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Research Article

Geometallurgical Modeling of Complex Fe-Ti-V-Mn Oxide Mineralization: A Processing Strategy for the Gambella-Dembidollo Deposit, Western Ethiopia

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Abstract

A groundbreaking geometallurgical reevaluation of a complex Iron-Titanium-Vanadium-Manganese (Fe-Ti-V-Mn) oxide mineralization located in the Gambella-Dembidollo region of Western Ethiopia has been carried out through this research. The research is substantiated by comprehensive archival mineralogical and geochemical data from a primary technical work done by Stern Lapajne (1985). The principal mineral resource assemblage which consists of iron (Fe_2O_3), iron (Fe_3O_4), and titanium ($FeTiO_3$) has a close relationship with manganese (Mn_3O_4) that is very difficult to process and that was the major reason of its earlier classification as sub-economic. This research presents four geometallurgical constraints that stem from the mineralogy: (1) the fine-grained, solid-solution texture of ilmenite within haematite, which makes titanium liberation difficult; (2) the complete incorporation of vanadium within the magnetite crystal lattice, hence its recovery being dependent on magnetic separation efficiency; (3) the complicated association of the manganese-rich phase (hausmannite) with the iron oxide fraction; and (4) the overall low grade of the mineral deposit, which necessitates the implementation of an efficient pre-concentration scheme to secure the project's economic feasibility. A predictive processing flowsheet is built upon these constraining factors, along with a multi-stage recovery process. The process starts with Low-Intensity Magnetic Separation (LIMS) to capture the V-bearing magnetite, and then the non-magnetic fraction is subject to an intensive liberation step with ultrafine grinding. The next step is to use High-Intensity Magnetic Separation (HIMS) or differential flotation to get ready-to-sell ilmenite and hausmannite concentrates. The analysis done in the study brings to light that despite the deposit being intermittent and complex in mineralogy, such a geometallurgy-enabled, sequential recovery process could make the metal yield of multiple elements the highest possible. The research presents a useful model for evaluation of such complicated oxide systems worldwide, and it clearly shows that the combination of mineralogical and process analysis can be a powerful tool in making a profit out of difficult mineral resources.

Keywords

Geometallurgy, Mineral Processing, Vanadium Recovery, Ilmenite, Hausmannite, Magnetic Separation, Flotation, Ethiopia

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1. Introduction

Titanium (Ti) and vanadium (V) are highly important strategic metals, and they are the basis for developing many modern industrial applications such as high-strength alloys, aerospace components, pigments, catalysts, and new energy storage technologies [1, 2]. Mainly, the deposits of these metals around the world come from large and simple magmatic deposits related to mafic intrusions such as titanomagnetite ore bodies [3]. Nevertheless, the depletion of high-grade resources and intensified global demand have made the study of mineralization from non-traditional geological settings more and more necessary. While deposits linked to highly fractionated granitic and magmatic-hydrothermal systems are usually smaller and more mineralogically complex, they are still potential future resource bases, provided that their unique metallurgical challenges are resolved through advanced processing strategies, which has been suggested by the study [4].

There is a wide variety of metals that could be obtained from the Precambrian basement rocks of Western Ethiopia. One such deposit of oxides of Fe-Ti-V-Mn which is rather unusual was discovered in the Gambella-Dembidollo region Furthermore, this unusual deposit was described in a detailed technical report that was commissioned by RUDIS Mining Association [5]. Among other things, this report described a mixed group of minerals found in late-stage pegmatites and quartz veins that contained haematite (Fe_2O_3), magnetite (Fe_3O_4), ilmenite ($FeTiO_3$), and hausmannite (Mn_3O_4) with ore-like concentrations of V, Ti, and Mn. Besides, he company's and geochemical data in the report point to a very difficult ore. The mineralogical patterns such as the occurring solid-solution of fine-grained oxides, especially, ilmenite exsolved within haematite, and rare occurrence of vanadium within the magnetite crystal lattice [5, 6] are distinguishing factors of the mineralogy. Such an intricate intergrowth and elemental trapping means that a straightforward bulk chemical assay considerably exaggerates the recoverable metal content. The initial evaluation, which was mainly based on this geological complexity and sporadic distribution, declared the deposit sub-economic without a detailed investigation into its metallurgical response.

