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Decoupling the effect of hydraulic oil contamination on the flotation performance of UG2 PGE ore and its interaction with alteration minerals

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ABSTRACT

Oil contamination inadvertently arising from underground mechanised South African platinum mines is known to compromise the subsequent flotation performance. Anecdotal observations suggest that this is further exacerbated in the presence of phyllosilicate alteration minerals. Two ores of varying degrees of alteration from the Bushveld Igneous Complex were utilized in this study to investigate the effects of oil on UG2 platinum group element (PGE) ore flotation and investigate the interaction mechanisms between the oil and phyllosilicate alteration minerals. Mineralogical characterization of the ores indicated a higher percentage of the alteration phyllosilicate minerals in the altered ore (9.2 wt%) in comparison to the normal ore (5.6 wt%); with talc predominating in both ores. Baseline batch flotation test work indicated a reduction of grade with hydraulic oil addition in the normal ore (Pt by 4.5 g/t and Pd by 3.6 g/t), whereas valuable metal grades in the altered ore showed no change. In contrast to the grades, the Pt and Pd recovery dropped by 6 % and 12 %, respectively, in the altered ore floats whereas nearly constant recoveries were obtained for the normal ore as oil concentration increased. The dynamic froth stability and slurry viscosity both increased in the presence of oil and were greater in the altered ore compared to the normal ore. The observed flotation performance of the normal ore was attributed to the increasing froth stability which promoted the recovery of gangue minerals and consequent grade decrease. For the altered ore, the greater increase in the slurry pulp viscosity with oil addition was proposed to lead to poor gas dispersion and reduced interaction between bubbles and particles resulting in the reduction of recovery. The addition of sodium metasilicate successfully mitigated these effects causing a decrease in the viscosity, improvement in particle dispersion and better froth drainage. This study highlighted the potentially harmful effects of oil spillages from mechanised mining and its complex interaction with alteration minerals contained within the ore.

1. Introduction

Mechanised underground mining is often an attractive prospect over conventional mining methods with many newer hard rock mines globally adopting this strategy (Rupprecht, 2018; Willis et al., 2004). This is due to the benefits it offers compared to conventional mining methods, which include increased productivity, safety, profit, small mining crew, and quick orebody access (Pickering, 1995). However, oil from machinery used in mechanized mining, such as the load-haul-dump (LHD) may inadvertently leak, which may contaminate the ore. The study conducted by Bos and Quast (2000) demonstrated that oil contaminants may impact the downstream flotation performance negatively. Their study investigated the effect of various hydrocarbons (oils and degreasers) on the grades and recoveries of a copper–gold ore. All hydrocarbons tested had some qualitative effect on the froth characteristics, some producing a more stable froth, while others produced a less stable froth, with associated lower and higher grades, respectively. The authors speculated that certain oils were adsorbing non-selectively to hydrophilic gangue minerals, causing them to become hydrophobic and report to the concentrate, lowering grade. Similarly to the Bos and Quast (2000) study that was initiated due to anecdotal evidence, the current study deals with anecdotal evidence from a South African mechanized platinum mine that reported problems associated with the processing of ores contaminated with hydrocarbon oils. The

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mine also reported that the problems appeared to be exacerbated when processing ores with high contents of phyllosilicate alteration minerals. This study attempts to provide a generalised understanding of the problems posed by hydrocarbon contamination in the flotation process, with an emphasis on interactions with alteration minerals.

Platinum group minerals (PGM) are naturally fine-grained, with grain sizes mostly below 10 μm and require fine grinding for liberation (Penberthy et al., 2000). A consequence of the fine grinding is the creation of an abundance of ultrafine phyllosilicate alteration minerals such as talc, chlorite and serpentine with high surface area that bring about their own set of challenges in flotation. These include: (i) slime coating which inhibits the collector adsorption on the surface of valuable minerals, ultimately affecting the recovery, (ii) increase in slurry viscosity as a result of aggregation of finely liberated particles which subsequently results in reduced particle-bubble interaction, poor gas dispersion and ultimately recovery loss, (iii) grade dilution due to the recovery of liberated naturally floatable gangue such as talc associated with orthopyroxene (Chen and Peng, 2018; Dzingai et al., 2021; Molifie et al., 2023; Ndlovu et al., 2013; Shabalala et al., 2011). The presence of these alteration minerals is due to the hydration reactions naturally occurring in near-surface ores (Guilbert & Park, 2007), as well as hydrothermal alteration reactions occurring in more deep-seated ores, as is the case for the Zimbabwean Great Dyke ore (Oberthür et al., 2013).

Hydrocarbon oils such as kerosene, transformer oil and diesel oil are widely used as collectors in the flotation of molybdenite (Lin et al., 2018). Molybdenite is a naturally floatable mineral that is characterized by its anisotropic surface properties. It is commonly found in porphyry copper ores. In such ore, chalcopyrite is mainly recovered first, whereas molybdenite and other gangue minerals are depressed (Gutierrez et al., 2020; Jorjani et al., 2011; Yan et al., 2020; Yuan et al., 2019). Hydrocarbon oils are used to reactivate the surface hydrophobicity of molybdenite after initially depressing it in the concentration of the copper minerals (such as chalcopyrite). The collection capacities of these hydrocarbon oils are reliant on their dispersibility in water, with transformer oil having a greater dispersion capability than the other two oils (Lin et al., 2017; Lin et al., 2018). Additionally, kerosene and diesel oil are also commonly used in coal flotation as collectors (Jia et al., 2000; Polat et al., 2003). Bos and Quast (2000) studied the effects of oil on the flotation of copper sulphide minerals. They deduced that oils such as hydraulic oil, engine oil, and transmission oil affect the copper grade mainly due to oil coating the surface of liberated gangue minerals, enhancing their hydrophobicity and promoting recovery. The use of distillate oil was observed to increase the copper grade as a result of improved froth stability.

