Hydrogeology, Mineralogy, and Chemical Fractionation of Mine Wastes Associated with Gold Mines: A Case Study from the Sabie Goldfield, South Africa

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***Abstract*—**The Sabie Goldfield is an important goldfield in South Africa. Comparative hydrogeological, mineralogical, and chemical fractionation associated with the mine tailings of this goldfield are discussed in this paper. Two main tmine tailings storage facilities were considered in this study, namely, Nestor and Glynns Lydenburg. Eroded tailings and seepage samples were collected from the Nestor Mine tailings storage facility. In addition sediments eroded from the Glynns Lydenburg MTSF were also considered. Hydrochemical results showed the variation in the drainage from the two different mines in the Sabie goldfield, namely, Nestor and Glynns Lydenburg Mines. Following the development of the dammed tailings pond, the secondary minerals were dissolved, producing acidic waters contaminated by Al (339.6 mg/L), Cu (111.3 mg/L), Mn (11.4 mg/L) and Zn (25.2 mg/L). Therefore, the potential use of recycled water from the Nestor MTSF is diminished by the presence of corrosive ions like Fe and Cl^- in highly acidic fluids that promote corrosion of pipes and pumps in the water recycling system. The acid producing minerals such as pyrite and ferricopiapite are present in the mine wastes of Nestor MTSF compared to acid neutralizing mineral dolomite present in the Glynns Lydenburg MTSF. Chemical fractionation patterns of the potentially toxic elements showed that the geochemical behavior of metals is primarily controlled by the mineralogical composition of the mine wastes. Potentially toxic elements such as As, Al, Cd, Fe, Mg, Mn, U, V, and Zn are readily released into water soluble fraction from the Nestor MTSF. In the Glynns Lydenburg MTSF, the potentially toxic elements, are principally adsorbed or co-precipitated with amorphous and crystalline Fe oxides, but they may also be associated with oxidizing of primary sulphides and residual fractions. Further detailed studies should focus on the fractionation of metal species along the Sabie River system.

***Keywords*—**chemical fractionation, mine tailings storage facilities, Sabie Goldfield, potentially toxic elements

I. Introduction

Together with the Pilgrim's Rest Goldfield, the Sabie Goldfield had produced nearly 185 Mt of ore at a typical grade of approximately 8 g/t by 1988 as estimated by [1]. The ore in the discordant reefs is a mix of gold-quartz-sulphide mineralization that has settled on various host rocks [2]. Mine tailings storage facilities (MTSFs) of various ages are the most visible land features in the Sabie Goldfield, specifically the Nestor and Glynns Lydenburg. These MTSFs are the potential sources of environmental degradation through various mechanisms such as dust pollution, acid mine drainage and soil contamination.

Geochemical characterization and predictive modelling are important in the management of mine wastes like tailings and waste rock. Several studies were carried out worldwide to determine the acid potential or neutralization of mine waste using static acid base accounting (ABA) tests (e.g. [3], [4], including the Sabie Goldfield [5]. However, ABA alone is insufficient to provide enough input data for predictive modelling. Predictive modeling must be supported by more detailed geochemical characterization, which includes determining the nature of sulphide mineral oxidation, mineralogy, acid consumption type and extent, gas transport mechanisms, water transport, and balance.

The present paper focuses on the assessment of hydrochemistry, mineralogy as well as chemical fractionation of mine wastes from the Sabie Goldfield.

II. Materials and Methods

A. Site description

The Sabie Goldfield is located in the Mpumalanga Province, South Africa and it is characterized of gold mine tailings storage facilities from abandoned mines (Fig. 1).

There are various rocks of different ages ranging from Swazian to the Quaternary. The main lithological units in the study area are the Black Reef Formation that hosts the Nestor MTSF and the Oaktree Formation of the Malmani Subgroup (part of Chuniespoort Group) that hosts the Glynns Lydenburg MTSF, which all belong to the Transvaal Supergroup ([6].

