consequently a schematic representation may be compiled without implying exact mechanistic steps:

Initiator reaction:

$$\underset{\text{pyrite}}{FeS_2(s)} + O_2(aq) \longrightarrow Fe^{2+}(aq) + SO^{2-}(aq) + \underset{\text{acidity}}{H^+(aq)} \quad |1|$$

Propagation cycle:

$$Fe^{2+}(aq) + O_2(aq) \xrightarrow{\text{bacteria}} Fe^{3+}(aq) \quad |2|$$

$$Fe^{3+}(aq) + FeS_2(aq) \longrightarrow Fe^{2+}(aq) + SO^{2-}(aq) + \underset{\text{acidity}}{H^+(aq)} \quad |3|$$

The sulphidic component ($S_2^{=}$) in pyrite is oxidized to sulphate (SO_4^{2-}) whereby H^+ is generated and Fe^{2+} ions are released |1|. Once this reaction has been initiated by atmospheric oxidation a cycle is established whereby Fe^{2+} is oxidized to Fe^{3+} |2|; the ferric ion is capable of oxidizing pyrite – thereby taking over the initial role of oxygen – to produce additional Fe^{2+} and acidity |3|. Recently, it has been emphasized[24–26] that bacterial action, for example by *Thiobacillus ferrooxidans,* can assist the oxidation of Fe^{2+} (aq) in the presence of dissolved oxygen.

Whatever the precise details of the above reaction sequence, the oxidation of sulphidic mineral coal mining wastes is now well known and has been revealed as the source of acid mine runoff resulting in ecological problems, due to acidity and the leaching of other base metal sulphides.[25,26]

Similar problems pertain to gold mining operations, since pyrite is the predominant ore mineral in the Witwatersrand reefs – it may exceed 90% of the ore minerals present – whilst pyrrhotite occurs sporadically and marcasite is a very rare constituent.[7] Liebenberg, in discussing the refractory properties of Witwatersrand ores, mentions that "the presence of the sulphate radical (SO_4^{2-}) suggests that the leach solutions consist of dilute sulphuric acid derived from decomposed sulphides."[4] A qualitative spectrographic analysis revealed the presence of the following elements: Au, Ag, B, Cu, Co, Cr, Ti, Fe, U, Th, Pb, Hg, Mn, V, Ni, Zr, Al, Mg, Ca, Ba, Na, K, Li, P and the platinum-group metals: (by the same author) "this analysis shows that a number of mineral constituents, including chromite, zircon, gold and platinum-group metals, that are normally highly refractory to acid attack had been leached *in situ.*"

Similarly, it follows that the degree of ginding has a direct bearing on the recovery of gold: extremely fine particles militate against recovery.[4] Furthermore, the nature of occurrence may convey an extreme degree of refractoriness to the mineral under consideration, as in the case of uranium-bearing thucolite, which is not concentrated by plant processes.[27] Consequently the residue dumps have become enriched with a multitude of mineral ores of potential economic value. However, whilst such minerals have escaped hydro-metallurgical recovery within plant processes, it is evident that *in situ* leaching of slimes dams does occur, wherever sulphidic ores are contained. Whereas pyritic ores of a higher grade have been recovered for the manufacture of sulphuric acid subsequent to the extraction of uranium oxide, since 1952[14], many slimes dams constructed earlier and now covered by vegetation, certainly possess a high pyrite content. On the other hand, the average 3–4% pyrite content characterizes many dams which are in current use.

Bearing in mind that these slimes dams, as earth dams, have not been constructed to prevent completely seepage from taking

Table 1. Analysis of metals in dry mass samples of pelitic sediments (concentrations in mg/kg; Fe as %)