Talc on the other hand, is commonly employed as a sorbent in the oil spill remediation process to remove oil from water bodies and surfaces (Ladd and Smith, 1970; Zadaka-Amir et al., 2013). It is a naturally hydrophobic mineral characterized by its anisotropic surface properties and such properties makes it useful in clean-up of oil spillages. Additionally, talc agglomerates in the presence of oil which ultimately increases the suspension viscosity (Polowczyk and Kozlecki, 2017; Yang et al., 2012). In terms of flotation, this may result in additional performance issues due to higher slurry viscosity. Notably, talc is easily recovered to the froth phase due to it being naturally hydrophobic and also contributes to froth stability. Farrokhpay et al. (2018) studied the effect of talc on the froth phase and observed an increase in froth stability with increasing talc content along with the copper grade dilution. Despite extensive studies on oil and talc, there has been little to no research on the impact of oil on mineral flotation and how high alteration mineral content may affect this.

The objective of this study is to investigate the effect of hydrocarbon oil contamination inadvertently produced during underground mining operation on the flotation performance of PGE ores and how it may be exacerbated in the presence of alteration phyllosilicate minerals such as talc. A potential solution to mitigate any detrimental effects of the oil contamination is also explored.

2. Materials and methods

2.1. Ore preparation

Two 300 kg samples of UG2 ore were taken from the underground operations at Two Rivers Platinum (TRP) mine in South Africa. These samples were consistent with the standard mining cut. One of the samples was taken to represent a 'normal UG2' ore, whereas the other was taken from an area in the mine where there is known to be a greater degree of internal dilution by silicate minerals (orthopyroxene, plagioclase). These areas of greater dilution usually contain higher abundances of silicate alteration minerals such as talc. The two samples are therefore designated as 'normal' and 'altered'. The two samples were crushed, packaged in drums and transported to the University of Cape Town (UCT). Upon arrival, the two samples were dried in a pan overnight, followed by jaw crushing and dry screening to ensure a top size of 100 % passing 3 mm. Each sample was blended, riffled, and split using a 10-way Dickie and Stockler rotary splitter into 4.1 kg representative aliquots. This mass corresponds to the solids concentration of 37 wt% in an 8 L flotation cell. Secondary grinds of 70 % passing 75 μm were utilized for flotation test work, with each ore needing its own milling time to produce the required grind. A rod mill charged with 22 rods of various diameters was used for grinding.

2.2. Mineralogy

Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN) was used to determine the bulk mineralogy and PGM mineralogy of the two ores. A QEMSCAN FEI 650F instrument operating at 25 kV and 10 nA was used. Bulk samples of the flotation feeds were further split down and prepared into 30 mm diameter polished resin blocks mounted with nano-carbon. All samples were carbon coated prior to QEMSCAN analysis to ensure charge dispersal in the scanning electron microscope. Mineral grades for each ore were measured using the bulk mineral analysis method on QEMSCAN with a pixel size of 3 μm and field size of 733 μm. Quantitative X-ray diffraction (XRD) and X-ray fluorescence (XRF) were used to validate the QEMSCAN measured mineral grades. For XRD, a 3.5 g representative aliquot of each ore was micronized in the presence of ethanol to produce fine powder for analysis. A Bruker D8 X-ray diffractometer with a LynxEye detector and CoKα radiation was used for analysis. Equivalent aliquots were submitted for XRF analysis on a Panalytical XRF instrument in the Department of Geological Sciences, UCT to determine the bulk chemical composition of the ores. The PGM mineralogy was characterised using the trace mineral search analysis method on QEMSCAN. A total of 28 surfaces per ore were analysed in the PGM search.

2.3. Batch flotation

Batch flotation tests were conducted in an 8 L modified Leeds batch flotation cell. The ores were intentionally contaminated with known dosages of hydraulic oil prior to milling, to investigate the effect of oil on flotation. Oil dosages were increased in increments of 100 g/t up to 500 g/t. These dosages were chosen based on information from the mine site where concentrations of up to ~ 300 g/t had been measured on incoming feed. The batch flotation test work was performed at the secondary grind and solids percent of 37 wt%. All the chemicals used were

Table 1
Reagents used in batch flotation of the normal and altered ores.

Reagent	Dosage (g/t)	Conditioning time (min)
Senkol 821 (collector)	110	Added in the mill
Hydraulic oil AWS68 (fresh oil)	0–500	Added in the mill
Sendep 30D (depressant)	20	2
Senfroth 200 (frother)	30	1

supplied by AECI Mining Chemicals other than the hydraulic circulating oil that was provided by the mine. Table 1 summarizes the reagent suites, dosages and conditioning times used. Details of the synthetic plant water composition and flotation procedure are given in Wiese et al. (2005). For the test work exploring mitigation, 1500 g/t sodium metasilicate ($Na_2O:SiO_2$) purchased from Sigma Aldrich was added before the depressant and conditioned for 5 min, followed by the addition of other reagents in chronological order as described in Table 1. Batch flotation tests followed a standard procedure, with a 2 cm froth height, 15 s scraping interval, 12 L/min air flow rate, and the collection of 4 concentrates at cumulative times of 2, 6, 12 and 20 min. The experiments were conducted in duplicate, and the standard error determined. Samples of the feed, concentrates and bulk tailings were sent to an external accredited laboratory for Pt and Pd fire assay and finished by ICP-OES.