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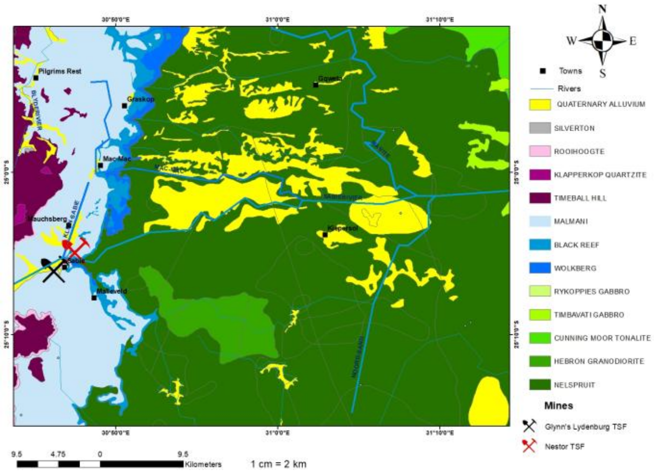

Fig. 1: Location of the Sabie Goldfield

B. Sampling and Analyses

The seepage accumulated on the paddocks of the Nestor MTSF was collected and it was traced downstream towards the Klein Sabie River wherein another sample was collected. Standard sampling procedures were followed ([7] and physicochemical parameters such as pH, electrical conductivity (EC), oxidation-reduction potential (Eh), dissolved oxygen (DO), and temperature were measured onsite. Samples were analyzed for metals and anions using ICP-MS and IC. The element concentrations were compared to the South African [8] water quality guidelines and the [9] World Health Organization.

Five solid mine waste samples were collected from the eroded tailings. The samples were collected near the MTSF (NT01 and NT02), traced downstream under the Klein Sabie Bridge (NT03). Furthermore, two samples from the nearby Glynns Lydenburg MTSF (GT01 and GT02) were also assessed. X-ray diffraction (XRF) was used to determine the mineralogy of solid samples. A four-stage sequential chemical extraction was carried out in order to define the distribution of metal species in various geochemical portions of tailings and sediments from the mine wastes following procedures described by [10]. Sampling was carried out during the dry season/winter of 2021 (July-August).

III. Results and Discussion

This study focused on determination of the quality of seepages, mineralogy and chemical speciation of mine wastes emanating from the abandoned MTSF in the Sabie Goldfield.

A. Quality of seepages from the Nestor MTSF

Table I presents field parameters in seepage samples from the Nestor MTSF. The pH of the samples ranges between 2.34 and 3.11 and seepages also have high redox potential (221.5-253.1 mV), low dissolved oxygen and elevated dissolved solids as indicated by high EC values (up to 24500 µS/cm). Therefore, pH and EC values are above the recommended guidelines [8] and [9].

TABLE I Values of Field Parameters in Seepage Samples

Sample ID	pH	Eh (mV)	EC (µS/cm)	DO (mg/L)
NS01	2,34	253,1	24500	5,99
NS03	3,11	221,5	1058	3,2
SANS241 (2015)	≥5≤9.7	N/A	1700	N/A
WHO (2011)	5.5	N/A	N/A	N/A

The dominant cations in seepage samples are Ca and Mg respectively while Cl and SO_4 are the dominant anions (Table II). With the exception of SO_4, all cations and anions occurs below the recommended guidelines [8] and [9].

TABLE II Major Cations and Anions in Seepage Samples

Sample ID	Ca (mg/L)	Mg (mg/L)	Cl (mg/L)	SO_4 (mg/L)
NT01	61,2	7,66	47,3	6350
NT03	7,86	2,16	35,2	2970
SANS241 (2015)	≤150	≤70	≤300	≤500
WHO (2011)	≤200	≤50	≤250	N/A

In the seepage samples, the concentrations of selected potentially toxic elements indicate a considerable variation (Table III). All recorded values occurs above the recommended values by [8] and [9], except Cu.

TABLE III Trace Metals Concentration in the Seepage Samples from Sabie Goldfield

Sample ID	Al (mg/L)	As (mg/L)	Cu (Mg/L)	Fe mg/L)	Mn (mg/L)	Zn (mg/L)
NT01	393,6	26,8	74,94	4964,1	25,82	15,47
NT03	51,38	10,8	0,19	15,11	11,4	0,17
SANS241 (2015)	≤300	≤0.01	≤2	≤2	≤0.4	≤2
WHO (2011)	N/A	≤0.01	≤2	N/A	≤0.4	≤0.05

Based on the geochemical modelling using PHREEQC software, the majority of cations in the seepages from the Nestor MTSF, specifically Ca, Mg, Fe, and Cu, were predicted to precipitate as sulfates [11].