No.	Date	Locality	Cr	Mn	Fe	Co	Ni	Cu	Zn	Cd	Hg	Pb
1	22-02-75	Robinson Lake Pleasure Resort	220	3 520	8.0%	2 500	7 840	1 640	4 720	1.50	0.06	98
2	22-02-75	Furrow from Randfontein Estates G.M.	533	616	10.2	100	167	150	250	0.23	5.44	410
3	09-02-75	Stream from West Rand Consolidated Mines	423	145	7.0	139	345	245	439	0.17	2.16	290
4	22-02-75	Stream from Krugersdorp at Randfontein-Roodepoort Road	638	4 990	7.3	318	949	395	662	0.98	2.05	820
5	09-02-75	Stream from Witpoortjie	548	190	11.5	84	124	158	116	0.09	2.62	165
6	09-02-75	Roodepoort Stream	572	170	8.4	100	160	240	316	0.18	14.84	390
7	09-02-75	Stream from Durban Roodepoort Deep G.M.	461	200	13.4	306	1 944	423	514	0.50	13.24	196
8	09-02-75	Reservoir near Roodepoort-Discovery	780	144	13.0	132	248	140	100	0.10	0.23	65
9	09-02-75	Florida Lake	657	414	9.6	129	278	129	243	0.40	1.20	100
10	09-02-75	Stream from Rand Leases G.M. at Meadowlands Road	464	176	21.3	142	296	364	192	0.18	1.43	125
11	09-02-75	Western inflow to New Canada Dam from Consolidated Main Reef Mines	213	100	20.2	43	65	76	126	0.13	2.00	280
12	09-02-75	Eastern inflow to New Canada Dam on Orlando Road	508	196	11.0	100	110	280	240	0.37	10.16	366
13	11-02-75	Inflow to Wemmerpan from Robinson Deep Ltd.	580	400	10.4	136	288	158	192	0.05	12.45	174
14	11-02-75	Stream from Wemmerpan and Rocherville Dam at Airport Rd.	630	348	7.5	125	215	163	230	0.39	5.71	325
15	11-02-75	Stream from Simmer and Jack Mines Ltd. at Airport Road	522	209	8.8	263	157	148	141	0.07	3.43	148
16	11-02-75	Natalspruit at Alberton-Heidelberg Road	344	600	9.0	220	348	164	564	0.60	3.43	134
17	11-02-75	Western inflow to Elsburg near Germiston-Boksburg Road	596	252	9.3	100	100	164	188	0.07	8.57	240
18	11-02-75	Eastern inflow to Elsburg at Germiston-Boksburg Road	415	185	9.7	138	208	110	163	0.11	12.22	220
19	11-02-75	Stream at Hildamere	344	266	10.6	91	135	81	144	0.10	1.52	216
20	15-03-75	Furrow from Sappi Entra Mill	528	3 000	3.2	96	260	148	444	0.90	4.37	186
21	15-03-75	Furrow from Impala Platinum Refinery	744	220	8.1	130	194	250	188	0.25	3.44	280
22	12-02-75	Inflow to Geduldam from New State Areas Ltd.	640	124	15.0	64	60	184	92	0.07	1.60	165
23	12-02-75	Rietspruit near Van Dyk Consolidated Mines	744	92	13.0	64	78	96	68	0.06	0.69	335
24	12-02-75	Stream from Sally's G.M.	172	104	9.8	24	68	36	60	0.18	1.14	100
25	12-02-75	Outflow from Nigel Dam	564	282	6.5	123	282	182	173	0.04	1.48	378
		Standard shale[30]	90	850	4.7	19	68	45	45	0.30	0.40	20
		Enrichment factor (max. values excluding sample 1)	9	6	4.5	17	28	9	7	3.00	35.00	40

place[28], our results draw attention to the fact that insidious seepage, characterized by high acidity and high concentrations of dissolved metal ions, does presently occur, hitherto largely unnoticed and unchecked. A notable execption is van der Walt *et al.*[29], who found large quantities of dissolved metals in the effluent of one South African gold mine.

Sampling points and sample analysis

The Vaal-Limpopo watershed runs east-west along the Witwatersrand resulting in the gold-mining areas between Randfontein and Nigel being drained by streams and rivers flowing in a southerly direction to emerge as tributaries of the Vaal River (see Fig. 1). The West Rand is drained by the Mooiriviersloop and the western tributary of the Klip River. The eastern tributary of the Klip River accounts for the drainage of the Central Rand situated to the west of Johannesburg, whereas the eastern section contains the rivers Natalspruit and the Elsburgspruit. On the East Rand, this article deals with the Rietspruit, originating near Brakpan, and an unnamed tributary of the Blesbokspruit, as shown in Fig. 1.

The Rand Water Board monitors streams and rivers draining the Witwatersrand proper by means of water analyses for which monthly results are published annually. The latest available report[18] served to identify critical sites for selecting sampling points. However, field reconnaissance led to several additions, whereas flood conditions having prevailed shortly before sampling was undertaken, resulted in omissions having to be made, after we discovered that the fine-grained sediments had been eroded.