2.4. Oil adsorption tests

Oil extraction was conducted on the feed and concentrates using petroleum ether as an organic solvent. The slurry contaminated with a known oil dosage was milled, vacuum filtered and submerged in petroleum ether solvent. The mixture was filtered, and the filtrate evaporated using a hot water bath. The amount of oil adsorbed was determined gravimetrically as the initial known dosage minus the oil left after evaporation. This method was adapted from Wang et al. (2017).

2.5. Rheology

The rheological measurements were conducted with the AR1500EX-TA rheometer fitted with standard vaned rotor geometry. Ore samples were prepared in distilled water and the solids concentration of 40 vol% was utilized. A pre-shear of 400/s was used for the two ores for a duration of 60 s and an equilibration time of 5 s. All rheological experiments were conducted in triplicate. The Bingham model was applied to all rheological data.

2.6. Froth stability

A frothing column with a diameter of 20 cm and height of 100 cm was utilised to investigate the effect of varying oil concentration on the 3-phase froth stability of the UG2 ores. The same reagents and dosages were utilised in the order as the batch flotation test. The tests followed the same methodology as described by Bikerman (1973). The column was fitted with four baffles and an overhead stirrer to ensure effective suspension of the slurry. All the experiments were performed in triplicate and the standard error determined. Froth stability was determined as the slope of the maximum froth height versus superficial gas velocity plot.

3. Results and discussion

3.1. Mineralogical composition of the ores

The two ores consisted predominately of chromite with the normal ore containing 42.4 wt% chromite compared to 33.9 wt% in the altered ore (Table 2). The second most common mineral in both ores was orthopyroxene, with a similar proportion of ~ 31 wt%. The plagioclase content in the altered ore was almost double the quantity in the normal ore (20.9 wt% compared to 11 wt%). Both ores contained phyllosilicate alteration minerals (serpentine, talc, and chlorite), with the proportion higher in the altered UG2 than in the normal UG2 (9.1 wt% versus 6.2 wt %). The serpentine content was relatively low in both ores relative to talc and chlorite. The chlorite content of the altered UG2 was approximately double that of the normal (3.2 wt% versus 1.9 wt%). Talc contributed around half of the total phyllosilicate alteration minerals in both ores; however, slightly higher in the altered UG2 compared to the normal UG2 (5.8 wt% versus 3.6 wt%). Other minerals in minor occurrence include the base metal sulphide minerals (BMS – chalcopyrite, pentlandite and pyrrhotite), mica, quartz and olivine.

Table 2
QEMSCAN bulk mineralogical composition (wt%) of the two UG2 ores. * represents phyllosilicate alteration minerals.

Mineral	Normal ore (wt%)	Altered ore (wt%)
Chalcopyrite	0.1	< 0.1
Pentlandite	< 0.1	< 0.1
Pyrrhotite	0.1	< 0.1
Other BMS	0.1	< 0.1
Olivine	1.0	0.1
Orthopyroxene	30.3	31.5
Clinopyroxene	5.3	2.4
Amphibole	1.8	1.1
Serpentine*	0.7	< 0.1
Talc*	3.6	5.8
Chlorite*	1.9	3.2
Plagioclase	11	20.9
Mica	0.9	0.4
Carbonate	0.2	0.4
Quartz	0.4	0.1
Chromite	42.4	33.9
Other	0.2	0.2

Fig. 1 depicts the PGM mineral liberation and association results of the normal and altered ore. The majority of the PGMs were liberated in the normal ore (46 %) relative to the altered ore (25 %). The effective liberation % (Liberated PGM and PGM locked in liberated BMS) was higher in the normal ore (67 %) in contrast to the altered ore (43 %). This inferred that a significant proportion of unliberated PGMs remained associated with gangue minerals. For the normal ore, the next most common occurrence of unliberated PGMs were PGMs enclosed in alteration silicates (8.5 %), whereas for the altered ore, it was PGMs associated with base metal sulphides locked in primary silicates (17.6 %) followed by PGMs attached to oxides (e.g., chromite).

3.2. Flotation

The aim of the batch flotation tests was to investigate the effect of hydraulic oil contamination on the flotation performance of the two UG2 ores. Oil dosages were increased in 100 g/t increments up to 500 g/t to establish whether there was a critical point at which the flotation performance was detrimentally affected.

3.2.1. Effect of oil addition on recovery

The addition of oil in the normal ore (Fig. 2a) resulted in a gradual increase in Pt recovery up to a maximum of 4 % (from 80 % to 84 %), whereas the Pd recovery was relatively consistent at ~ 80 % (except for the 400 g/t test which may be an outlier). In contrast to the normal ore, oil addition had a significant impact on the recovery of both Pt and Pd in the altered ore (Fig. 2b). A gradual decrease in Pt and Pd recovery was observed from 0 to 200 g/t oil, after which it plateaued until the 500 g/t oil condition. Pt recovery decreased by a total of 6 % and Pd recovery by 12 %. These results were consistent with the anecdotal observations from the concentrator, where losses in recovery were noticed when the ore had a higher alteration mineral content.

It should be noted that there is a significant difference in the performance of both ores. In the absence of any oil addition, the normal ore had Pt and Pd recoveries around 80–81 %, while the altered ore had a Pt recovery of 67 % and a Pd recovery of 74 %. This reflects the greater liberation of PGM in the normal ore (including PGMs locked in liberated BMS that are readily expected to be recovered) compared to the altered ore (Fig. 1). In addition, high alteration mineral contents are also known to negatively affect flotation recovery due to slimes generation (Molifie et al, 2023).