B. Mineralogy of mine wastes

There is huge variation in terms of mineralogical composition of the mine waste from the Sabie goldfield. Both primary and secondary phases of minerals have been identified. Table IV displays the semi-qualitative mineralogical composition of gold mine wastes expressed in weight percentage (wt. %). In all samples, quartz is the dominant primary mineral (52-93 wt. %). However, the primary acid-producing mineral pyrite is also present in the samples from the Nestor MTSF. The secondary Fe minerals identified in the Nestor MTSF are ferricopiapite (up to 71 wt. %), copiapite (1-5 wt. %) and jarosite (up to 4 wt. %), which

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are known to occur in acid mine drainage through the oxidation of primary sulfide minerals (mainly pyrite) as supported by the presence of gibbsite (7 wt. %). The precipitates of Fe plays a fundamental role in AMD water quality as they control the concentrations of Fe, sulfate, and other pollutants [12] as well as the quantity of acidity likely to be produced [13]. This implies that the tailings from the Nestor MTSF are potentially acid-producing and might have a negative impact on the surrounding ecosystem, specifically the Sabie River system. The dissolution of soluble secondary mineral phases that are formed at the dry Nestor MTSF is responsible for the development of highly contaminated seepage over a short periods of time, especially during wet season (summer). This is supported by low pH, high metal concentrations, as well as elevated sulfate concentrations recorded in the vicinity of the MTSF (Table I-III).

In the Glynns Lydenburg MTSF, dolomite is the second dominant primary mineral (>20 wt. %) followed by mica (9 wt. %) and no pyrite was detected. Furthermore, the secondary minerals identified include hexahydrite, (32 Wt. %), goethite (3 wt. %), and gypsum (up to 14 wt. %), which are absent in the Nestor MTSF samples. Therefore, the tailings from Glynns Lydenburg MTSF has a higher acid-neutralizing potential as they have carbonate mineral dolomite.

TABLE IV MINERALOGY OF MINE WASTES FROM SABIE GOLDFIELD

Sample ID	Dol	Qua	Mc	Py	Fec	Got	Gib	Gyp	Hex	Jar
NT01	ND	84	6	2	71	ND	ND	ND	ND	4
NT02	ND	93	7	1	ND	ND	ND	ND	ND	1
NT03	ND	58	5	3	ND	ND	7	ND	ND	3
GT01	20	32	9	ND	ND	2	ND	14	32	ND
GT02	28	52	9	ND	ND	3	ND	5	ND	ND

Abbreviations: Dol: dolomite, Qua: quartz, Mc: Mica, Py: pyrite, Fec: ferricopiapite, Got: goethite, Gib: gibbsite, Gyp: Gypsum, Hex: hexahydrite, Ja: jarosite.

C. Speciation of metals in mine wastes

All metal species in the sample collected from the Nestor MTSF (NT01) are found to be highly partitioned to the exchangeable fraction (F 1) of the tailings material while samples collected downstream of the MTSF have metal species partitioned on the inert fraction (Table V; Fig. 2). This suggests that the metal species in the NT01 are readily available and are potential contaminants to the surrounding environment. Furthermore, metals species found in NT02 and NT03 are geogenic in nature. The mobility and bioavailability of metal species extracted from the investigated tailings samples decreased in the following order: Fe>Al>As>Mn>Ca>Mg>V>U>Cd. Mn is released and bioavailable from the exchangeable, residual, oxidizable, and reducible fractions. As a result, Mn concentrations can have a negative impact on the ecosystem.

All metal species are partitioned on the fourth fraction in the Glynns Lydenburg MTSF. However, elevated Mn partitioning on the fourth fraction at sample site GT01 can be attributed to the dolomitic nature of the tailings stored in that facility. This is unimportant because significant concentrations of Mn, like dolomite, can co-precipitate with the carbonates in the MTSF. The mobility and bioavailability of metal species decreased in the order Fe>Al>As>Mn>Ca>Mg>Zn>V>U>Cd in the study samples from the Glynns Lydenburg MTSF (Table V; Fig. 2).