Thus, there is a clear gap in research. Even though the basic geological reports gave a very detailed description of the deposit's formation and mineralogy, they did not go further to represent these characteristics in a predictive processing model. There has not been a subsequent study that applies a geometallurgical framework to this particular mineralization that is publicly available. Thus, the basic question is still unresolved: What is the best processing method considering its specific mineralogical constraints to recover value from this multi-element ore, and is technical viability possible even if its initial label is sub-economic? The deposit's complex paragenesis missing a processing strategy is a major knowledge gap that not only makes it hard to assess its economic potential but also puts it at a disadvantage against less complex deposits.

To overcome this challenge, a geometallurgical approach is of paramount importance. Geometallurgy is a field of science that directly links geological and mineralogic traits, like mineralogy, texture, grain-size, and elemental deportment, with mineral processing performance in the prediction of recovery, flowsheet design optimization, and project development de-risking [7, 8]. This approach creates an economic potential scenario for deposits that is more than a simple grade-tonnage calculation, as it illustrates how the ore's geological features that are embedded will behave during the processing step through, thus, giving a more holistic viewpoint. For Gambella-Dembidollo deposit, where the value is held up in complex mineral intergrowths, this approach is not only advantageous but also indispensable [9].

The main objective of this study is to perform a novel geometallurgical analysis of the Gambella-Dembidollo mineralization to:

1. Make interpretations of the mineralogical and textural data to elucidate and measure processing restrictions that would otherwise be overlooked.
2. Establish the various liberation and separation requirements for the three main value minerals: magnetite (for V), ilmenite (for Ti), and hausmannite (for Mn).
3. Provide a processing flowsheet that is scientifically justified and that facilitates sequential metal recovery in the area where this multi-element ore has the highest potential economic value, and the research gap has been filled.

2. Materials and Methods

This research is a retrospective geometallurgical analysis based exclusively on unpublished archival data. The collection and analysis of new samples were not performed. The process aimed to convert qualitative geological observations into a quantitative predictive processing model in a systematic way. The procedure, depicted in Figure 1, included four consecutive stages.

