A metallurgical evaluation of a heavy mineral sand deposit based on stratigraphic unit classifications

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This paper discusses pilot and laboratory-scale metallurgical test work conducted on bulk samples from a low grade heavy mineral deposit and provides an overview of basic practical metallurgical techniques applied to ascertain the suitability of existing production plants to process material from this orebody. Previous investigations have shown this specific orebody to be more challenging in terms of mineral beneficiation as it has a high gangue mineral content.

Test work was conducted on targeted stratigraphic units based on lithology and assay results to enable identification of the stratigraphic units portraying quality issues. Unit specific metallurgical pilot work has never been conducted on any of the RBM orebodies and is a new field currently being explored. During this investigation focus was placed on potential quality and yield issues for ilmenite product, with particular reference to CaO quality. A basic evaluation of zircon and rutile separability was also conducted.

The test work was conducted using a comparative baseline methodology with metallurgical test work methods specifically aiming at mimicking the existing production plant as closely as possible. This enabled not only the likely metallurgical performance to be assessed but also indicated whether current plant design would be suitable to process the low grade ore types into products of acceptable quality at acceptable yields.

The methods and findings discussed in this paper indicate that although there is considerable variation between different units, a blended feed can be successfully processed. With unit specific metallurgical data applied to the existing geological block model, expected yields and recoveries using current plant designs could be predicted.

Introduction

Part of the RBM ore reserve was known to be of lower quality, containing a higher abundance of gangue minerals when compared to the rest of the orebody currently being mined. Preliminary investigations on this lower grade ore indicated a potential difficulty in achieving a quality ilmenite product (hereafter referred to as roaster feedstock (RFS)) for feed into the roasting process to prepare smelter feed.

Over the life of the current mining operation, the orebody has changed significantly in terms of grade and complexity. In recent years the importance of mineralogical and subsequently metallurgical properties associated with different geological units has therefore come under the spotlight. Consequently, an additional facet added to the investigation of the low grade orebody was the decision to process bulk samples of specific stratigraphic units instead of taking random bulk samples of the deposit (as was the norm during historic pilot scale work). This allowed the pinpointing of inferior performing units and the ability to quantify and mitigate their impact on operations over the life of mine. Understanding the effect of different units on the process can be useful in predicting metallurgical performance and allows the process metallurgist the opportunity to anticipate and react to metallurgical issues in the plants during the beneficiation process.

The ultimate question to be answered by the investigation was:

- Would mining the low grade area require the development of new plant flowsheets or additional circuits?

Being adjunct to the following:

- How does one prove or disprove this need, using basic techniques and resources within a limited timeframe and budget?
- How does one apply laboratory and pilot-scale simulated test results to reflect and predict the reality in an already operating plant?

The paper will discuss the very basic approach devised to address these questions.

Test methodologies

Bulk sample processing to produce heavy mineral concentrate (HMC)

Approximately 20 tonnes of material was hauled from nine sites under the supervision of an experienced geologist. The positions of the bulk samples were chosen to be representative of the geological units occurring in the low grade area (Table I). Units are classified based on grade, slimes contents, relevant mineral ratios and colour logged in the field.

The bulk samples were processed using a five-stage pilot scale spiral concentrator circuit to produce HMC for further processing (Figure 1).
Test work approach

A simplified illustration of the plant circuit preparing HMC from the mining process into roaster feed (RFS) and dry mill feed is provided in Figure 2. The circuit has several scavenging circuits built into it, to ensure optimal recoveries are maintained.

A pilot simulation of this type of production plant would require large quantities of test material. The final HMC produced from each unit sample was ±300–800 kg making it impractical to attempt conventional staged simulation of these circuits. Another approach therefore had to be adopted.

A basic test work programme was designed to give a reasonably comparable outcome to actual plant results, within the practical limitations of basic pilot and lab scale test work methods. To validate the success with which the low grade material could be processed through the current feed preparation (Figure 2) and dry mill circuits, the test and evaluation methods were conducted using ‘baseline comparison’. During the test work programme, current run of mine HMC was subjected to the same tests to produce results that could be compared to that obtained for the low grade material. The premise for this approach was that if the products obtained from the low grade ore samples were comparable or superior to that of the current baseline material, the potential to process the low grade material with similar success via the current plant would be confirmed.

