**Mineralogical and Textural Controls on the Magnetic Separation of Fe–Ti Oxides from Apatite-Rich rocks in the Upper Zone of the Bushveld Complex.**

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Apatite-rich rocks represent significant Fe-Ti-P mineralisation in the upper zone of the Bushveld Complex. This study investigates the mineralogical and textural controls on the magnetic separation of Fe-Ti oxides from two apatite-rich layers. Representative samples from the two layers were crushed, milled, and sieved into four size fractions. Each fraction was subjected to magnetic separation using Frantz Isodynamic Magnetic Separator at varying current settings to assess the recovery and concentrate quality.

The results demonstrate that magnetite is recovered at lower current settings, whereas ilmenite is concentrated in the intermediate current settings with iron-rich silicates (olivine, orthopyroxene and amphibole). The process produced an appetite- and plagioclase-enriched non-magnetic fraction. However, there was significant apatite recovery in the magnetic separates from lower to intermediate current settings. These findings demonstrated that mineralogical composition, texture, and mineral association are primary controls of concentrate quality and mineral recovery.

**Keywords**: Fe–Ti oxides, magnetic separation, automated mineralogy, association, liberation, Frantz Isodynamic Magnetic Separator

## 1. Introduction

The upper zone (UZ) of the Bushveld Complex is an iron, titanium, phosphorus, and vanadium resource (Fischer and Yuan, 2016; von Gruenewaldt, 1993; Tegner et al., 2006).) Mandende et al. (2023) identified apatite-rich zones in the uppermost UZ using a hyperspectral core scanner. Mandende and Mothupi (2024) demonstrated that these zones contain significant apatite, ilmenite and titanomagnetite, with apatite containing significant REE concentrations. The economic importance of these rocks depends on the ability to separate and concentrate the valuable minerals. Mandende and Mothupi (2025) showed that liberation of valuable minerals in the apatite-rich UZ rocks is higher in finer fractions (-45/+45 μm and -212+45 μm). A flowsheet involving magnetic separation of Fe-Ti oxides and flotation of apatite from magnetic separation tailings was proposed.

Despite increasing recognition of the Bushveld Complex UZ as a potential multi-commodity resource, limited work has directly evaluated its mineralogical and textural controls on magnetic separation. This study investigates the magnetic separation of the Fe-Ti-P ore to determine how particle size, mineral magnetic susceptibility, mineral liberation, and associations control the deportment of titanomagnetite, ilmenite, apatite, and gangue minerals. Magnetic separation using Frantz Isodynamic Magnetic Separator (FIMS) was followed by chemical and mineralogical analysis of the feed, magnetic and non-magnetic fractions.

## 2. Materials and Methodology

### 2.1 Sample selection and preparation

The samples were obtained from two apatite-enriched zones intersected in BV-1, between 236 and 260 m, referred to as the ‘upper apatite zone’, and from 558 – 572, referred to as the ‘lower apatite zone’. The BV1 core showing apatite mineralisation is provided in Figure 1.

The samples were crushed and milled to 100% passing 425 μm using jaw crusher and roller mill, respectively. Two bulk composite samples were obtained, with BV49 representing the upper apatite zone and BV51 the lower apatite zone. The composite samples were screened into four size fractions -425/+212μm, -212/+106μm, -106/+45μm and -45μm. The -45μm fraction was excluded from the sequential magnetic extraction.