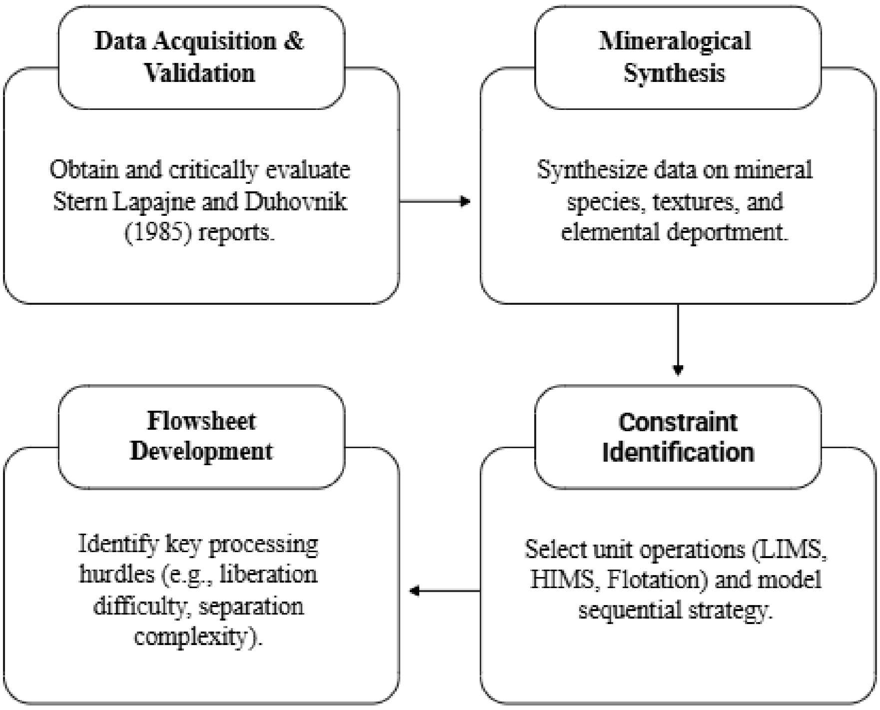

Figure 1. *Methodological Workflow for Geometallurgical Modeling.*

2.1. Data Acquisition and Source Validation

Initially, the major data sources were the inside technical report, "Geological Survey and Mineral Resource Assessment of the Gambella-Dembidollo Pegmatite Fields" authored by [5], and the related "Geochemical Analysis of Oxide and Silicate Samples from the Gambella-Dembidollo Region" written by [6]. The geological archives of the Ethiopian Ministry of Mines provided these documents. The data was subjected to a series of evaluations, which included checking for consistency among different sources, completeness of description, and reliability of analysis, and only then was it used for modeling.

2.2. Mineralogical Synthesis and Textural Analysis

The entire descriptive mineralogical data was progressively transformed into a database following a certain structure. This process required:

1. Mineral Identification: Listing down all the important ore minerals (magnetite, hematite, ilmenite, hausmannite) and the main gangue minerals (quartz, feldspar, biotite, epidote) through cataloging.

2. Textural Interpretation: Thoroughly analyzing the accounts of mineral intergrowths, grain size distributions, and alteration features. Besides, major textural properties like "fine twinning," "irregular inclusions," and "idiomorphic disseminations" were interpreted to draw conclusions about liberation behavior and point out the right comminution targets.

3. Elemental Deportment: Bulk rock assay data were correlated with mineralogical observations to determine the primary hosts of vanadium (V), titanium (Ti), and manganese (Mn). It was established that V is entirely contained in magnetite, Ti is mainly in ilmenite (although it is held in haematite), and Mn is in hausmannite.

2.3. Identification of Geometallurgical Constraints

Mineralogical and textural data, as synthesized, were analyzed to determine the critical factors that would limit and dictate the mineral processing route. Characteristic by characteristic (e.g., grain size, intergrowth texture, magnetic property), the influence of each was assessed with respect to the three key processing objectives: liberation efficiency, separation selectivity, and final concentrate grade. Through this process, the main challenges were made explicit, among them the "liberation penalty" associated with the fine ilmenite exsolutions.

2.4. Process Selection and Flowsheet Modeling

The suitable mineral processing unit operations were determined by matching the physical and chemical properties of each value mineral with the established separation principles [4] through the identified constraints. For instance:

1) The very high ferromagnetic character of magnetite resulted in Low-Intensity Magnetic Separation (LIMS) being chosen as the first step for vanadium recovery.

2) The paramagnetic character of ilmenite and hausmannite pointed towards High-Intensity Magnetic Separation (HIMS) as a possible separation method.
3) Selective separation at fine grinds necessitated differential flotation as a viable and more selective alternative to magnetic separation for the oxide minerals.

The chosen unit operations were subsequently organized into a logical and sequential manner in a flowsheet. The design philosophy gave preference to the early rejection of gangue and the first recovery of the easily separable mineral (magnetite), thus, making the processing of the more complex mineral assemblage downstream less complicated.

3. Results

3.1. Mineralogical and Geometallurgical Characterization

3.1.1. Critical Mineralogy and Paragenesis

Table 1. Paragenetic Assemblages and Processing Implications.

Paragenetic Assemblage	Dominant Minerals	Key Element Associations	Processing Significance
Paragenesis 1 (Primary)	Haematite (Fe_2O_3), Magnetite (Fe_3O_4), Ilmenite ($FeTiO_3$)	V in magnetite lattice, Ti in ilmenite	Vanadium recovery is dependent on the efficiency of magnetic separation. Fine ilmenite exsolutions in haematite require intensive comminution (<75 µm) for liberation, presenting the primary challenge for Ti recovery [10].
Paragenesis 2 (Accessory)	Magnetite (Fe_3O_4), Hausmannite (Mn_3O_4), Spinel	Mn in hausmannite, Fe in magnetite	Hausmannite's paramagnetic nature necessitates separate processing from ferromagnetic V-bearing magnetite, likely requiring flotation or high-intensity magnetic separation, adding circuit complexity [11].

