Mineralogical characterisation of Matsitama banded iron ore

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Abstract. A recently discovered Banded Iron Formation (BIF) deposit on the outskirts of a village called Matsitama in the Central part of Botswana, remains unexploited due to inadequate knowledge of its mineralogy and economic value. Currently, Botswana relies on imports in order to satisfy all its iron and steel needs. Exploitation of the Matsitama iron deposit is of critical importance from a socio-economic point of view. To assess the viability and sustainability of potential economic exploitation of the deposit, characterization studies must be conducted on the ore. In this study, chemical and mineralogical examinations were carried out. Mineralogical examination was performed using X-ray Diffraction (XRD), X-ray Fluorescence (XRF) and specific gravity by pycnometer techniques were employed in this investigation. QEMSCAN technology was used to assess bulk mineralogy (BMA) and provide Particle Map Analysis (PMA) of the ore. Major minerals analysis by XRD showed that the ore mainly comprise 54.40% hematite, 44.00% quartz, 1.10% magnetite and 0.50% goethite minerals. XRF analysis established that the ore contains 55.9% Fe2O3 and 44.2% SiO2, with minor amounts of Al2O3, Cr2O3, P2O5 and TiO2 elements. QEMSCAN analysis indicated that 75% of the hematite is fully liberated and 25% associated with quartz. Characterization results showed Matsitama ore to have a moderate hematite grade, silica but low concentration of deleterious elements (<1%) which conform to generally acceptable limits for commercially traded iron ores.

1. Introduction
In recent years Botswana has experienced substantial growth in developments particularly in the construction industry which is a major consumer of iron and steel products. Despite this position, the country relies on imports in order to meet all its demand for iron and steel, with no local production. The Banded Iron Formation (BIF) deposit discovered in Matsitama is of significant importance to the socio-economic development of the nation and presents an opportunity to put Botswana on the world map as an iron ore producing country. Located near Matsitama village in the Central District of Botswana, about 100km west of the city of Francistown (figure 1), this deposit lies unexploited and has not been studied comprehensively.
From a geological context, iron occupies about 5% of the earth’s crust, making it one of the most abundant mineral resources (1). BIFs are the largest sedimentary type of iron ore deposits which occur through precipitation from mineral solutions and date back to the Precambrian period (2). They characteristically consist of alternating layers of iron oxide and silica and they are the major resource of iron ore for the world’s current production. (3,4). The increasing global demand for iron ore fuelled by massive consumption of steel worldwide is challenged by the depletion of high grade ores and stringent environmental regulations imposed on the iron and steel industry (5,6).

Chemical and mineralogical characterisation of Matsitama iron deposit will allow for the preliminary evaluation of its economic viability and guide the design of suitable processing routes as well as optimisation of downstream processes. In this study, the quality of Matsitama ore is compared to other hematite BIF ores in South Africa.

2. Materials and methodology

Samples of the Matsitama deposit were collected from surface outcrop as rocks. About 20 chunks of ore samples were collected from the same location and lithology as there were no potentially different ore types identified at the time of sampling. Representative samples were taken to SGS South Africa for chemical and mineralogical analysis using the following technologies:

- X-ray Fluorescence (XRF) - major element analysis
- Pycnometer - specific gravity testing
- X-ray diffraction (XRD) – Quantitative mineral phases
- QEMSCAN Bulk Modal Analysis (BMA) and Particle Map Analysis (PMA) – quantitative mineral analysis, iron deportment, mineral liberations and associations, grain size distributions

2.1. Sample preparation

Three Fe ore rocks (blocks) being analysed were cut in half. A half from each block was combined to make two composite samples as shown in figure 2. One of the composites was stage crushed to 100% passing 1mm. The crushed ore was split into two representative aliquots. A representative sample (10 – 15 g) was split out from one of the crushed aliquots to prepare two polished samples for QEMSCAN analysis. About 50g of the other representative portion was pulverized for XRD, XRF and Specific gravity testing analyses.
2.2. Quantitative X-ray diffraction
In this investigation the constituents of the samples were studied using X-ray diffraction data obtained from a PANalytic X’Pert PRO diffractometer with a Cu tube X-ray source. The radiation used was a Cu K-α with a wavelength of 1.540598 Å within the values of 2θ between 5 and 90 degrees at steps of 0.029 degrees with a time of 0.45sec/step.