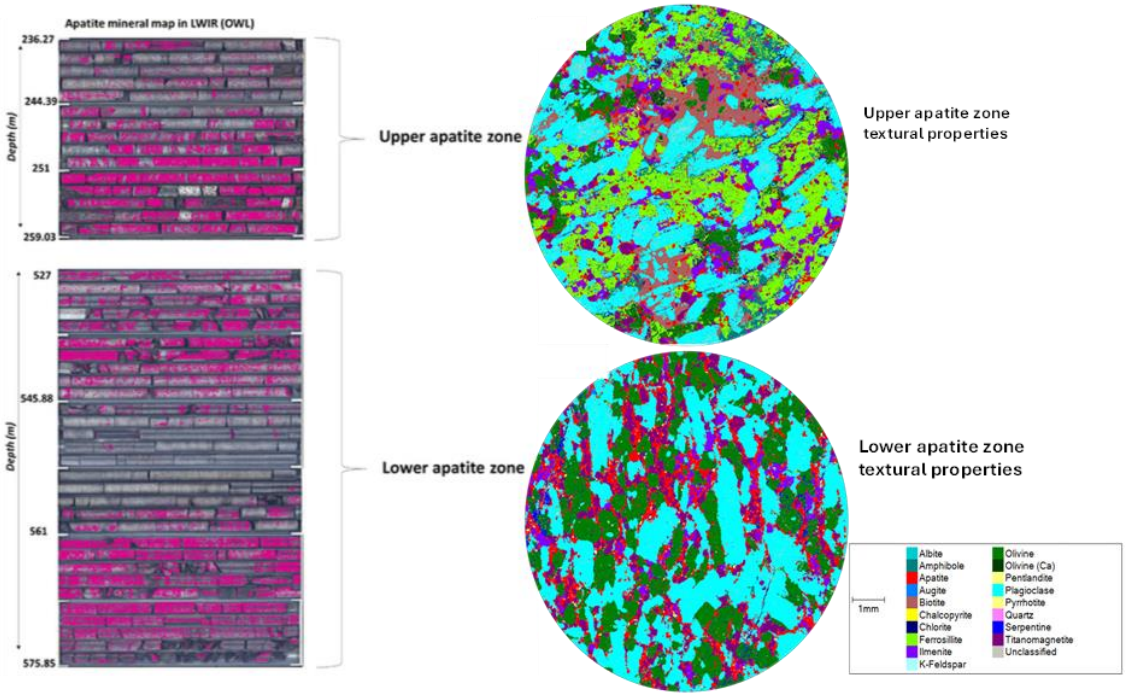


*Figure 1: Apatite mapped by hyperspectral core scanner and automated SEM-EDS mineral maps (modified from Mandende and Mothupi, 2024; Mandende et al 2023)*

## 2.2 Chemical and mineralogical characterisation

Chemical and mineralogical characterisation was conducted on the bulk BV49 and BV51 bulk composite samples, individual particle-size fractions, and sequential magnetic separation products using XRD and automated SEM-EDS.

### *2.2.1 XRF analysis*

Bulk chemical analyses were performed by wavelength-dispersive X-ray fluorescence (WD-XRF) using a PANalytical Axios spectrometer on fused beads. Major oxides, including $SiO_2$, $TiO_2$, $Al_2O_3$, FeO(t), MgO, CaO, $Na_2O$, $K_2O$, and $P_2O_5$ were analysed.

### *2.2.2 XRD analysis*

The samples were analysed using a Bruker D8 diffractometer with a Co Kα radiation tube. A 5 to 80° 2θ angular range was used, with a step size of 0.02° 2θ and a counting time of 0.2 seconds per step. Minerals were identified using Bruker EVA® software and quantified by the Rietveld refinement method using TOPAS® software. Major-element oxide chemistry was back-calculated from the XRD data and compared with measured XRF results to validate the data.

### 2.3 Sequential magnetic separation

Magnetic separation was performed using a Frantz Isodynamic Magnetic Separator (FIMS) model LB-1. Increasing electromagnetic current allows progressively less magnetic particles to be extracted (McAndrew, 1957; Wills & Finch, 2016). Previous studies have shown the benefits of integrating magnetic separation with mineral liberation and particle-scale mineralogy to understand separation behaviour (Leißner et al., 2016 and Siddique et al., 2023)

A permanent hand magnet was used to remove strongly magnetic particles before sequential magnetic separation. The non-magnetic portion of the sample was subsequently subjected to sequential magnetic extraction at increasing currents of 0.02 to 0.60 A. The magnetic concentrates at each current and the final non-magnetic material after 0.6 A were collected and weighed. The Frantz separator was operated at a forward slope of 20° and a side slope of 25. The feed rate and residence time were kept constant for each size fraction treated.

## Results

### 3.1 Bulk chemistry and mineralogy

The bulk composite samples BV49 and BV51, selected from the apatite-rich zone of the Upper Zone of the Bushveld Complex, were analysed by XRF. The results (Table 1) demonstrate that both samples have elevated FeO(t), TiO2 and $P_2O_5$, as evidence for iron, titanium and phosphorus mineralisation.

