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The Recovery of Pgms from the UG2 Silicate Stream by Fine Grinding and Froth Flotation

Duncan Goqwane[1], Willie Nheta[1], Derek Hugh Rose[1,2]
[1]Mineral Processing and Technology Research Centre, Department of Metallurgy, University of Johannesburg, Doornfontein Campus, P.O Box 17911, Johannesburg, 2028, South Africa.
[2]Mineralogy Division, MINTEK,200 Mailbongwe Drive, Randburg, 2125, South Africa.
duncanjrgoqwane@gmail.com; wnheta@uj.ac.za, derekR@mintek.co.za

Abstract **–** The Bushveld Igneous Complex (BIC) hosts the largest reserves of Platinum Group Metals (PGMs) in the world with most of the Platinum Group Element (PGE) mineralization occurring within the Merensky Reef, UG2, Platreef and Middle Group Chromitites reef. This research sought to investigate the PGMs locked in the silicates of the UG2 ore from the Eastern Limb. As most of the PGMs are locked in the silicate stream, these are disposed in the tailing dams. The silicate stream was characterized using the XRF, XRD, SEM and fire assaying through nickel sulphide collection. 1kg of the sample was milled in the rod mill to 80% passing 53 µm and floated in a D12 Denver flotation cell to recover the PGMs from the silicate stream based on Response Surface Methodology. It was found that the major mineral phases in the silicate stream were quartz, sphalerite, pyrrhotite, chalcopyrite and chromites. The size of the sulphide mineral that hosted the PGMs in the silicate was 20 µm. The highest concentrate grade obtained after flotation was 19.19 g/t of Pt. The as-received sample also had 0.95 g/t of Au which was recovered.

Keywords**:** Fine grinding, PGMs, collector, depressant, frother, flotation, silicate, Upper Group 2

1. Introduction

The Bushveld Complex (BC) in its entirely consists of the Rooiberg Suite, the Lebowa Granite Suite and the Rustenburg Layered Suite. The most economically important rocks of the BC are the Rustenburg Layered Suite that contains the Platinum Group elements (PGE) mineralization [1]. Platinum and palladium are the most abundant PGEs found in the BC. They usually occur in a form of mineral phases with elements such as sulphur, tellurium, bismuth arsenic, and iron. These minerals are associated with base metal sulphide (BMS) minerals, which occur along the grain boundaries [2]. However, there is a need of liberating platinum group minerals (PGMs) from the host matrix of the associated minerals in the UG2 such as the silicate matrix because it leads to poor recovery of PGMs. Most of the silicate gangue mineralogy that makes up the UG2 ore in the Eastern Limb consists of orthopyroxene, plagioclase feldspar, and clinopyroxene [3]. There is also the presence of Chromite, which makes up 60–90% of the UG2 ore and predominates over silicate minerals including orthopyroxene (5–25%) and plagioclase (1–10%). Less than 0.1% of the reef by mass is made up of BMS, with chalcopyrite, pentlandite, and pyrrhotite being the most prevalent [4]. PGMs are detected in the chromite matrix, and they are locked in the silicates.

The Mill– float– mill – float (MF2) circuit, which is the foundation of the majority of UG2 concentrators in the market, has the advantage that it minimizes the tendency for over-grinding of both the precious mineral and gangue mineral [5]. However, to liberate the PGMs, the majority of UG2 ore is coarsely ground to around 80% passing 75 microns [6]. It is known that it is more difficult to liberate UG2 ore because it contains high proportion of fine grained PGMs minerals which have a grain size of < 10 µm, which makes the flotation less effective when valuable minerals are only partially liberated and completely enclosed in gangue silicates. Most of UG2 flotation tailings contain larger amounts of very fine composite silicate or PGMs particles, which require finer grinding to liberate and recover by flotation. However, fine grinding causes problems when it comes to recovery by flotation process due to the low mass and large surface area which results in factors like high consumption of reagents, low particles momentum, low probability of bubble particle collision, entrainment of fines and high pulp viscosity and slimes coating of which affect the recovery [5].

This project focuses on studying the impact of fine grinding of the silicate stream of the UG2 ore on flotation performance. The impact of particle size, collector, and depressant dosage on the PGMs recovery was investigated based on the Response Surface Methodology (RSM).