3.2.2. Effect of oil addition on grade

The addition of oil had a significant effect on both Pt and Pd grades in

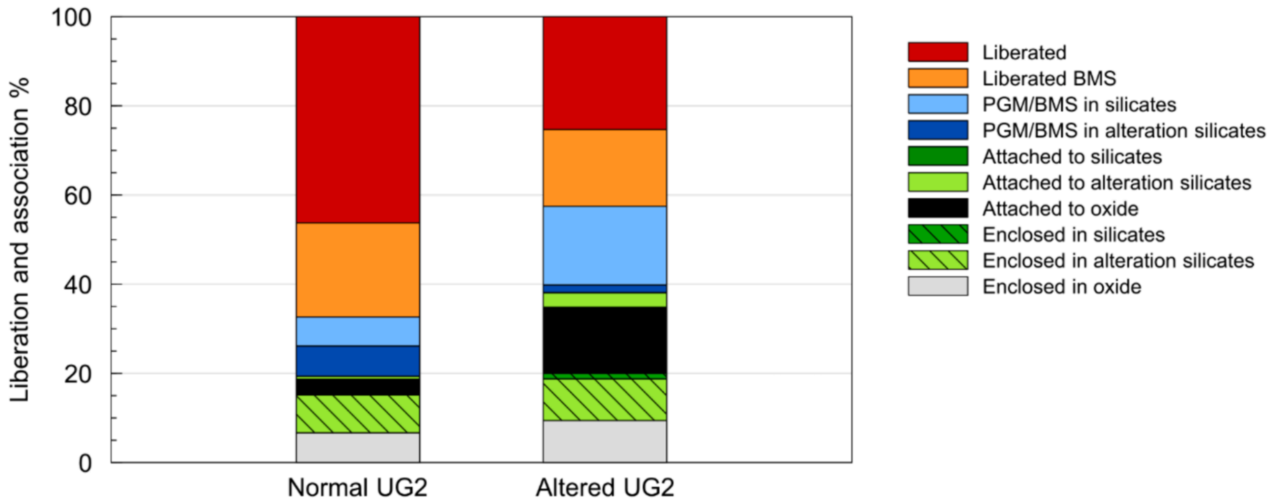

Fig. 1. The proportion of liberated PGM, where a liberated PGM is defined has > 80 % of the PGM particle by area. The association of unliberated PGM is also given. The 'PGM/BMS' category refers to the PGM associated with BMS which are in turn associated with other minerals. Alteration silicates represent talc, chlorite, serpentine and amphibole. The number of particles analysed was 167 and 161 in the normal and altered ores, respectively.

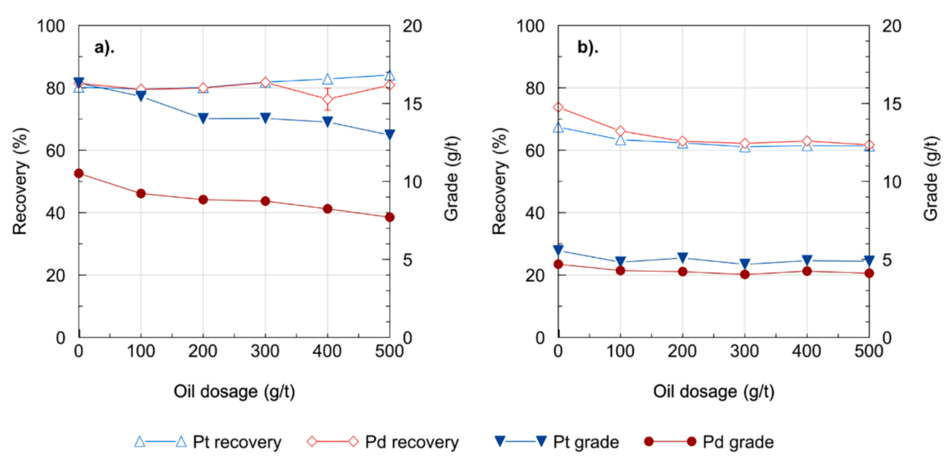

Fig. 2. Pt, Pd grade and recovery at various oil concentrations in the normal (a) and altered (b) ores. Error bars represent the standard error of duplicate floats.

the normal ore, decreasing by roughly 20 % to 27 %, relative, over the investigated oil range (Fig. 2a). A gradual, almost linear, decrease in grades was observed with increasing oil concentration. The addition of different oil dosages in the altered ore had less effect on the grades (Fig. 2b). The variation in absolute values for the grades of both metals was very small, but in relative percentages there was about 12 % reduction in grade. Concentrate grades are low for both ore types, being in the range 11 to 16 g/t for Pd and Pt, respectively, in the normal ore, and 4.7 to 5.6 g/t in the altered ore. These represent upgrade ratios of 11 for the normal ore and 4.5 for the altered ore. This, again, highlights the difficulty in processing ores with high alteration mineral contents. The baseline flotation grades with no oil addition were also higher for the normal ore, which was expected due to the lower grades of alteration minerals in the normal ore (Table 2).