Inspection of the map reveals that the majority of samples listed in Tables 1 and 2 were collected from either impoundments, streams or rivers. In a few instances samples were collected from furrows. A representative sediment grab sample was taken from Lake Robinson some distance from the

Table 2. Hydrochemistry of effluents from mining wastes

Sample	pH	Cl^-	SO_4^{2-}	Na	Mg	Ca	Mn	Fe	Cr	Co	Ni	Cu	Zn	Cd	Pb	Hg
2	7.5	66	2 520	370	112	423	0.54	0.1	–	–	340	20	20	0.1	–	
3	7.1	147	2 300	77	40	575	0.40	–	–	2 400	11 600	6 720	2 620	2.6	–	
4	3.7	47	2 950	53	106	530	18.10	3.0	20	2 250	1 540	1 220	4 680	7.0	81	<0.1
5	3.3	2 355	275	7	4	68	0.6	1.0	1	120	400	150	700	0.7	140	
6	8.1	26	80	13	5	14	0.04	–	1	–	–	20	–	0.1	–	
7	3.9	86	1 330	84	102	510	13.80	1.0	5	2 444	9 300	540	3 800	5.2	8	<0.1
8.	7.5	15	67	28	3	10	–	–	1	–	–	20	–	0.1	–	
9	7.4	14	57	49	4	13	–	–	1	–	–	20	–	–	–	
10	3.1	46	1 600	47	54	246	14.6	16.0	18	650	2 560	180	1 220	0.7	27	1.6
11	3.4	64	870	41	35	57	2.8	3.0	1	320	880	60	620	0.3	5	
12	3.8	47	490	24	24	64	3.6	10.0	1	320	880	80	1 100	0.8	5	
13	3.0	5 595	3 200	150	205	340	97.1	128.0	22	2 580	6 800	200	5 500	1.3	38	0.4
14	3.4	68	1 235	43	63	136	14.2	50.0	8	1 340	2 360	200	2 680	2.2	78	
15	3.5	196	1 735	77	104	246	35.2	10.0	5	1 340	1 480	120	1 450	0.45	57	
16	3.2	393	1 995	190	115	250	9.6	128.0	9	1 800	2 920	60	4 050	0.30	51	0.1
17	7.3	189	450	125	21	72	–	–	–	60	110	20	100	0.15	–	
18	3.0	152	4 500	142	270	348	40.6	124.0	72	2 610	15 900	540	13 200	6.10	32	0.1
19	4.3	82	775	64	50	138	4.0	1.0	1	270	1 520	40	500	0.80	8	
20	7.5	205	515	580	23	72	1.3	1.7	–	–	240	24	100	0.90	–	
21	2.8	176	2 800	171	140	308	24.8	62.0	87	1 820	11 500	1 000	10 300	9.0	5	0.1
22	3.0	24	1 345	36	63	200	7.8	11.0	80	1 550	3 650	620	2 900	1.35	5	
23	6.3	82	465	57	33	57	11.8	–	1	200	360	20	180	0.15	–	
24	7.5	17	1 900	172	240	185	7.0	–	1	60	110	–	–	0.05	5	
25	4.0	57	340	36	19	52	4.4	–	–	270	1 920	60	1 150	0.20	–	
River water[31]		8	11	6	4	15	0.007	0.1	1	0.2	1	3	10	0.1	0.5	0.05
Enrichment (max)		700	440	100	71	40	15 000	1100	87	11 000	16 000	2 200	1 300	61	300	30

The major ions, Fe and Mn are given as mg/1, and trace metals in µg/1.

shore, access having been gained by way of a jetty leading to the structure of an earlier diving tower (sample 1). Surface sediment and water sample 2 originated from a furrow from the nearby slimes dam, whereas samples 3 and 4 were collected from deposits in streams which drained the Krugersdorp mining area and fed the Mooiriviersloop.

Sediment samples 5–7 were gathered from streams and rivers which drained the Krugersdorp-Roodepoort mining area and fed the western tributary of the Klip River, whilst samples 8–12 came from impoundments and streams which fed the eastern tributary of the same river. Similarly, samples 13–16 were collected from the Natalspruit and its feeder streams.

Samples 17–25 were taken from the rivers of the East Rand and their feeder streams; furrows were more appropriate for collecting samples in two cases (samples 20 and 21).