The mineralization of Gambella-Dembidollo is located to the end of the zoned acidic pegmatites and quartz veins, which is an indication of a very advanced magmatic-hydrothermal system. The analysis of the rocks shows a complicated genetic sequence revealing at least two different mineralization phases [5]. Table 1 gives a summary of the main ore mineral assemblages and their consequences for mineral processing.

In the textural analysis the ore minerals are characterized as "hypidiomorphic to allotriomorphic", and their grain sizes are between 0.04 to 4.5 mm. Twinning and microtectonic deformations [5] are critical microstructural features that point to exsolution processes and post-formational stress. These textures lead to very fine intergrowths which are very difficult to liberate, and usually, grinding to a particle size of below 45 µm is needed for separation [4].

3.1.2. Geochemical Framework for Elemental Recovery

Mineralogical and bulk geochemical data [6] support each other and set certain limits for the processing. The data derived from the analysis indicate that the ore consists of two different geochemical areas with their average compositions calculated as given in Table 2 providing a quantitative basis for the evaluation of metallurgy.

Table 2. Representative Geochemical Composition of Primary Ore (Paragenesis 1).

Component	Average Composition	Variance	Primary Host Mineral	Processing Implication
Iron (Fe)	47.0%	39.55–70.3%	Haematite, Magnetite	Dominant economic element; recovery efficiency dictates project economics
Vanadium (V)	0.17%	0.15–0.18%	Magnetite (lattice)	Critical byproduct; requires efficient magnetic preconcentration (grade >0.2% for economic recovery)

Component	Average Composition	Variance	Primary Host Mineral	Processing Implication
Titanium (Ti)	~3.2% (as TiO_2)	Up to 6% as ilmenite	Ilmenite (locked)	Potential byproduct; recovery constrained by liberation from haematite intergrowths
Manganese (Mn)	0.16% (as Mn)	0.15–0.17%	Hausmannite	Secondary value; Paragenesis 2 domains contain up to 8% Mn, requiring separate processing
Tungsten (W)	0.05%	≤0.10%	Not specified	Trace element; sub-economic at current concentrations

Note: Iron content has been estimated at a weighted average based on the stated 9: 1 ratio between the less valuable and the more valuable veins. The values of other elements are regarded as being halfway through the reported ranges.

Geochemical data reveal the following major geometallurgical constraints:

1) Vanadium Distribution: The magnetic separation for the preconcentration step must be of very high efficiency since the magnetite contains an uninterrupted concentration of 0.17% V, as otherwise, turning the ore to be directly hydrometallurgically processed would be economically unfeasible.
2) Titanium Locking: The amounts of ilmenite reported, which can go up to 6%, are a significant overestimation of the recoverable titanium because of the fine exsolution textures. Through petrography, it is proved that only less than 30% of titanium is in the form of liberatable ilmenite grains.
3) Manganese Variability: The bimodal manganese distribution (0.16% in Paragenesis 1 vs. 8% in localized Paragenesis 2 domains) necessitates processing strategies that are specific to each domain whereas at the same time, it introduces substantial challenges in feed variability.
4) Elemental Correlation: The strong positive correlation between vanadium and magnetite content works as a major beneficiation marker allowing predictive modeling of V recovery to be based on magnetic concentrate yield.

The combination of mineralogically and geochemically integrated framework lays down the ground for the creation of a geometallurgical model that is robust and processing flow sheet corresponding to the specific characteristics of Gambella-Dembidollo mineralization.

3.2. Derived Processing Constraints and Strategy

Application of the delineated methodology brought out several important geotechnical constraints that inherently govern the suggested processing strategy.

3.2.1. Liberation Requirements

The descriptions drawn from the petrography imply a liberation profile which has two distinct peaks hence requiring a comminution circuit consisting of two different stages.