*Table 1: Major oxides composition of the bulk composite samples from the apatite-rich zones*

| Oxide | BV49 | BV51 |
|---|---|---|
| $SiO_2$ | 28.7 | 29.1 |
| $TiO_2$ | 8.1 | 6.3 |
| $Al_2O_3$ | 9.1 | 10.1 |
| FeO(t) | 28.8 | 29.1 |
| MgO | 2.8 | 4.5 |
| CaO | 11.2 | 11.3 |
| $Na_2O$ | 1.7 | 1.8 |
| $K_2O$ | 1.0 | 0.3 |
| $P_2O_5$ | 6.3 | 5.6 |

The quantitative XRD results (Figure 2) indicate that the composite samples comprise a Fe-Ti-P mineral assemblage and mafic silicates.

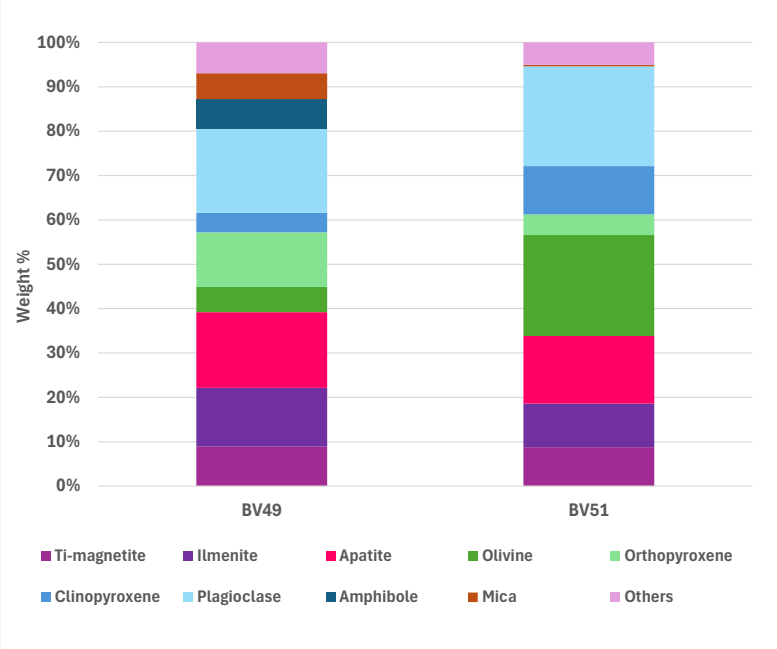


*Figure 2: Modal mineralogical composition of the two bulk composite samples from the apatite-rich zones*

### 3.2 Magnetic separation

The results (Figure 3) of the sequential magnetic separation indicate differences in mass pull between BV49 and BV51 samples. The mineralogical composition of the head (-212+106µm) and magnetic separates is presented in Figure 4.

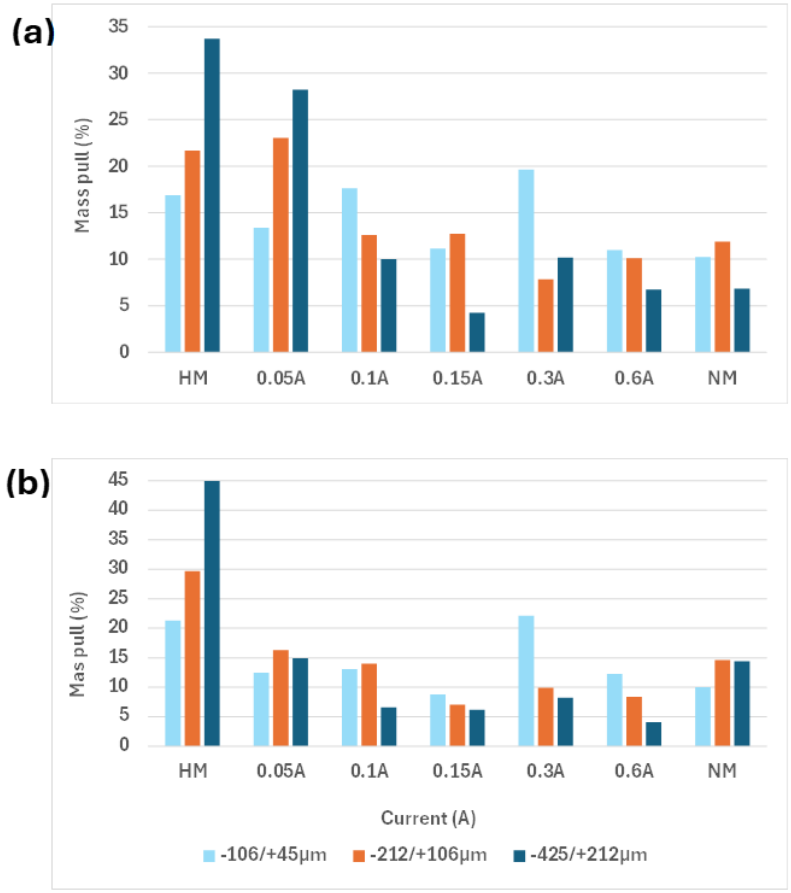


*Figure 3: Magnetic response of the two samples BV49 (a) and BV51(b) fractions with increasing magnetic current, including hand magnet (HM) and non-magnetic (NM) fraction*