2. Materials and Methods

2.1. Materials

The UG2 ore (silicate stream) sample used in this project was sourced from a platinum mine in Limpopo Province, South Africa. The flotation reagents $CuSO_4$, Sodium Isobutyl Xanthate (SIBX) and Nerilose were supplied by BetaChem, South Africa and Senfroth (purity of 98 %) was sourced from Senmin, South Africa. H_2SO_4 and lime which were used as pH modifiers were supplied by Associated Chemical Enterprises, South Africa.

2.2. Mineralogical and morphology characterization of the silicate stream

The chemical composition of the silicate stream was determined using the X-ray fluorescence (XRF) Rigaku ZSX Primus II with SQX analysis and the major phase components were determined using the X-Ray Diffraction (XRD) Rigaku Ultimal V. This analysis was done by using the Rigaku Ultima IV which is equipped with the PDXL analysis software loaded with PDF ICDD cards. 10 gram of the pulverized sample was placed in the aluminium sample holder then placed in the XRD machine which scanned at a range of 5 to 90° 2-theta angle at a scanning rate of 0.5°/ min with a step of 1A° by means of a goniometer which can measure a 2-theta angle from 0° to 162°. Furthermore, the XRF voltage used was 40 kV and the current was 30mA. Nonetheless, the data was collected with a diffraction source equipped with a CuK source characterized and the X-ray generator that targeted a maximum power of 3 kW.

The surface topography of the silicate stream sample was determined using Scanning Electron Microscopy/Energy X-ray Dispersive Spectroscopy (SEM-EDS). The PGEs grade was determined using the nickel sulphide fire-assay method followed by inductive coupled plasma (ICP) spectrometry.

2.3. Milling experiments

The PGMs silicate stream sample was milled in a stainless-steel rod mill. 13 rods of 21.5mm diameter stainless steel were used as the grinding media. 1kg of the sample and 540 ml of water were mixed in the rod mill pot and milled for different milling times. A milling curve was then constructed, and the time required to mill the sample to 80 % passing 53 µm at the speed of 183 rpm for the liberation of the gangue and valuable minerals was determined.

2.4. Design of flotation experiments

The batch laboratory flotation experiments were designed using Response Surface Methodology (RSM). While using mathematical and statistical method, the laboratory experiments were optimized, and the software's optimized results were then put to another round of testing to make sure they delivered the best PGMs recovery possible. Table 2 shows parameters that were varied to improve the recovery of PGMs by using the central composite design (CCD) of RSM because it is more accurate, it further assumes the biases in range to increase the accuracy. These reagent combinations were then used to carry out the flotation experiments and a total of 20 flotation runs was required.

Table 2: Reagent dosages and combinations used in RSM.

Flotation test run	SIBX (g/t)	Nerilose (g/t)	Senfroth (g/t)
1	284.1	500.0	10.0
2	150.0	700.0	15.0
3	200.0	500.0	10.0
4	250.0	700.0	5.0
5	200.0	500.0	10.0
6	200.0	836.4	10.0

7	150.0	700.0	5.0
8	200.0	500.0	10.0
9	200.0	163.6	10.0
10	200.0	500.0	10.0
11	200.0	500.0	10.0
12	200.0	500.0	18.4
13	150.0	300.0	15.0
14	250.0	300.0	5.0
15	250.0	300.0	15.0
16	115.9	500.0	10.0
17	200.0	500.0	1.6
18	150.0	300.0	5.0
19	250.0	700.0	15.0
20	200.0	500.0	10.0

2.5. Flotation experiments

1 kg of the silicate stream sample was prepared for each flotation run (1-20) and poured into the Denver cell. Sulphuric acid and lime were used as pH modifiers to maintain the operating pH of 8-9. The pH of the mixture was measured using a pH meter first while conditioning the pulp for 2 minutes. After measuring the pH of the mixture and set into the required value, the activator (CuSO4) followed by the collector (SIBX) were added according to the design of experiment and conditioned for 2 minutes. After 2 minutes, a depressant (Nerilose) was added for all the flotation runs and conditioned for 2 minutes. After the conditioning, Senfroth frother was added and conditioned for 1 minutes. Flotation started by operating the agitator to a speed of 2000 rpm and blowing in air from the agitator to form the froth. Flotation concentrates were collected for 5 minutes by scrapping off every 10 seconds for each flotation run. 20 runs were completed and for each run the concentrate, and the tailings were collected, and oven dried at 100ºC overnight. After drying, the samples were analysed using fire assaying to determine the grade and recovery of the PGEs.