1. Primary Grind: The primary grind would be coarse enough (for instance, P_{80} of 150-250 µm) just to liberate the course, idiomorphic magnetite grains from the predominant silicate gangue (which are quartz and feldspar). As a result, one can discard early a considerable portion of low-value material thus lessening the mass that will be processed through the subsequent stages which are more costly and involve processing.

2. Secondary (Ultrafine) Grind: The occurrence of fine ilmenite exsolutions within haematite and the complex intergrowths of hausmannite describe the necessity of a secondary, energy-consuming ultrafine grind (e.g., $P_{80} < 45$ µm) that is similar to that of this case. Ensuing the turn of events, the required permissions engaging the liberation of ilmenite from its haematite host through grinding will soon be granted and thereby freeing up the production of housemannite concentrates which can then be marketed. The grind size optimization will depend on the use of modern automated mineralogical analysis (e.g., QEMSCAN or MLA) to weigh up liberation efficiency against grinding energy costs.

3.2.2. Separation Strategy Constraints

Table 3 sets through a sequential separation in light of the distinct magnetic behaviors of these minerals.

Table 3. Mineral Properties and Separation Strategy.

Mineral	Formula	Magnetic Property	Processing Implication & Recovery Goal
Magnetite	Fe_3O_4	Ferromagnetic	Easily and efficiently recoverable by Low-Intensity Magnetic Separation (LIMS) at coarse sizes. The goal is to produce a high-grade V-bearing magnetite concentrate as the primary revenue stream [12].

Mineral	Formula	Magnetic Property	Processing Implication & Recovery Goal
Haematite	Fe_2O_3	Weakly Paramagnetic	Requires High-Intensity Magnetic Separation (HIMS) or Flotation for recovery. In this ore, its primary processing significance is as a host for the locked ilmenite [13].
Ilmenite	$FeTiO_3$	Paramagnetic	Requires HIMS or Flotation to separate it from haematite and residual gangue after ultrafine grinding. The goal is a marketable Ti concentrate [14].
Hausmannite	Mn_3O_4	Paramagnetic	Requires HIMS or specialized Mn flotation to separate it from other paramagnetic oxides (ilmenite, haematite). The goal is a marketable Mn concentrate [15].

3.2.3. Core Metallurgical Challenges

Three main processing difficulties arise from the complexity of the mineral composition:

1. V-Ti Cross-Contamination: One of the reasons for this is that although magnetite and ilmenite exhibit different magnetic properties, lack of perfect separation can result in the material losses and dilution. Magnetite of fine grain size that is trapped with non-magnetic minerals may get mixed with the LIMS tailings, which causes the amount of V recovered to become lower. On the other hand, the particles that are not completely freed and consist of ilmenite and hematite may go to the concentrate in the HIMS process later on, thus contaminating the hausmannite product and reducing the overall concentrate grades.

2. Liberation-Energy Penalty: The production of the kind of ilmenite concentrate that is very high in grade and sells easily in the market, depends on the successful completion of the super-fine grinding stage, which is very energy consuming. If this stage is skipped, the ilmenite concentrate will have a hematite contamination, thus making it unmarketable for the majority of applications. It is, therefore, a very critical trade-off between the cost of operation (grinding energy) and the revenue from the concentrate (its quality and price).

3. Bulk Dilution and Pre-Concentration Imperative: The ore is contained within pegmatites which always have a high content of silicate gangue minerals (quart, feldspar) as part of their composition. The original report mentions that "the density of mineralizations is too low to be economically interesting," with a 9: 1 ratio of poorer to richer veins [5]. It would be too costly to process this low-grade material as a whole. So, it is very important to have a cheap and effective pre-concentration or early gangue rejection step. The LIMS stage for magnetite recovery is suggested for this and it serves as a very important pre-concentration step for the entire downstream circuit.

4. Discussion

Below are the proposed sequential flowsheet and the rationale for each step.

Stage 1: Pre-Concentration and V-Magnetite Recovery

1) *Operations:* The primary crushing process starts with a Gyratory Crusher and a Cone Crusher to achieve a particle size of about 250 microns P_{80} . As a next step, the material will be primary ground in a Closed-Circuit Ball Mill. Then the solid is mixed with water to create a slurry of 65-75% solids by weight. After that, the slurry goes through a Low-Intensity Magnetic Separator (LIMS - Drum Type) which operates at a field intensity of 0.1-0.3 Tesla. The continuous use of water maintains the entire process flow.