3.2.3. *Effect of oil addition on solids recovery*

It could be inferred from the recovery and grade data presented in Fig. 2 that the differences noted were likely as a result of differences in the amount of solids recovered to the concentrate. However, to confirm this, the solids recovery as a function of oil dosage for the normal and altered ores are shown in Fig. 3. Clearly, there is a gradual increase in the solids recovery (from 9.4 % to 13.6 %) as oil dosage increases for the normal ore. The altered ore, on the other hand, has about a 1 % increase in solids recovery as the first 100 g/t dosage is added, and thereafter

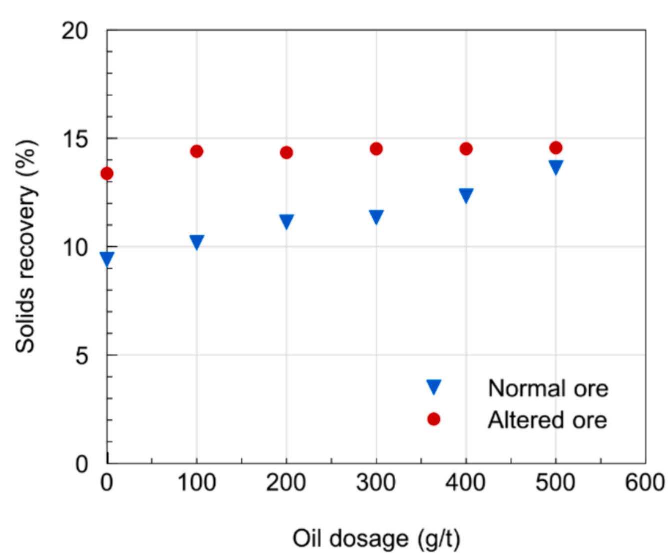

Fig. 3. Solids recovery for the normal and altered ore as a function of the oil addition.

stabilises at about 14.5 % solids recovery. It is the increase in solids recovery that drives the increase in recovery and decrease in grade for the normal ore. It appears that oil addition for this ore is acting non-selectively by increasing both valuable and gangue mineral recovery. However, solids recovery changes do not drive the reduction in recovery seen for the altered ore, upon oil addition. In this case, there appears to be an alternative mechanism at work that will be further discussed below.

3.2.4. Concentrate mineralogy

To further understand the effect of oil and the minerals responsible for grade dilutions, the combined concentrates (C1-C4) of the conditions at which no oil and 500 g/t oil were used were analysed with QEMSCAN. Fig. 4 confirms that the addition of oil caused an increase in the mass recovery of all the major minerals present, orthopyroxene, talc, plagioclase, and chromite. There was a greater increase in the total mass recovered for the normal ore than for the altered ore, as already shown in Fig. 3. Qualitatively, the graph appears to show non-selective recovery of both hydrophobic talc and hydrophilic gangue minerals (plagioclase, chromite, and orthopyroxene). In order to interrogate this data quantitatively, the mineral upgrade ratios (concentrate grade divided by feed grade) are shown in Table 3.

Firstly, for both the normal and altered ores, the upgrade ratio of the base metal sulphides were negatively affected by the addition of oil. This confirms what was found in the metallurgical data but goes further to suggest that grade also decreased for the altered ore. The Pt and Pd grades suggested that only the normal ore was affected in this way. Secondly, by focussing on the upgrade ratios of the traditionally non-floating gangue, which includes pyroxene, chlorite, plagioclase, chromite and the "other" minerals, it is clear that there is virtually no difference between the upgrade ratios between the ores when no oil is present or when 500 g/t oil is present. This confirms what can be qualitatively observed in Fig. 4. Talc is being upgraded in both ores, which is to be expected. There is a slight decrease in the upgrade ratio when oil is added for the normal ore, however, the magnitude may not be significant. In general, the upgrade ratios confirm what was qualitatively apparent from Fig. 4, that oil addition results in a general increase in solids mass recovered, but that this increase is non-selective except in the case of the BMS, where selective reduction in upgrading occurs.

3.2.5. Oil deportment

The petroleum ether-oil extraction method was performed on the combined concentrates (C1-C4) recovered when adding 500 g/t oil to the normal and altered ores. This was done to investigate whether the oil was (i) preferentially adsorbing onto solids that report to the concentrate or tailings, or (ii) not adsorbing to solids and remaining in the liquid. The flotation cell mass balance results are shown in Fig. 5. These showed a non-selective recovery of oil-coated particles to either the concentrate or the bulk tailings in the normal ore. The oil per solids recovered was nearly the same in the concentrate and tailings, at around 490 g/t. In contrast, the majority of the oil coated solids in the altered ore reported to the bulk tailings as compared to the concentrate. The oil per solids mass concentration was 555 g/t in the tailings and 232 g/t in the concentrate. This is a significant difference which infers that during flotation of the altered ore, most of the coated oil particles are non-floatable and report to the tailings, which is consistent with the relatively small increase in solids recovery noted for the altered ore

Table 3
Mineral upgrade ratios for normal and altered ores when no oil was present and when 500 g/t oil was added.

Mineral (UGR)	Normal ore		Altered ore	
	No oil	500 g/t oil	No oil	500 g/t oil
BMS	5.1	2.8	4.6	1.9
Orthopyroxene	1.2	1.2	1.4	1.3
Clinopyroxene	1.1	1.1	1.1	1.1
Talc	5.5	4.8	3.6	3.8
Chlorite	1.9	1.8	0.7	0.8
Plagioclase	0.8	0.9	0.4	0.4
Chromite	0.4	0.5	0.5	0.5
Other	1.4	1.3	1.4	1.5

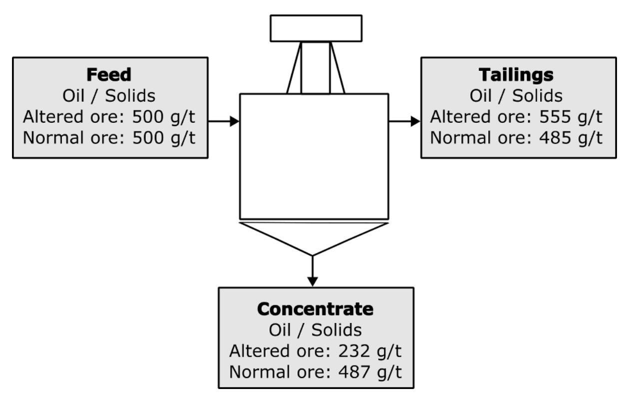

Fig. 5. Oil mass balance conducted around the flotation cell for the two ores. This was based on the oil added to the feed prior to milling and the extracted oil from the combined concentrates (C1 to C4).