3. Results and discussion

3.1. Chemical composition of the PGM silicate stream

The chemical composition of the UG2 silicate stream ore is presented in Table 1. It shows the presence of BMS (Ni, Fe and Cu) in low quantities of 0.30, 23.40 and 0.02 % wt respectively. The Si (12.29%) and Cr (12.08%) present are the gangue minerals that are associated with the sulphide mineral in the UG2 ore. According to [7], PGEs are found as single grains or in association with BMS in the UG2 reef. These single-grain PGMs can be found locked in different gangue minerals or on the boundary between chromitite and silica gangue grains. Therefore, this acknowledges with the fact that the presented ore is indeed a UG2 ore due to the presence of the chromite and silica minerals. The nickel sulphide fire assaying method revealed that the UG2 silicate stream contained 4.37 g/t PGEs.

Table 1: Elemental composition of the PGM silicate stream composition

Element	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V
Element %	0.07	3.21	4.20	12.29	0.01	0.07	0.02	0.18	0.17	0.47	0.17

Element	Cr	Mn	Fe	Ni	Cu	Zn	Sr	Zr
Element %	12.08	0.28	23.40	0.30	0.02	0.07	0.03	12.08

3.2 Mineralogical phases of the UG2 silicate stream sample

The mineralogical phases of the UG2 silicate stream sample were analysed using XRD and the results are shown in Figure 1. Major mineral phases in the sample were Quartz, Sphalerite, pyrrhotite, chalcopyrite and chromitites.

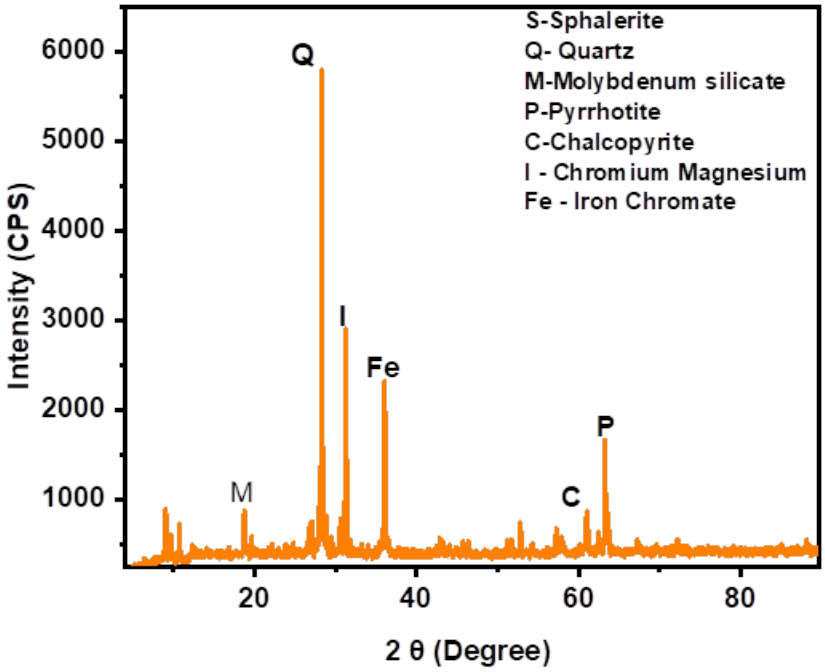

Fig. 1: XRD pattern of the silicate stream from the UG2 ore

3.3. Surface topography and petrographical study of the ore sample

The SEM-EDS (TESCAN, Vega 3XMU) was utilized to determine the surface topography of PGMs present in the silicate stream and the results are shown in Figure 2. Figure 2 (A-D) shows the backscattered electron (BSE) photomicrographs showing locations of where the EDS spectra were collected for the different minerals. Figure 2A shows spectra 1 taken on bright mineral phase (PGMs), B shows spectra 2 taken on light grey mineral which is chromite, C shows spectra 3 taken on dark mineral phase (pyroxene) and D is a close-up view of A showing the dimensions of the PGMs. The magnification of each micrograph is 90 µm and the major minerals which were identified using the SEM were chromite (Figure 2B) which has cracks as well as silicates (pyroxene and plagioclase) which occur in between the chromite grains (Figure 2C). The PGMs tend to occur in the silicates next to chromite (Figure 2A). This BMS has the grains of the PGE. The qualitative data of spectrum 1 in Figure 2A is reported in Table 2. Therefore, the bright phase in Figure 2A and 2D was determined to be a Ni, Fe sulphide mineral containing Pt, and Os, with minor contributions from Ag and Pd. This correlates with the XRD results which suggest that the PGEs are locked in the silicate minerals.