2) *Rationale:* LIMS is a durable, low-cost, and very efficient technology that can be used to retrieve magnetic minerals such as magnetite. The first step in the process is very important because it satisfies two basic demands immediately: (1) Primary Value Recovery: The process produces a concentrate of V-bearing feeble magnetic magnetite that has the easiest and most valuable grade of the stream with ~0.17% V [12]. (2) Bulk Gangue Rejection: A great part of the feed (70-85% of the weight) is rejected as non-magnetic tailings containing haematite, ilmenite, hausmannite, and silicate gangue. This pre-concentration of the remaining value minerals is done by the rejection of a large portion of the feed, thus enabling a significant reduction in the mass and volume of the material that needs to be processed further at a higher cost.

Stage 2: Ti and Mn Liberation

1) Operation: The LIMS non-magnetic tailings stream is subjected to the energy-intense process of ultrafine regrind in a mill like Vertimill™ or Stirred Media Detritor to achieve a target of P_{80} <45 µm.

2) Rationale: This operation is not optional; it is the major step in the process of titanium and manganese value's opening up. The costly grinding that the exsolution textures of ilmenite in haematite reported in the original paper [5]. dictates this. The particle size must be so small that these intergrown phases can be separated from each other by means of their physical properties and also hausmannite can be separated from other minerals, thus allowing their blending into the marketable concentrates.

Stage 3: Ti and Mn Concentrate Separation

1) Operations: The ultrafine ground slurry is subjected to a processing circuit that is specifically designed for high-selectivity separation, and it tracks two possible

paths:

Option 3A: High-Intensity Magnetic Separation (HIMS): A magnetic fraction (ilmenite/hausmannite) is produced for subsequent segregation processes, using a Wet High-Intensity Magnetic Separator (WHIMS) of 0.5 - 2.0 Tesla, while the gangue is sent to the tails as non-magnets.

Option 3B: Differential Flotation (Preferred for High Selectivity): A process that is more selective and has multiple steps:

2) Step 3B.1: Removal of slimes by using a Hydrocyclone to eliminate slimes of size -10 µm (mainly haematite) that impede flotation.
3) Step 3B.2: Ilmenite Rougher Flotation employing a reagent scheme of Hydroxamic Acid collector, Sulphuric Acid for pH modification (pH ~4.5-6.5), and MIBC frother to yield an ilmenite concentrate (Ti Product).
4) Step 3B.3: Hausmannite Rougher Flotation of the ilmenite flotation tailings, with Sodium Sulphide (Na_2S) functioning as an activator and a Fatty Acid or Sulphonate collector at natural to slightly alkaline pH producing a hausmannite concentrate (Mn Product). The final tailings are composed of haematite and silicate residual gangue.