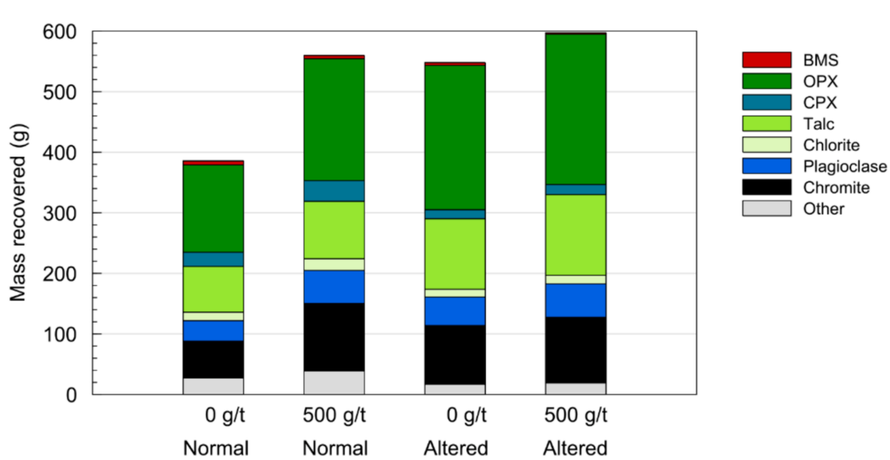

Fig. 4. A comparison of the mineralogical composition of the concentrate at 0 and 500 g/t oil of the normal and altered ores. BMS represents the base metal sulphide minerals, OPX is orthopyroxene, CPX is clinopyroxene and 'other' represents the remaining minerals which were recovered in small quantities.

compared to the large increase for the normal ore.

3.3. Slurry viscosity

The effect of oil on the slurry viscosity of the two ores is illustrated in Fig. 6. In the absence of oil, the apparent viscosity of the altered ore was slightly higher than the normal ore. This was attributed to the slightly higher talc content in the altered ore, which coagulates via interparticle electrostatic interactions, raising the viscosity (Becker et al., 2013). An increase in the apparent viscosity of both the normal and altered ore was observed with the addition of oil (from 0 to 3 mL of oil) with the highest oil concentrations resulting in the greatest apparent viscosity. The increase in viscosity is attributed to the formation of talc-oil aggregates with oil bridging the individual talc platelets (Ndlovu et al., 2011; Ndlovu et al., 2013; Polowczyk and Kozlecki, 2017). High slurry viscosity and yield stress may lead to poor gas dispersion and reduced particle-bubble collisions within a flotation cell, which limits bubble-particle interaction, thus reducing the transfer of valuable mineral particles from the pulp to the froth phase (Bakker et al., 2009; Shabalala et al., 2011).

3.4. Froth stability

Froth stability tests were used to investigate the effect of oil on the froth stability of the normal and altered ore, since froth stability has a significant influence on the overall flotation performance (mass pull, grade and recovery). A froth that is stable will have a high froth recovery, resulting in increased valuable mineral recovery but with a consequent grade dilution due to entrainment (Bradshaw et al., 2005; Hadler et al., 2010). In an unstable froth, valuable minerals (hydrophobic) are lost back to the pulp zone due to bubbles bursting. Fig. 7 shows that the baseline (no oil) froth stability factor was slightly higher in the altered ore as compared to the normal ore. This was likely due to the higher talc content in the altered ore as compared to the normal ore (Farrokhpay et al., 2018). Higher talc content in the altered ore would result in more optimally hydrophobic particles reporting to the froth phase, which results in a more stable froth phase.

The froth stability then increased significantly upon addition of oil, for both the normal and altered ores. There was an overall increase in froth stability of approximately 34 % in the normal ore and 47 % in the altered ore. The highest froth stability factors were observed at the 400 g/t oil condition. It is generally noted that when there is an increase in froth stability, there is also an increase in solids recovery (Hadler et al, 2010). Therefore, the increase in froth stability observed for the normal ore is consistent with the 45 % increase in solids recovery noted for that ore (Fig. 3). However, the altered ore only had a 9 % increase in solids recovery compared with the 47 % increase in froth stability. However, the increase in froth stability for both ores is coherent with the increase in viscosity and the previous studies that showed the formation of talc-oil aggregates.

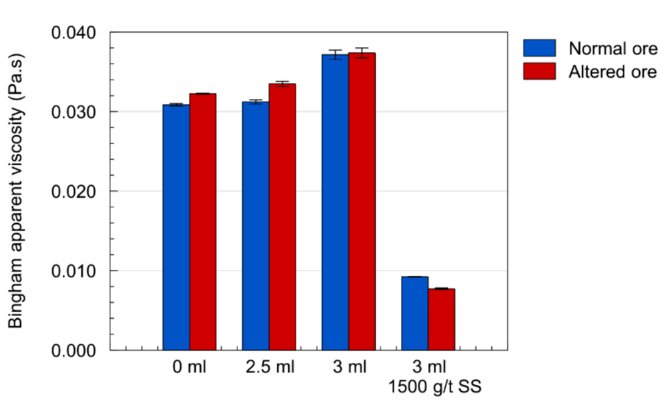

Fig. 6. Bingham apparent viscosity of the normal and altered ore flotation feeds (at 40 vol% solids) as a function of oil concentration. The effect of 1500 g/t of sodium metasilicate addition on apparent viscosity at an oil concentration of 3 mL is also given. Error bars represent the standard error.