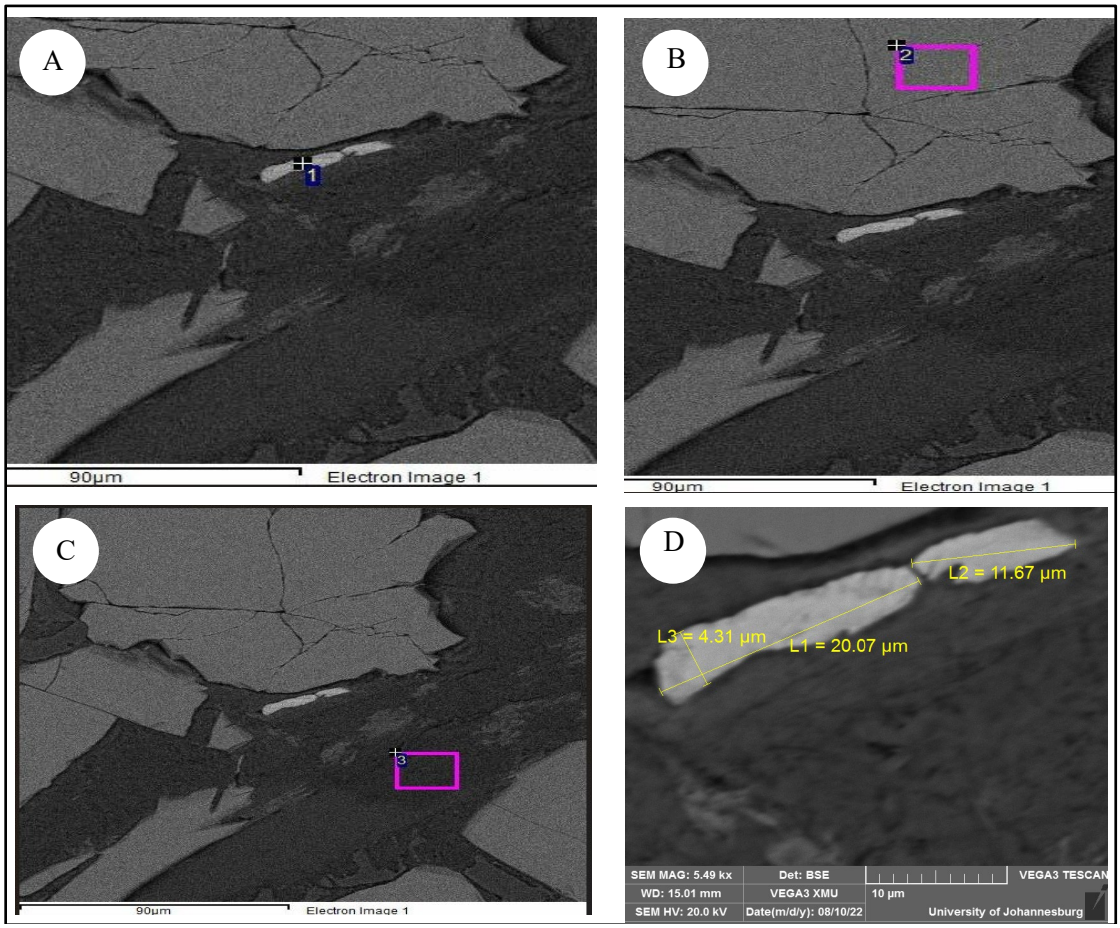

Fig. 2: Backscattered electron (BSE) photomicrographs showing locations of where the EDS spectra were collected for the different minerals.

Table 2: Elemental composition of mineral phase at spectrum 1.

Element	Pt	Os	Ag	Pd	Ni	Fe	Cr
% wt	0.17	0.15	0.08	0.04	0.98	10.17	0.31

3.4. Milling curve of the UG2 silicate stream

Figure 3 shows the milling curve which was used to obtain the time required to reach a target grind of 80 % passing 53 µm. Thus, the time required to reach the target grind is 120 minutes. Prior to flotation, the sample (silicate stream) had to undergo size reduction through milling to liberate the valuable minerals. The black line shows the cumulative % mass passing 53 µm obtained at 10, 20, and 30 minutes. The orange line is an extrapolated linear line at 80% crossing 53 m, indicating that 120 minutes was required to mill the sample in the rod mill.