2.3. QEMSCAN
QEMSCAN technology is an automated electron beam technique that functions on a Scanning Electron Microscopy (SEM) platform with four light-element Energy Dispersive X-ray Spectrometers (EDS) (Ayling et al., 2012). In this study, a QEMSCAN 650 instrument was used for analysis. Polished sample blocks were analysed using Bulk Modal Analysis (BMA) to confirm the bulk mineralogy as previously determined by XRD. Particle Map Analysis (PMA) was used to determine iron elemental deportment, iron mineral liberations and associations as well as grain size distributions. The PMA mode is suitable for detailed characterization of mineral particles up to 1mm in size (7).

2.4. X-ray fluorescence
Borate fusion XRF was used for identification of major minerals occurring in the ore sample.

2.5. Pycnometer
Specific gravity of the ore was determined by pycnometer method

3. Results and discussions
3.1. X-ray fluorescence
The results of the XRF analysis in table 1 show that the ore sample contained 55.9% and 44.2% of Fe₂O₃ and SiO₂ respectively. The ore contains 0.028% phosphorus which is low and acceptable as compared to the upper limit of 0.11% imposed by the steel industry. Phosphorus is regarded as an impurity due to its detrimental impacts in steelmaking (8). In addition, the ore contains a considerably negligible amount of alumina (0.14%). Exploitation of Matsitama ore would require significant size reduction to liberate Fe oxides and the ore would therefore be marketed as iron ore concentrate for pellet feed or fines for sinter feed. Alumina is beneficial for forming the SFCA bonding phases (9) which are the most desirable bonding phases in iron ore sinter (10).
Table 1. XRF results for iron ore sample.

| Elements  | Detection limits % | Assay % |
|-----------|---------------------|---------|
| Al₂O₃     | 0.05 - 100          | 0.14    |
| CaO       | 0.01 - 100          | <0.01   |
| Cr₂O₃     | 0.01 - 100          | 0.06    |
| Fe₂O₃     | 0.01 - 100          | 55.9    |
| K₂O       | 0.01 - 100          | <0.01   |
| MgO       | 0.05 - 100          | <0.05   |
| MnO       | 0.01 - 100          | <0.01   |
| Na₂O      | 0.05 - 100          | <0.05   |
| P₂O₅      | 0.01 - 100          | 0.028   |
| SiO₂      | 0.05 - 100          | 44.2    |
| TiO₂      | 0.01 - 100          | 0.02    |
| V₂O₅      | 0.01 - 100          | <0.01   |
| LOI       | (-)50 - 100         | 0.21    |
| SG        | 0.01 – 13           | 3.66 (no units) |

Matsitama ore contains 54.4% hematite, corresponding to a medium grade ore. It is also evident that the ore is significantly contaminated with quartz which is the silica-bearing mineral. The silica content is very high (44.00 % SiO₂) compared to the generally accepted level of 6% for commercial ores.

3.2. Specific gravity by pycnometer
The specific gravity of the ore sample was found to be 3.66. Quartz has a specific gravity of 2.7 while that of hematite is about 5.3. The concentration criterion for this ore was found to be 2.53 which indicates that gravity separation should be relatively easy. The concentration criterion is a density quotient which gives an idea of the type of separation possible for an ore; when the value is greater than 2.5 then gravity separation is relatively easy (11).

3.3. X-ray diffraction
The results obtained from quantitative analysis by XRD shown in table 2 indicate that Matsitama ore comprised ~54% hematite, ~44% magnetite, ~0.5% goethite and ~44% quartz. The diffractogram in figure 3 shows that these were the only detected mineral phases in the sample. Hematite was the most abundant iron containing mineral phase present in the sample making up ~97% of the Fe oxide/hydroxide group.