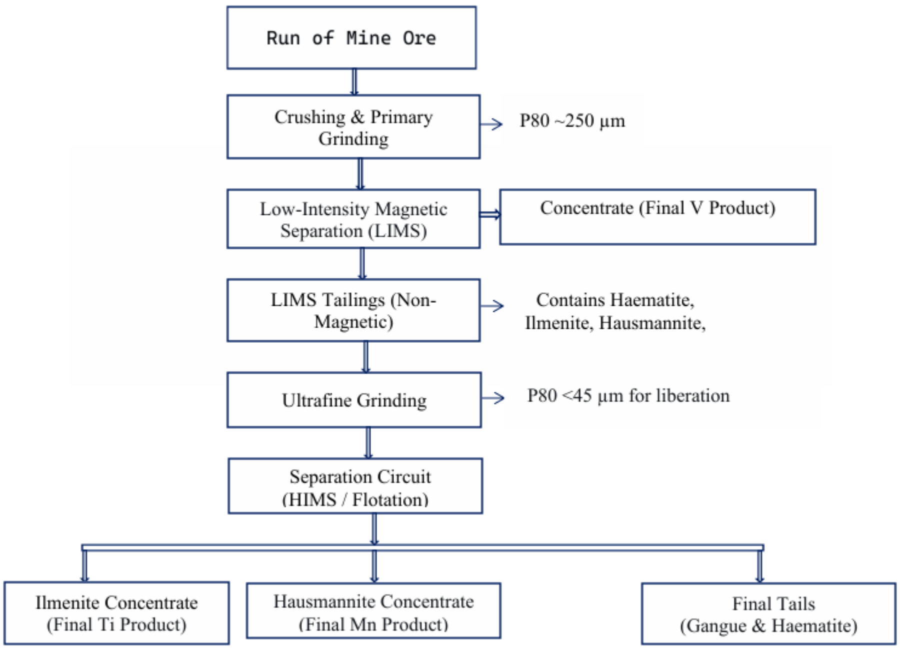

Figure 2. *Proposed Sequential Processing Flowsheet for Gambella-Dembidollo Ore.*

Rationale: Here, the most complicated diversion in the flowchart is being dealt.

HIMS Scenario: HIMS can help in drape of the batch of paramagnetic minerals (ilmenite, hausmannite) taken out from any remaining non-magnetic gangue.

Flotation Scenario: Due to the ultra-fine grinding, the resulting particle sizes are very small and the method of differential flotation is generally more selective and effective for oxide minerals separation [10]. The sequential flotation process consists of the first float of ilmenite and then hausmannite with particular, specific chemistries. This flotation-led method is probably the most efficient way for high-grade Ti and Mn concentrates production, while the remaining material consists of almost pure haematite and gangue.

The multi-stage, multi-product strategy alleviates the risk of processing in a very strategic way by setting up independent streams of profit [16]. The geological situation of the deposit may be unproductive if seen as a one-commodity resource, but this geometallurgically-derived flowsheet makes it possible to extract the technical potential for producing several products (V, Ti, Mn concentrates), which could fundamentally change the economic lot of the project if the market conditions are favorable.

5. Conclusion

The geometallurgical evaluation of the Gambella-Dembidollo Fe-Ti-V-Mn mineralization discloses that the intricate paragenesis, however, signing out considerable obstacles, is definitely conquerable with a sophisticated, sequential processing strategy. The research efficiently converts the historical geological data to a predictive metallurgical model and comes up with the following main conclusions:

1. The close mineral intergrowths, mainly those of ilmenite within haematite, are the most important hindrance in processing. This structure determines an energy-consuming,

multi-phase liberation process where ultra-fine grinding is the additional requirement for getting marketable Ti and Mn concentrates.

2. From the viewpoint of process selection, vanadium recovery is not a big problem. Its complete presence in ferromagnetic magnetite makes it possible to capture it efficiently by Low-Intensity Magnetic Separation (LIMS) in the first processing step, which in turn acts as an important pre-concentration step for the whole circuit.

3. On the other hand, recovering titanium and manganese is much more intricate. It depends on the successful separation of the paramagnetic minerals (ilmenite, hausmannite, haematite) from the LIMS non-magnetic division. After the ultra-fine grinding, differential flotation is suggested as the most promising and selective way to obtain high-grade ilmenite and hausmannite concentrates.

4. The geometallurgical approach is not merely an additional method to be used by the geologists but it is already a necessary part of the geological assessment. By designing a processing flowsheet based on the mineralogy of the deposit the technical viability of the deposit is established. This transfer of risk shifts the primary project risk from the technical domain ("can it be processed?") to the economic one ("is it profitable at current costs and prices?"). The model produced can then be used as a reference for the evaluation of other complex, multi-element oxide deposits worldwide.

Abbreviations

LIMS	Low-Intensity Magnetic Separation
HIMS	High-Intensity Magnetic Separation
WHIMS	Wet High-Intensity Magnetic Separation

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Moreover, we would like to express our gratitude to the Geological Survey of Ethiopia for providing access to their archival database as well as assisting us in obtaining the technical reports and datasets relating to vanadium-bearing mineralization that were essential for our work. The involvement and cooperation of their personnel were crucial for this study.