All surface sediment samples (at least 1 kg of fine-grained, clayey material to ensure representative sampling) were collected by means of a stainless steel trowel and transferred directly to polythene containers. Water samples 2–25 were collected at the corresponding sediment sampling points.

The heavy metal content of the sediment samples was determined after separation of the pelitic fraction of $< 2\mu m$ and chemical dissolution as described in an earlier paper. Subsequently, both sediment and water samples were analysed by means of atomic absorption spectroscopy, whereas standard methods were employed for the determination of major ions.[17]

These investigations were intended to monitor potentially toxic metals being discharged into the environment following the disposal of mining wastes. Since the slimes retention dams do not only receive the gangue but also serve to retain other mining wastes, it is impossible to distinguish between effluents resulting from modern, controlled hydrometallurgical processes and the effects of acid leaching processes taking place unchecked outside the production plant. Although considerable quantities of water originating from the Witwatersrand goldfields result in a dilution of mining effluents and an increase in pH values – favouring the precipitation of heavy metal compounds – such effects are subject to local and seasonal fluctuations.

The pelitic sediments from the Witwatersrand goldfields were characterized by means of X-ray diffraction clay mineral analysis; the results are listed in Table 3. The fine-grained fraction of $< 2\mu m$ contains the clay minerals illite, kaolinite, chlorite, smectite and a characteristic pyrophyllite component. The chemical analysis of sediments (dry mass samples) are listed in Table 1. A comparison with the average shale composition derived from argillaceous rocks for a large number of uncontaiminated samples[17,30] led to the following conclusions: Discarding the results for Lake Robinson – which shall be treated separately – the maximum mercury and lead values revealed the most significant enrichment factors, of approximately 35–40. In other words, the amalgamation of gold and the addition of $Pb(NO_3)_2$ in the cyanide process, a procedure followed for the past 80 years or so, has had a profound influence on the heavy metal enrichment of the pelitic sediment fraction of $< 2\mu m$. Disregarding the maximum enrichment of nickel (sample 8), the elements chromium, copper, cobalt and nickel had elevated levels which exceeded the standard values by a factor of 10–15. Since none of these elements (nor their compounds) are employed in the hydrometallurgical recovery and refining of gold (or uranium), these relatively high values must be ascribed to the presence of chromite, which is widely distributed in the Witwatersrand reefs; chalcopyrite is intimately associated with gold; cobaltite is distributed in patches and pentlandite has a rare occurrence.[7]

On the other hand, the concentrations of zinc and manganese often exceeded a 5-fold enrichment factor. It would appear that the zinc values are attributable to losses associated with the zinc-

Table 3. Relative proportions of clay minerals in sediments from gold mining wastes

Sample No.	Illite	Kaolinite	Chlorite	Pyrophyllite	Smectite
1	Gypsum				
2	XX	XX	–	XXX	–
3	XX	X	–	XX	–
4	XX	XX	–	XXX	–
5	XX	XX	–	XX	(X)
6	XX	X	–	XX	–
7	XX	X	X	X	(X)
8	XX	XXXX	–	X	(X)
9	XX	XXX	X	–	–
10	X	X	–	–	(X)
11	XX	–	–	X	–
12	XXXX	X	X	–	–
13	XXX	XXX	XX	–	–
14	XXX	X	XX	–	–
15	XXX	(X)	XX	(X)	–
16	XX	–	(X)	–	XXXX
17	XXX	–	XX	–	–
18	XXX	X	X	X	–
19	XXX	(X)	XX	X	–
20	XXXX	–	X	–	–
22	XXXX	–	X	–	–
23	XXXXX	–	X	–	–
24	XXX	–	–	–	–
25	XXXX	–	XXX	–	–

The more crosses the greater the proportion of mineral.

dust reduction process described earlier, whilst manganese losses may be attributed to the recovery of uranium ores.[14]

The high iron values are generally attributed to the iron mineralization commonly encountered in South African ores and which is notable in the Witwatersrand ores.[7]

Table 2 reveals that the mining effluents exhibited extremely low *p*H values, typical of acid mine drainage, and also contained characteristically high sulphate concentrations. The contents of dissolved manganese, iron, cobalt, nickel, copper and zinc exceeded the normal surface water values[31] by a factor >1000 for each individual metal in the case of maximum values. Enrichment of dissolved chromium, cadmium and lead was less widespread but, nevertheless, the respective values were alarmingly high in several of the investigated samples.

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