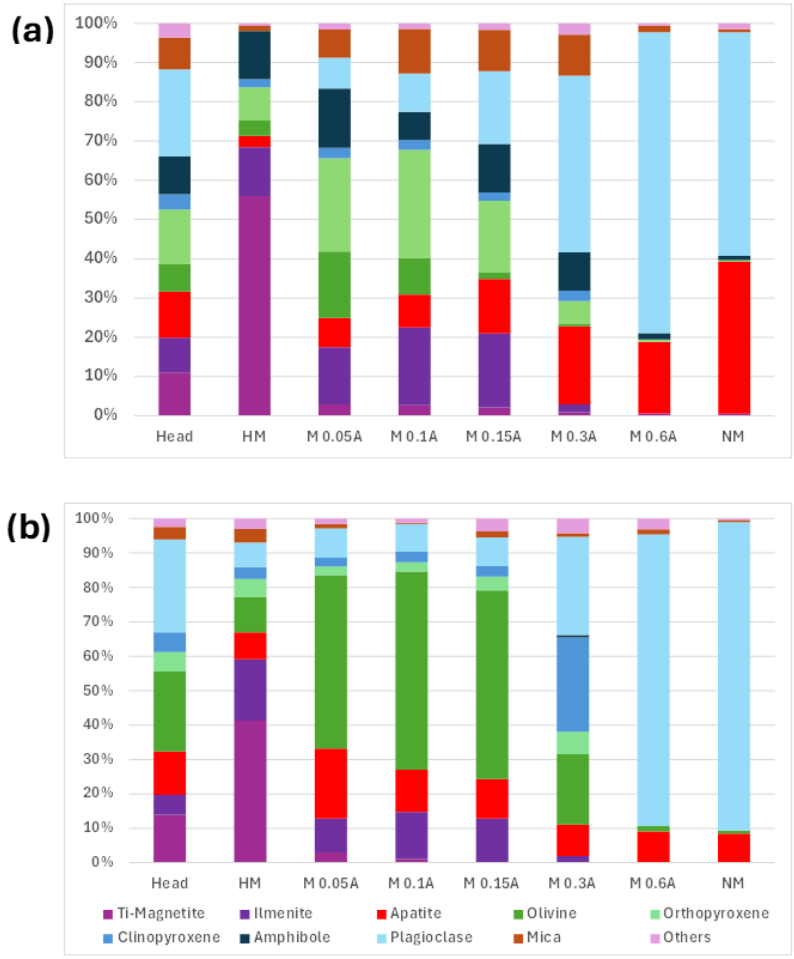


*Figure 4: Mineralogical composition of the feed (-212+106 µm) for the BV49 (a) and BV51(b) composites, magnetic and non-magnetic products*

## 3. Discussion

The sequential magnetic separation results for +106 µm fractions (BV49 and BV51) show a progressive change in modal mineralogy with increasing magnetic current. The hand-magnetic products were strongly enriched in titanomagnetite, and Ilmenite was concentrated mainly in the low- to intermediate-current separates (0.05 to 0.15A). Olivine and orthopyroxene were enriched in the intermediate currents, showing similar behaviour to ilmenite.

Apatite also showed different behaviour in the two samples. In BV51, apatite was enriched in the lower current separates, reaching 22.1% at 0.02A, whereas in BV49 it was concentrated in the non-magnetic product (38.6%). This difference suggests that apatite deportment was affected by its association with Fe-Ti oxides and paramagnetic silicate minerals.

At higher magnetic currents, plagioclase became strongly enriched in both samples, reaching 76.7% at 0.60 A in BV49 and 84.8% in BV51. The non-magnetic products were also dominated by plagioclase. Overall, the results indicate that increasing magnetic current progressively separates particles according to their magnetic properties, but the recovery is influenced by liberation, inclusions, and mineral associations. Automated SEM-EDS mineralogy data will provide more evidence of mineralogical and textural controls on magnetic separation.

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