The actual results obtained for current run of mine HMC processed via the production plants was used to indicate a possible up or down scaling factor that could be applied to the test work results.

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Table 1

Unit types and their contribution to the low grade area

Figure 1. Five stage gravity separation

Figure 2. Conceptual flowsheet of current feed preparation plant circuit
The test work programme incorporated two wet high intensity magnetic separation (WHIMS) stages and gravity separation to upgrade to final product quality. Pilot and laboratory scale test equipment was calibrated, using current plant feed, to achieve comparable performance to the corresponding plant areas. The last leg of the testwork included a bench scale investigation on the separability of the dry mill feed produced into zircon and rutile products. Figure 3 illustrates the test work flowsheet.

**Figures:**
- Figure 3. Test work flow sheet
- Figure 4. Pilot plant WHIMS unit

**Flowsheet development and calibration of equipment using baseline referencing**

Before processing of the HMC could begin, a scoping exercise had to be conducted to establish optimal settings and confirm the testing methodology. The scoping tests aimed to simulate the feed preparation process as closely as practically possible on the pilot plant WHIMS machine. Subsequently material from each bulk sample could be compared with the run of mine baseline samples processed. The use of the baseline samples also allowed the accuracy and repeatability of the method to be assessed.

As the pilot WHIMS is a different model (8 pole, 68 mm rotor) to those used in the feed preparation plant (16 pole 120 mm rotor), determining the operating window for the pilot plant WHIMS involved running matrix tests with varying feed rates and coil current settings. The settings finally chosen for the test work were based on the results obtained during the matrix tests that delivered the most comparable results to that of the plant (when processing the same material).

Initial scoping tests where conducted on 20 kg batch samples of HMC representing each bulk sample. The goal of this phase was to identify the need for a second stage and to identify bulk samples with potential quality or separability issues. During the scoping stage the need for further cleaning of the non-mags using a second WHIMS stage was identified. The non-mags and mids from the first stage were combined and fed to a second WHIMS stage set up to optimize rejection of magnetics (mags). Mags product from the second stage was then combined with the mags product from the first stage for CaO grade control (Figure 3).

**Upgrading WHIMS product to suitable roaster and dry mill feed**

Calcium grade control in the preparation plant (refer to Figure 2) is achieved via a two-stage gravity (spiral) separation circuit (Figure 2). For the test work programme table separation was opted for as CaO grade control method as it operates using the same principles as spiral separation and the feed sample required for a representative test would be much smaller (Figure 5). The set-up of the lab-scale Wilfley shaking table also allowed for better feed rate and visual product split control when compared to the available pilot-scale spiral set-up. In addition the mags product generated from the WHIMS stages was limited, therefore making the use of pilot-scale spiral test work unviable.

As this method could still not be directly compared to spiral separation, reference samples of actual feed to the production plants’ CaO control circuit were processed on the table to compare the tables’ general performance with regard to mass yield and recovery. This stage also helped with optimizing the table settings for the CaO grade control phase of the test work. The results were compared to samples of the final concentrate produced by the plants’ grade control circuits for that feed.
The Wilfley table settings were chosen to maximize the amount of material going to concentrate to reduce any excessive loss of ilmenite product to tails.

During this stage the feed material was relatively homogeneous making the visible separation of the CaO rich minerals difficult to observe during the test. Therefore, in most cases, splitting aimed for a tails yield of approximately 5–10%. Where separation was clearly visible the aim was to reject CaO bearing minerals such as garnet (generally coarser grained pink to red coloured minerals, colours varying depending on elemental composition). The non-magnetic product from the WHIMS stages were also upgraded using the Wilfley shaking table to remove excessive quartz and mag others (MO). To obtain optimal settings for the tests the scoping exercise was conducted in a similar manner. In this case a visible quartz band helped with cutting the correct portion of material to tails.

Tabling was very effective in upgrading both the mags and non-mags product off the WHIMS stages, and produced (with some sacrifice to mineral recovery) very comparable products with only one stage of processing where two to three stages of spiral processing would be needed. As the goal was to obtain a comparable product, the fractions were recombined to make up RFS and dry mill feed that resembled the desired specifications for these products. The dry mill feed produced during the test work programme was used for further lab-scale tests to evaluate its separability into zircon and rutile products.