Table 2. Crystalline mineral phases and their abundances (values normalized to 100% of the crystalline proportion of the sample) as determined by XRD

| Mineral    | Approximate formula | Approximate abundance % |
|------------|---------------------|-------------------------|
| Hematite   | Fe₂O₃               | 54.40                   |
| Quartz     | SiO₂                | 44.00                   |
| Magnetite  | Fe₃O₄               | 1.10                    |
| Goethite   | α- FeO•OH           | 0.50                    |
| Total      |                     | 100.00                  |

3.4. QEMSCAN
The bulk mineralogy of the iron ore as determined by QEMSCAN BMA analysis is presented in table 3. The investigation established that the iron oxide/hydroxide group constituted 56% of the sample. Quartz was identified as the major gangue mineral with other minerals occurring as traces.

Table 3. QEMSCAN bulk modal analysis results.

| Mineral          | Approximate abundance |
|------------------|-----------------------|
| Fe Oxides/Hydroxides | 56.25                |
| Quartz           | 43.70                 |
| Pyroxene/Amphibole | 0.04                  |
| Other            | 0.01                  |
| Total            | 100.00                |

Figure 3: XRD diffractogram of ore sample.
Figure 4 shows SEM images of minerals detected in the ore sample and their quantities. The light particles are Fe$_2$O$_3$ and the dark particles are SiO$_2$. Particles with ‘in between’ shades are also depicted.

Figure 5 shows that 74.97% of Fe oxide/hydroxide was fully liberated, 20.51% was present in the middlings while 4.52% was associated with quartz. The grain size distributions curve of the two major components making up the sample (Fe oxides/hydroxides and quartz) is presented in figure 6. Approximately 70% of the Fe oxide/hydroxide is greater than 45µm grain size range. It can be deduced that there is an almost even distribution of Fe grains in different size fractions.
In assessing the liberation characteristics, four classes were considered:

- Liberated – more than 80 % area of the particle is the mineral of interest
- High (Hi) middlings – between 50 and 80 % area of the particle is the mineral of interest
- Low (Lo) middlings – between 30 and 50 % area of the particle is the mineral of interest
- Locked – less than 30 % area of the particle is the mineral of interest.

![Figure 5: Percentage mass liberation of Fe oxide/hydroxide](image)

4. Conclusions
From mineralogical and elemental analysis, it can be concluded that:

- Matsitama iron ore constitutes of hematite, magnetite, goethite and quartz minerals.
- The ore has a relatively low iron content (about 56% Fe), a high level of silica gangue (about 44%), with a low concentration of deleterious elements.
• From our literature reviews, Matsitama ore deposit can be considered economically recoverable based on its grade, however, the size of the deposit and processing requirements must be determined as they significantly affect feasibility of ore exploitation.
• Further work is necessary to estimate the size of the deposit and also to assess the sustainability of resource exploitation.
• Concentration criterion for the ore was determined to be 2.53, indicating that gravity separation can be easily achieved.
• If processed, the ore will be milled significantly, meaning it would be marketed as iron ore fines for sinter feed or iron concentrate for pellet feed.

South Africa has massive iron ore deposits with varying iron content. The Sishen and Thabazimbi deposits are reported to have Fe content of 64.8% and 61% respectively. These are high grade shipping ores which in most cases do not require beneficiation. These high grade hematite ores are reported to have benefited from supergene enrichment over years. Literature review revealed the presence of ore types containing 57.6% hematite associated with 37.5% silica. These ores are similar with Matsitama ore in hematite grade, but they have undesirable associations.

5. Recommendation for beneficiation
Characterization of Matsitama ore showed that the ore was moderate grade hematite and requires proper beneficiation before metal extraction. Liberation studies show that the two major constituent minerals (hematite and quartz) are liberated at around 45 microns therefore the ore can benefit from stage grinding at about 90% passing 50µm. The concentration criterion for this ore is more than 2.5 therefore concentration by gravity separation is encouraged. Spirals may be sufficient to enrich the ore to a grade that is acceptable for metal extraction. The middlings can be further milled to a finer size to liberate the hematite from quartz and spiralled again. Further purification may be obtained by using wet high intensity magnetic separation to achieve a required grade.

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