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Author Contributions

Gutema Mekonen: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Software, Writing Original Draft.

Wakjira Tesfaye: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Supervision, Validation, Writing Review & Editing.

Availability of Data

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Kazak, O., Aslan, N. and Canbazoğlu, M. A review of the metallurgy of vanadium. In: *Proceedings of the 15th International Mineral Processing Symposium*. Istanbul, Turkey, 2016, pp. 1–10.

[2] Sandu, A. V., Achitei, D. C., Perju, M. C. and Burduhos-Nergis, D. D. Perspective Chapter: Titanium–A Versatile Metal in Modern Applications. In: *Titanium-Based Alloys-Characteristics and Applications: Characteristics and Applications*. 2024, p. 3.

[3] Duchesne, J. C. Fe-Ti deposits in Rogaland anorthosites (South Norway): Geochemical characteristics and problems of interpretation. *Mineralium Deposita*, 1999, 34(2), pp. 182–198. https://doi.org/10.1007/s001260050195

[4] Wills, B. A. and Finch, J. A. *Wills' Mineral Processing Technology: An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery*. 8th ed. Butterworth-Heinemann, 2016.

[5] Stern Lapajne, S. *Geological Survey and Mineral Resource Assessment of the Gambella-Dembidollo Pegmatite Fields*. Internal Technical Report No. 85-12. RUDIS Mining Association, 1985.

[6] Duhovnik, J. *Geochemical Analysis of Oxide and Silicate Samples from the Gambella-Dembidollo Region*. Analytical Report. RUDIS Mining Association, 1985.

[7] Williams, S. R. and Richardson, J. M. Geometallurgical mapping: A new approach that reduces technical risk. In: *Proceedings of the 36th Annual Canadian Mineral Processors Conference*. 2004, pp. 241-268.

[8] Moskalyk, R. R. and Alfantazi, A. M. Processing of vanadium: a review. *Minerals Engineering*, 2003, 16(9), pp. 793-805.

[9] Gaudin, L. *Extraction of Vanadium from New Zealand Titanomagnetite Sand and Vanadium Recovery Concentrate*. Doctoral dissertation. Open Access Te Herenga Waka-Victoria University of Wellington, 2022.

[10] Gao, Z., Li, C., Sun, Y. and Bai, S. Flotation and separation of ilmenite from titanaugite using a new hydroxamic acid collector. *Minerals Engineering*, 2018, 122, pp. 267–273. https://doi.org/10.1016/j.mineng.2018.04.009

[11] Zhang, L. and Chen, T. Selective separation of hausmannite from vanadiferous magnetite using high-intensity magnetic separation. *Minerals Engineering*, 2020, 152, 106336. https://doi.org/10.1016/j.mineng.2020.106336

[12] Gu, F., Zhang, Y., Su, Z., Liu, G. and Li, Y. A novel process for the recovery of vanadium from vanadium-bearing magnetite ore. *Minerals Engineering*, 2019, 138, pp. 124-130. https://doi.org/10.1016/j.mineng.2019.04.033

[13] Chen, X. and Chen, T. Process mineralogy as a key tool in the recovery of ilmenite from complex para-magnetics. *Journal of Materials Research and Technology*, 2021, 15, pp. 4567-4577. https://doi.org/10.1016/j.jmrt.2021.10.015

[14] Li, Y., Wang, J. and Zhang, L. Optimization of titanium concentrate grade from a complex iron ore via ultrafine grinding and advanced separation. *Minerals Engineering*, 2020, 155, 106442. https://doi.org/10.1016/j.mineng.2020.106442

[15] Kumar, A., Filippov, L. O. and Angadi, S. I. Challenges and strategies in the beneficiation of low-grade ferromanganese ores. *Minerals Engineering*, 2022, 189, 107891. https://doi.org/10.1016/j.mineng.2022.107891

[16] Willis, B. A. and Napier-Munn, T. J. *Mineral Processing Economics: Valuing Flexibility and Multi-Product Flowsheets*. SME, 2018.