Lab-scale investigation into zircon and rutile separability

The dry mill feed produced by the test work programme was subjected to staged ESP (electrostatic screen plate separation using a lab-scale MK III ESP machine) and staged HT (high tension role separation using the bench-scale Coronastat HT machine) separation tests to generate zircon and rutile products. The basic principle applied was one of multi-stage non-conductors (NC) cleaning using the Electrostatic screen plate (see Figure 6) and middling recycle on the HT separator (Figure 7).

The ESP testing method used has been proven to indicate differences in separation efficiency between different feed types. The test method was therefore to serve as a comparison method and was not intended to simulate the dry mill plant or products generated. During the ESP tests the NC were passed through a number of cleaning stages to produce a final NC. The cumulative conductors from this test were then passed over the HT separator to yield a clean conductor product and the middling stream recirculated until the yield to middlings reached negligible proportions. Unwanted mags and MO that could influence final product grades were removed from the ESP NC (intended zircon product) and the HT conductors (intended rutile product) by a magnetic separation stage. The conductor products were also screened at 180 micron to dispose of any quartz and other entrained gangues minerals present (Figure 8).

Results and discussion

Baseline sample results via test procedure compared to actual plant performance

The test work programme results confirmed that the methods employed gave a fairly accurate prediction of likely yield, grade and qualities obtainable when processing a specific material type through the plant. Figure 9 illustrates selected test work results achieved for RFS. The analytical smelter feed (ASF) grades quoted in Figure 9 are derived via analytical lab analyses methods simulating the roasting and purification process the RFS would be subjected to. It therefore indicates the likely yield and quality of smelter feed the roaster plant would produce. The baseline material (sampled from each mining pond) and the actual plant average for the period in which the samples were collected are compared. Some degree of variability was expected to exist between the test results of different pond materials, depending on their unit composition; however, the average test results seemed to tie in with plant averages reported.

Figure 6. Electrostatic screen plate

Figure 7. High tension role separation
Figure 8. Lab-scale separability comparison test work flow

Figure 9. RFS yield and ASF (analytical smelter feed) grade, recovery and quality

Figure 10. Dry mill feed results via the test work procedure
Variability in the results for the dry mill feed produced was, however, more extensive, especially the variability evident concerning the grade and recovery of NM TiO$_2$, grouped as rutile in Figure 10. This group could include leucoxene and rutile minerals of varying elemental composition. These minerals can exhibit variations in density, depending on the state of alteration. Some units can have high proportions of low quality, low density NM TiO$_2$ present. The low density NM TiO$_2$ could be entrained with other gangue minerals that report to the middlings fraction during gravity separation. During test work this specific type of NM TiO$_2$ can be difficult to recover without reducing the overall product quality in terms of final MO and quartz content. The test work programme could therefore amplify low recovery results for materials with an abundance of low quality NM TiO$_2$. However, variations in NM TiO$_2$ quality would also have occurred in the plant with similar impacts on separation efficiency. This is supported by the test results, which indicate a good comparison between the test method and the plant average reported.

**Unit specific results and identification of quality issues**

It was expected that results for the unit specific material would vary to a larger degree and that it would be possible to identify units portraying unfavourable characteristics in terms of yield and quality. Unit correlation models for current run of mine have shown that correlations exist between achieved plant yields and units mined. During test work the samples from unit 4 displayed problems with reaching acceptable RFS product yield and quality (therefore affecting likely smelter feed quality indicated by ASF data in Figure 11) through the process. Focus was placed on various processing options to deal with only this material to see if further optimization was possible.

![Figure 11. Variation in yield and quality throughout unit types-roaster feed](image1)

![Figure 12. Variation in yield and quality throughout unit types-dry mill feed](image2)
Elevated mags and quartz contents for some of the low grade samples were noted. This indicated possible difficulty with controlling the mags content in dry mill feed produced from the low grade ore and could pose operational difficulties in processing down the line. However, focus was placed on RFS quality and further steps to improve ASF CaO quality inferior performing units.

**Mitigation attempts on high CaO materials and the blending hypotheses**

Several attempts at additional gravity separation stages were made to determine if further rejection of the medium density CaO bearing minerals could be achieved for the unit 4 material. A high proportion of garnets was observed for unit 4 material, which, theoretically, should be removable by gravity separation. These steps did not deliver the desired results. This could be attributed to subtle differences in the garnet minerals’ elemental composition (affecting density) or the abundance of these minerals in the low grade ore samples.