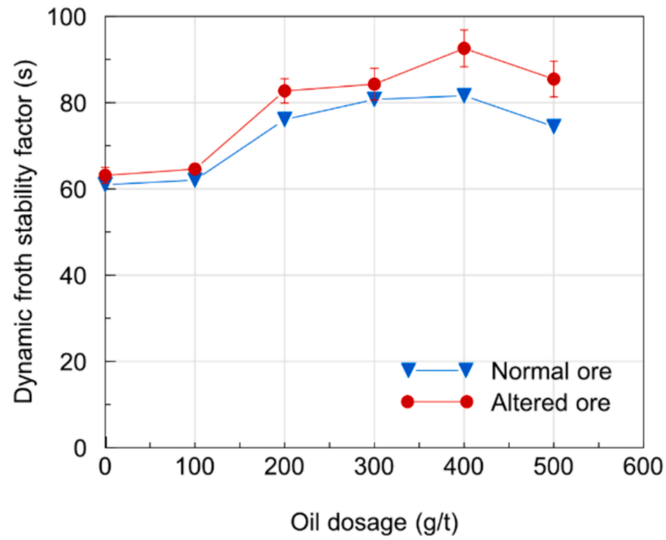

Fig. 7. Three-phase froth stability at various oil concentrations. The error bars represent the standard errors of triplicate measurements.

3.5. Potential mitigation strategy

The flotation and supporting tests indicated that the harmful effects of hydraulic oil were caused by the viscous impact of oil, which were exacerbated in the altered ore compared to the normal ore. In the study conducted by Molifie et al. (2023), it was proven that high dosages of sodium metasilicate can reduce the slurry viscosity effect caused by high grades of phyllosilicate alteration minerals. This was attributed to the dispersion of particles along with its mild depressing effect. Following this, the use of sodium metasilicate was adapted in this study to mitigate the viscous effect of oil. Majumder et al. (2006) also showed that sodium metasilicate can lower the viscous effect caused by oil in a coal-water–oil slurry, where oil is normally used as a flotation collector. The results given in Fig. 6 confirm the reduction in slurry viscosity with the addition of sodium silicate for both ores.

Flotation tests were conducted with and without sodium silicate at zero, 300 g/t and 500 g/t oil addition. The relative difference between Pt and Pd grades and recoveries were calculated as follows:

$$Relative\ difference\ in\ grade\ (\%) = \frac{Grade\ with\ NaSi - Grade\ without\ NaSi}{Grade\ without\ NaSi} \times 100$$

Relative recovery differences were calculated in the same way.

Fig. 8 shows that there were large improvements in the grade when using sodium silicate at all conditions of oil addition. The normal ore had the greatest improvement in grade when no oil was present, and improvements were less at 300 and 500 g/t oil addition. However, they were still substantial, being about 35 % better than when no sodium silicate was used. Similar results were observed for Pd.

Recovery improvements were variable. Recovery decreased upon the addition of sodium silicate for the normal ore, becoming worse as the oil dosage increased. However, for the altered ore, when oil was present, addition of sodium silicate improved the Pt recovery by 16 to 22 % (and similarly for Pd). This is similar to the findings of McFadzean et al. (2023) who found that sodium silicate addition was most useful when there was a high alteration mineral content since it was then that the dispersant effect of sodium silicate had the greatest benefit. In addition,

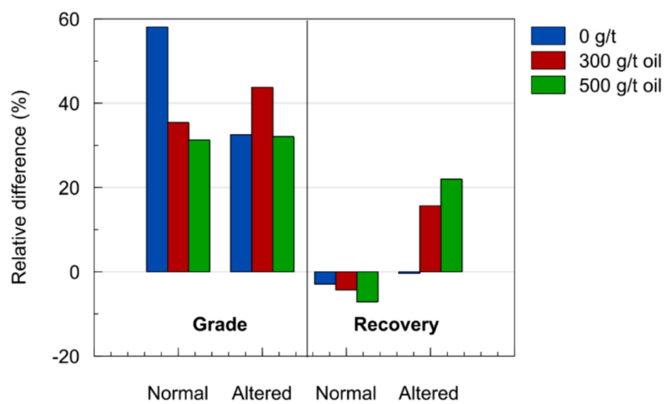

Fig. 8. Relative platinum grade and recovery difference between conditions with no sodium silicate and conditions with 1500 g/t sodium silicate. Sodium silicate was tested at zero oil addition, 300 g/t and 500 g/t oil addition.

these authors found that if the mass pull was managed during sodium silicate addition, that the lost recovery could be regained by pulling more mass. In effect, recoveries per unit solids recovery were found to be greater when using sodium silicate.