TABLE V SPECIATION OF ELEMENTS IN MINE WASTES OF THE SABIE GOLDFIELD

Sample ID	**Fraction**	**Concentration (mg/L)**					
		Ca	**Mg**	**U**	**V**	**Cd**	**Zn**
NT01	F1	349	9,3	0,84	5,06	0,02	77
	F2	0	0,06	0	0,06	0	0.0
	F3	1,85	0,1	0	0,04	0	0.2
	F4	2,38	0,31	0,02	0,18	0	18
NT02	F1	7,6	0,44	0,02	0	0	0.2
	F2	0	0	0	0,34	0	0.0
	F3	2,33	0,77	0,02	0,92	0	1.4
	F4	3,39	4,85	0,14	11,38	0	62
NT03	F1	456	3,79	0,1	0	0	1.5
	F2	1,88	0,2	0	0,34	0	1.4
	F3	3,82	0,24	0,1	2,66	0	1.5
	F4	4,22	11,25	0,28	18,12	0	64
GT01	F1	9956	663,53	0,02	0	0	10
	F2	122	50,88	0	0,84	0,02	2.0
	F3	61,8	0	0,02	1,52	0	5.3
	F4	7,11	6,1	0,12	11,84	0	89
GT02	F1	901	9,27	0	0,02	0,02	4.1
	F2	6,45	1,06	0	1,04	0	1.3
	F3	4,72	0,77	0,06	2,36	0	1.8
	F4	12,3	33,94	0,12	9,74	0	58

In addition to Fe, which is present in all four fractions except NT01 (F3), the majority of Al occurrences in mine wastes are concentrated in the first and fourth fractions, i.e., the fractions containing exchangeable metals and the residual fraction. This suggests that the Al and Fe in mine wastes are not very bioavailable (4th fraction) and will only be released when the ionic composition changes (1st fraction). Furthermore, Cd is present in all mine wastes samples (NT01, GT01 and GT02). Total Zn, U, As, and V were highly partitioned in residual fraction in the Glynns Lydenburg MTSF. This suggests that these metal species have low mobility and availability from the MTSF to the surrounding environment.

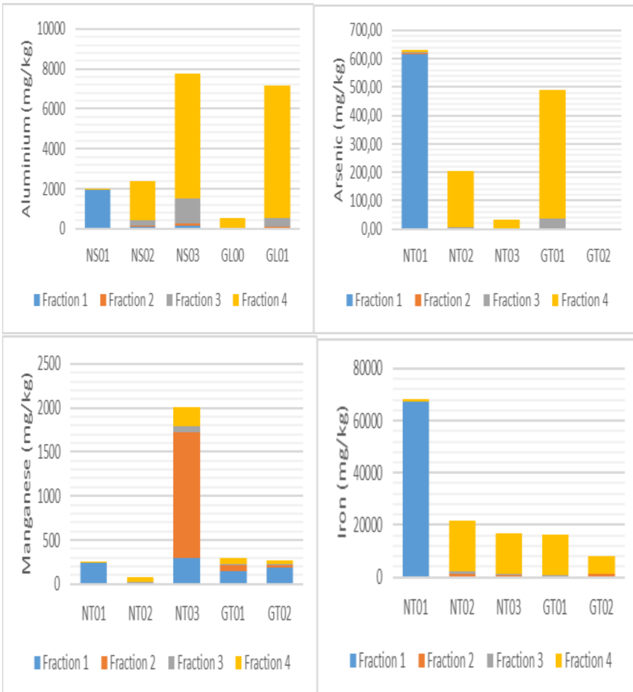

Fig. 2: Concentration of metal species in different fractions of mine wastes

IV. Conclusion

The seepage from the Nestor MTSF is typical mine water (low pH/acidic, high redox potential, elevated concentration of metal species and sulphate). There is huge variation in terms of mineralogy in the mine wastes of the Sabie Goldfield. Acid generating minerals are present in the Nestor MTSF while acid neutralizing minerals are present in the Glynns Lydenburg mine wastes. Majority of metal species are portioned on exchangeable fraction in the Nestor MTSF as well as in the crystalline structure (inert fraction) in mine tailings of the Glynns Lydenburg, with the exception of Mn.

Recommendations

- Rehabilitation of the Nestor MTSF as it pose threat to the nearby water resources, specifically the Sabie River system.

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