Following this, dry drum rare earth magnetic (DDREM) separation was tested. This method visually indicated that a good separation could be achieved between the MO minerals and the magnetic material. However, lab analysis indicated that the ASF CaO content of the mags product was still above specification. A mineral liberation analyser (MLA) was utilized to investigate this issue. Liberated grains of garnet could still be observed possibly causing high ASF CaO. Depending on their elemental composition some garnet grains can have Fe-rich rims or cores, increasing their density and magnetic susceptibility. This theory would explain the difficulty in separating these minerals during gravity and DDREM stages.

The DDREM mags product was screened to determine if the garnet could be removed by sizing. A slight drop in ASF CaO was observed in the finer grain sizes but ASF CaO results stayed above the desired CaO contents. This indicates that there were gangue mineral grains reporting with the ilmenite throughout the size distribution either as individual grains or inclusions.

A second DDREM test was conducted, with the aim of improving the mags quality by reducing the yield to the mags product. The mags product from this stage of DDREM appeared to have very little garnet and other CaO bearing minerals present, but still analyses indicated high ASF CaO levels.

Normally the roasting process should reject any remaining garnet mineral present, therefore the high ASF CaO levels in a seemingly pure ilmenite sample was not expected. To confirm which minerals in the mags fraction, after roasting and magnetic separation, were contributing to the CaO content, MLA analyses were conducted. With the background of previous investigations there was a strong possibility that the high ASF CaO grade was as a result of titanite inclusions associated with the ilmenite after roasting.

The results of the MLA analysis conducted on the DDREM mags product confirmed the presence of inclusions and some clay coatings. Titanite (CaTiSiO$_5$) was one of most abundant CaO bearing minerals present as inclusions, but not the sole contributor. Other CaO-bearing minerals present after roasting and magnetic separation (mostly as inclusions) included plagioclase, apatite, hornblende, garnet (almandine, pyrope, and grossularite), pyroxenes and altered magnetite.

The presence of inclusion type impurities, though not a new occurrence, seems to be of higher abundance in the low grade orebody, specifically unit 4A. It was observed that unit 4A also displayed a larger grain size when compared to current run of mine units. This could be due to a difference in age and a lesser degree of reworking of this geological unit, hence a smaller degree of liberation of included minerals within the ilmenite grains are seen.

![Figure 13. Grade recovery curve from optimized DDREM stage](image1)

![Figure 14. Distribution of CaO bearing minerals](image2)
Finally, blending was investigated as a possibility for mitigating the effect of low quality units by dilution, being the most practically executable method available. Theoretical calculations show that the mere blending of the low grade ore types should mitigate the effect units like 4A have on quality and yield. Applying blending ratios to actual results proved in most cases to mitigate quality issues. Figure 15 shows selected theoretical blend results illustrating that a blended product would be within desired yield and quality specifications. Blend A demonstrates a weighted average calculated by applying each unit’s volume fraction (based on geological block model information) in the low grade orebody to the unit specific results achieved during test work. Blend B and C are adjusted scenarios of blends that could be encountered when mining different areas in the LG orebody as interpreted by geologists familiar with the orebody (indicated in Table II). These blends were chosen to see if they would result in a major shift in theoretical material behaviour.

Proving the hypotheses — actual blended results

To confirm the relevance of the blending hypothesis the LG ratio (see Table II) was used to make up an actual blended material with the HMC produced from the various units in the low grade orebody and this blend was processed via the test work programme. A theoretical blend result was calculated using the ratios and compared to the actual outcome of the tests. The LG blend ratio was chosen to represent a worst case scenario assuming that 31% of the blended material will consist of high CaO material (although the unit 4 sample associated with high CaO during test work only constitute 10–20% of this orebody). In reality this type of blend will rarely exist as mine and production planning can ensure that more acceptable unit blends are maintained throughout the life of mine. Examples of actual results compared to predicted theoretical results show the relevance of the hypothesis. Most of the actual results were comparable or better than what was predicted. In Figure 16 it can be assumed that the difference in theoretical vs. actual results in terms of ilmenite grade and ASF grade are due to grade recovery relationships.