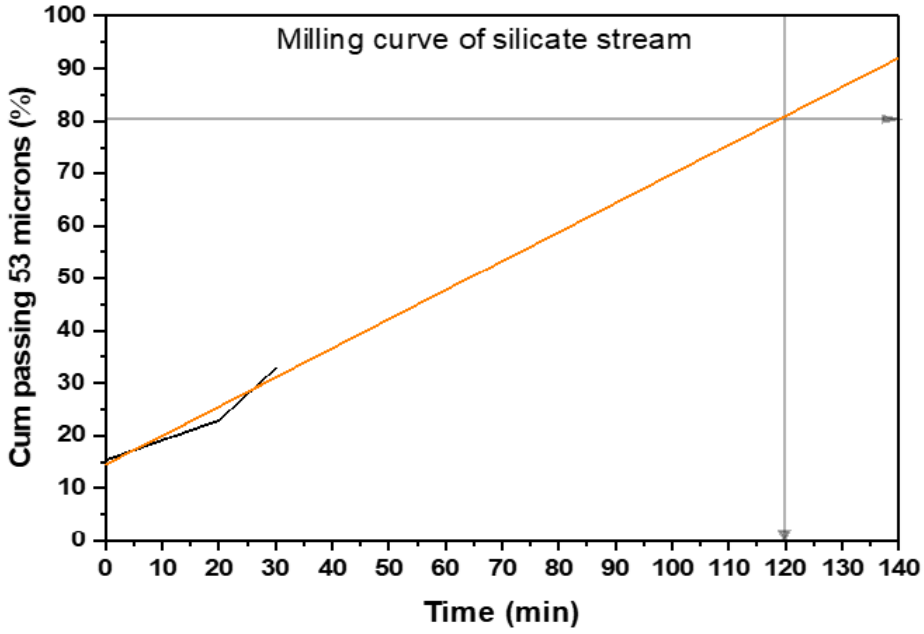

Figure 3: Milling curve of silicate stream

3.5. Flotation experiment results

Batch rougher flotation experiments were carried out in a Denver flotation cell and the results are shown in Table 2. Base metals were used to monitor recovery of PGMs since it is well known that PGMs are associated with BMS in the UG2 ore. The reagent dosages were prepared according to the results of RSM design of experiments (Table 2). The results revealed that flotation run 7 had the highest Cu recovery, flotation run 14 had highest Ni recovery and flotation run 12 had highest Fe recovery. Concentrates form flotation runs 7, 11, and 17 showed the presence of PGEs and the Pt grades were 2.47, 16.57 and 19.19g/t respectively. Therefore, the concentrate from flotation run 17 (200g/t SIBX,500g/t Nerilose and 1.6g/t Senfroth) contained most of the Pt and using its reagent conditions and a grind size of 80% - 53 µm led to the liberation of PGEs from the locked size of the sulphide mineral. This confirms that the degree of liberation was sufficient for this project aimed at improving the recovery of PGMs.

Table 3: Flotation results on recovery of BMS.

Flotation test run	%Cu Recovery	%Ni Recovery	%Fe Recovery
1	35.0	12.6	9.3
2	26.6	9.6	9.5
3	19.7	6.9	7.2
4	34.4	10.1	15.3
5	30.6	10.8	16.1
6	35.1	12.9	11.6
7	63.9	12.4	18.7
8	36.3	16.6	14.9
9	38.4	14.3	15.1
10	34.9	9.6	17.2
11	29.0	15.0	15.8

12	37.3	15.9	22.7
13	31.3	13.3	10.4
14	63.1	17.0	18.2
15	41.6	15.8	17.8
16	42.3	14.0	18.4
17	45.3	14.0	21.9
18	34.9	11.1	11.0
19	45.9	14.1	21.7
20	35.3	1.4	13.4

4. Conclusion

In this work, to understand the mineralogical characteristics of the silicate stream, XRF, XRD and SEM-EDs techniques were used for the analysis. Characterization results showed that major mineral phases in the mining silicate stream are quartz, sphalerite, pyrrhotite, chalcopyrite and chromitites. The silicate stream contains PGMs locked in silicate minerals and there is a need to liberate them by milling finer. Flotation results based on RSM revealed that the best reagent suit for processing this stream is 200g/t SIBX, 500g/t Nerilose and 1.6g/t Senfroth. However, through metallurgical aspects applied in this project, a solution for the environmental impact in mineral processing plant was amended by fine grinding and reprocessing the silicate stream through froth flotation to recover the PGMs. Nonetheless, this project demonstrated that by milling to 80% passing 53µm, it is possible to recover the BMS and PGMs locked in the silicate stream. Further investigation needs to be done on the correlation between the BMS and PGEs in the silicate stream.

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