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Research Article

Petrogenesis and Co-Product Beneficiation of Neoproterozoic Fe–Ti–P–V Magmatic Systems in Ethiopia

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Abstract

Neoproterozoic mafic-ultramafic layered intrusions within the East African Orogen in Ethiopia host major, yet historically underdeveloped, reserves of igneous phosphate, titanium, and vanadium. Deposits such as the Bikilal Layered Gabbro Complex (BLGC; ~580 Mt @ 3.02% P_2O_5, 5.4% TiO_2, and 17.67% Fe_2O_3) and the Melka Arba Intrusion (87.5 Mt @ 3.21% P_2O_5 and 6.66% TiO_2) were previously constrained by a single-commodity exploration paradox. Earlier pre-feasibility evaluations focused solely on apatite extraction via dry pneumatic classification, incurring high P_2O_5 loss (~39%) in fine fractions (<45 μm) and generating a negative Net Present Value (-US$ 142M). This study formulates a unified petrogenetic model linking tholeiitic magma differentiation, immiscible Fe–Ti–P–F oxide-apatite melt segregation, and REE fractionation across Ethiopian complexes. Quantitative EPMA analyses reveal high-purity hydroxyfluorapatite (40.85% P_2O_5 avg), low-magnesium ilmenite (51.95% TiO_2 avg), and vanadiferous titanomagnetite (1.18% V_2O_5 avg). To address historical process bottlenecks, we present an integrated wet beneficiation circuit (wet ball milling, LIMS, WHIMS, and multi-stage froth flotation). Mass-balance modeling demonstrates that co-recovering apatite (78.5% P_2O_5 recovery), ilmenite (280 kt/a @ 51.2% TiO_2), and V-titanomagnetite (620 kt/a @ 1.2% V_2O_5) transforms project economics, yielding a positive NPV10% of +US$ 385.4M and an Internal Rate of Return (IRR) of 24.6%.

Keywords

Apatite, Ilmenite, Vanadiferous Titanomagnetite, Wet Beneficiation, Co-product Recovery, Techno-economics

1. Introduction

Neoproterozoic orogenic belts across the East African Orogen host extensive basic to ultrabasic intrusive complexes whose economic potential remains underutilized [1, 2]. In Ethiopia, igneous apatite-bearing titanomagnetite and ilmenite bodies represent the principal domestic source of agricultural phosphate feedstock and industrial heavy metals [3-5]. However, historical exploration campaigns suffered from a single-commodity paradigm: evaluating multi-element magmatic systems strictly for a single primary mineral phase while discarding valuable co-products as waste [5].

In the Bikilal Layered Gabbro Complex (BLGC) of West Wollega, earlier technical studies evaluated the deposit purely as a source of phosphate rock for fertilizer production [3]. To bypass regional dry-season water constraints near Gimbi, process flowsheets relied on dry pneumatic classification [6]. This approach rejected all fine particles below 45 μm, causing

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a 39% loss of total P_2O_5 to fine tailings and yielding an economically unviable project with an NPV of -US$ 142 million [3].

Research Gap & Objective: Published literature treats Ethiopian magmatic P–Fe–Ti–V deposits as isolated regional targets [4, 7, 8] without establishing a unified petrogenetic model or an integrated co-product process flowsheet. This paper synthesizes geological, geochemical, micro-probe, and resource block model datasets across the BLGC and Melka Arba deposits.

It establishes the petrogenetic mechanism of silicate-oxide liquid immiscibility and presents an optimized wet beneficiation flowsheet designed to co-recover phosphate, titanium, and vanadium.

2. Geological Setting & Petrogenetic Mechanism

The BLGC (West Wollega) and Melka Arba complex (Bale Zone) intrude Neoproterozoic metamorphic volcano-sedimentary sequences of the Mozambique Belt [4, 5]. The BLGC defines an asymmetric, inward-dipping synformal layered structure extending over 30 km along strike [3, 5]. Concentric lithological zonation progresses from an unmineralized central olivine gabbro core outward through leucogabbro-anorthosite and hornblende gabbro into mineralized peripheral pyroxenite and hornblendite layers [3, 5].