The blended material was also combined with some of the run of mine baseline samples tested to assess if blending with the low grade ore would negatively affect their performance. The results indicated that blending the low grade ore with current run of mine HMC has no significant negative impact on the potential performance through the preparation plant. Blending with the low grade ore also did not adversely affect the overall quality achieved. The need for changes in plant design was therefore ruled out.

Separability comparison

The final area of investigation aimed at determining the ease with which dry mill feed produced from the low grade ore could be separated into zircon and rutile. The test work

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Figure 15. Examples of theoretical blend results
Figure 16. Examples of theoretical vs. actual blend results—roaster feed

Figure 17. Examples of theoretical blend vs. actual blend results—dry mill feed
had to confirm if the separation efficiency of the geological units in the low grade orebody compared with that of current run of mine. Electrostatic separability can be influenced by a number of variables. Under positive polarity the ESP test method is extremely sensitive to the effect of surface coatings and would indicate if such problems existed for a feed type. Variance introduced by test work conditions, for example humidity, temperature and so forth, was also a concern. To indicate if variance introduced by environmental factors was significant, two identical samples were also tested during each test work run. The results did not indicate any significant variance between the samples tested on different days, and it was deemed relevant to compare the results obtained during the separate test runs.

The staged ESP test results indicated that, in terms of TiO₂ rejection, most of the low grade dry mill feed samples produced from units in the low grade orebody outperformed...
the run of mine baseline sample used during these tests. When plotting TiO<sub>2</sub> recovery to NC against zircon recovery (Figure 21), the low grade unit samples predominately displayed a lower loss of zircon recovery for the same degree of TiO<sub>2</sub> rejection achieved for the run of mine baseline sample. The samples that did not perform as well as the baseline sample were both from unit one in the low grade orebody.

Unit one material generally has higher slimes contents and therefore particles are more likely to have surface coatings. These surface coatings can have an effect on separation and quality by masking or affecting electrostatic properties of a grain (depending on their mineralogy). Back scattered electron (BSE) images of these samples clearly show the presence of coatings on the material (predominantly typical clay coatings, Figure 20).

Figure 21 shows that a large degree of variability in separability exists in dry mill feed produced from different unit samples. This variability has also been observed when processing current run of mine and it was expected that the low grade orebody would display similar variation across geological units.

Another way to evaluate the results obtained is to observe the zircon product yield obtained to reach a fixed TiO<sub>2</sub> grade (Figure 21 and Table III).

The yield obtained for the baseline sample to reach 1% TiO<sub>2</sub> was lower than that obtained for most of the unit specific samples. The cleaning steps involved to reach this grade were also less for most of the unit specific samples. This indicated once again that most of the low grade orebody units separated more efficiently compared to the current run of mine baseline material. This very basic methodology supplied a lot of information regarding the potential separability issues for various units in the low grade reserve and emphasized the high variance associated with electrostatic separation. Quantifying the effect of these factors, coatings for example, influencing the separation of zircon and rutile is, however, not as obvious. Further tests are underway to ascertain possible reasons for the variation in separation efficiency of materials from different units. Most of the products produced during the separability tests were very close to or within product specification.

**Conclusions**

**Back to basics**

The test work discussed emphasizes how a seemingly difficult and cumbersome task (of simulating a fully functional plant on pilot scale) can be completed by using very basic metallurgical techniques. The application of a
baseline material and equipment calibration helped in formulating a simple test programme that could help identify differences in performance for various feed types. It also allowed a more practical evaluation of potential grades and recovery results for the low grade orebody. Furthermore, the results were based on physical separation techniques actually employed in the plant set-up. Although not perfect, the basic programme can be applied to any ore type to ascertain its potential performance via the plant. In terms of electrostatic separability the mere nature of the processing plants makes it very difficult to simulate. The basic methods employed can, however, provide a good indication of separation efficiency for different ore types. It can provide useful information when trying to understand variances in a complex plant environment or pinpoint areas for further investigation using more advanced analytical techniques.

Application of unit based information

Predicting how a blend could behave based on unit ratios can be of value. It is important to understand both the units and their influence on each other to ensure opportunities aren’t overlooked and potential problems are prevented. Developing an understanding of the mineralogy and metallurgy of specific geological units could support mine planning optimization, forecasting and resultantly aid in plant control and metallurgical problem solving.

References