3.6. Interaction mechanism between oil and particles

Fig. 9 summarises the proposed interactions between oil and minerals for the two ores. The addition of the oil to the normal ore resulted in the adsorption of the majority of the oil on the particle surfaces, which was further postulated to have caused the agglomeration of finely milled particles, especially talc (Polowczyk and Kozlecki, 2017; Sabir, 2015; Yang et al., 2012). As a result, the talc-oil agglomerates gave rise to increased froth stability (34 %) as well as increased slurry viscosity. The improved froth stability led to non-selective recovery of gangue minerals as evidenced by the concentrate mineralogy results, subsequently reducing the Pt and Pd grade. These gangue minerals comprised orthopyroxene, talc, plagioclase, and chromite. The oil had no negative

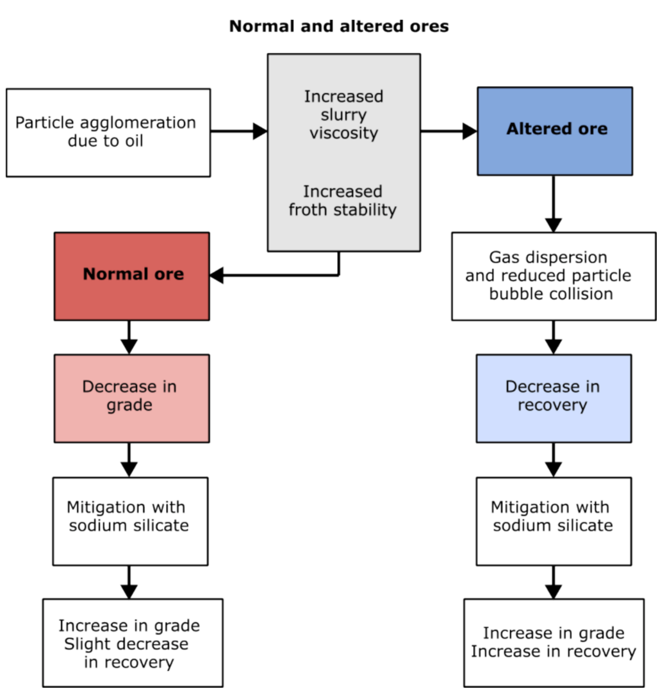

Fig. 9. A schematic outlining the proposed mechanisms causing decreased flotation performance in each UG2 ore (normal and altered) and the mitigation strategies explored.

effect on the recoveries. It was further found that no selective recovery of oil coated solids to either the concentrate or the tailings was observed in the normal ore. To mitigate the effects of the oil addition, 1500 g/t of sodium silicate ($Na_2O:SiO_2$) was used. The addition of sodium silicate improved the Pt and Pd grade, and this was attributed to better gangue drainage in the froth phase. In terms of recovery, a slight decrease in recovery was observed, which was attributed to reduced solids recovery in the presence of sodium silicate.

The altered ore had higher phyllosilicate alteration content (particularly talc) in comparison to normal ore. This is thought to have resulted in greater talc agglomeration compared to the normal ore, which further increased both the froth stability and slurry viscosity. The viscosity was higher in the altered ore compared to the normal ore due to the higher alteration mineral content and talc agglomerates formed by oil. The increased viscosity was inferred to cause poor gas dispersion and reduced bubble-particle collisions, leading to the recovery losses, 6 % drop for Pt and 12 % for Pd. The recovery loss was further explained by the oil adsorption study which showed that the majority of the oil coated solids selectively reported to the tailings. With regard to the grade, the oil had a negligible effect. The addition of 1500 g/t sodium silicate increased the baseline recoveries of Pt and Pd by 8 and 6 %, respectively. This was attributed to sodium silicate reducing the slurry viscosity and thereby preventing poor gas dispersion and reduced bubble-particle collision problems. With respect to the grade, sodium silicate improved both Pt and Pd grades because of improved froth drainage.

When implementing sodium silicate as a potential mitigation strategy, one however, must be cognisant that it also significantly reduces froth stability (Molifie et al., 2023) and therefore froth recovery must also be carefully managed to avoid any further detrimental effects.

4. Conclusions

The bulk mineralogical composition of the normal and altered UG2 ores revealed the dominant minerals were chromite, pyroxene, and plagioclase (in decreasing order of abundance). In terms of the alteration minerals, the altered ore had relatively high proportions of phyllosilicate alteration minerals (about 9 wt%) in contrast to the normal ore (about 6 wt%). Talc was the predominant alteration mineral, 6 wt% in the altered ore and 3.8 wt% in the normal ore. The addition of hydraulic oil in these ores resulted in different interaction mechanisms. The grade dilution observed in the normal ore was ascribed to the increased froth stability which led to the increased recovery of gangue minerals. With respect to the altered oil, the addition of oil (0–500 g/t) had far less effect on Pt and Pd grade but showed an overall gradual decrease in recovery (Pt − 6 % and Pd −12 %). The increased viscosity was postulated to cause poor gas dispersion and reduced bubble-particle collisions as well as slime coating by ultra fine particles, leading to recovery losses.

The addition of sodium metasilicate mitigated the deleterious oil effects with regards to flotation grade and recovery by improving the froth drainage as well as increasing the dispersion of particles, further reducing the slurry apparent viscosity. This study demonstrated different interaction mechanisms of oil with dominant effects in either the froth or the pulp leading to the observed reduction in grade for the normal ore and recovery for the altered ore. High phyllosilicate mineral contents lead to interparticle interactions in the presence of oil, which resulted in increased viscous effects. Mitigation with sodium metasilicate improved both the grade and recovery. This study highlights the potentially harmful effects of hydrocarbon spillages in mechanised mining and the complex interactions with alteration minerals within the ore.

CRediT authorship contribution statement

T.A Tshinavhe: Writing – review & editing, Writing – original draft, Formal analysis. **B. McFadzean:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **G. Nwaila:** Writing – review &

editing, Supervision, Funding acquisition, Conceptualization. **M. Becker:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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