Magmatic differentiation within these complexes followed a tholeiitic iron-enrichment trend [9, 10]. Fractional crystallization of plagioclase and olivine depleted the residual melt in Al_2O_3 and SiO_2 while driving enrichment in FeO^{tot}, TiO_2, P_2O_5, and F [1, 11]. Upon reaching critical P-T-X conditions (T ≈ 1020 ℃–1080 ℃, fO_2 near FMQ), the homogeneous silicate liquid unmixed into two immiscible phases: a silica-rich conjugate melt and a dense, low-viscosity Fe–Ti–P–F oxide-apatite liquid that gravitated into intercumulus spaces, crystallizing net-textured to massive titanomagnetite, ilmenite, and fluorapatite horizons [1, 2, 11, 12].

3. Mineral Chemistry & Resource Modeling

Quantitative mineral chemistry was determined via electron microprobe analysis (EPMA) across representative mineralized core samples from BLGC and Melka Arba [4, 5] (Table 1). Apatite across both intrusions is stoichiometric fluorapatite with low heavy metal impurities (Cd, Pb < 10 ppm) [4, 5]. Ilmenite occurs as discrete homogeneous grains with low MgO (<1.5%), suitable for pigment production, while titanomagnetite contains elevated vanadium (0.82–1.62% V_2O_5) [4, 5, 14].

Table 1. *Summary of geochemical characteristics, concentration ranges, mean values, and petrological-industrial significance of key mineral phases (apatite, ilmenite, and vanadiferous titanomagnetite).*

Mineral Phase	Key Oxide / Element	Concentration Range (%)	Mean (%)	Petrological & Industrial Significance
Apatite (BLGC & Melka Arba)	P_2O_5	40.05% – 41.52%	40.85%	Stoichiometric fluorapatite [5].
	CaO	53.80% – 55.20%	54.45%	High Ca/P ratio suitable for wet-process H_3PO_4 [13].
	Cadmium (Cd)	< 5 ppm – 12 ppm	< 8 ppm	Environmentally clean fertilizer feedstock [14].
Ilmenite (Discrete Grains)	TiO_2	50.49% – 53.82%	51.95%	High-grade feedstock for TiO_2 pigment production [4].
	MgO	0.29% – 1.76%	0.85%	<1.5% MgO meets chloride-route specifications [4].
Titanomagnetite (Vanadiferous)	Fe_2O_3tot	58.20% – 68.40%	63.10%	Ulvöspinel-magnetite exsolution textures [2].
	V_2O_5	0.82% – 1.62%	1.18%	Strategic ferrovanadium raw material feedstock [14].

Geostatistical block modeling using Ordinary Kriging (OK) on a 25 m × 25 m × 25 m grid defined global resources for BLGC [3, 15]. Melka Arba resources were calculated via volumetric domain modeling [4] (Table 2). In addition, trace element ICP-MS analyses at Melka Arba reveal Total Rare Earth Element (TREE) concentrations in apatite ranging from 2,453 ppm in pyroxenites up to 4,144 ppm in pegmatitic facies, dominated by LREEs (La, Ce, Nd) [4].

Table 2. *Summary of JORC-compliant mineral resource estimates, grade distributions (P_2O_5, TiO_2, Fe_2O_3, and V_2O_5), and supporting references for the Bikilal–Ghimbi Complex (BLGC) and Melka Arba deposits.*

Deposit / Domain	JORC Category	Tonnage (Mt)	P_2O_5 (%)	TiO_2 (%)	Fe_2O_3 (%)	V_2O_5 (%)	Source Citation
BLGC Soji-Bikilal (Indicated)	Indicated	435.0	3.00%	5.00%	16.40%	0.04%	[3]
BLGC Deep Extensions (Inferred)	Inferred	145.0	3.10%	6.60%	21.50%	0.04%	[3]
BLGC Global Resource Total	*Global*	*580.0*	*3.02%*	*5.40%*	*17.67%*	*0.04%*	[3]
Melka Arba Main Indicated	Indicated	87.5	3.21%	6.66%	-	-	[4]
Melka Arba Massive Fe–Ti Lens	Indicated	12.17	-	12.50%	58.40%	0.85%	[4]

4. Process Metallurgy & Flowsheet Re-Engineering

Micro-structural liberation analysis indicates that 42% of apatite crystals are fine-grained (20–75 μm) and closely intergrown with amphibole [5]. The historical dry pneumatic flowsheet rejected all material finer than 45 μm to prevent separator blinding, leading to a catastrophic 39% P_2O_5 loss to tailings [3, 6]. To resolve this metallurgical bottleneck, an integrated wet beneficiation circuit was designed and modeled (Figure 1).

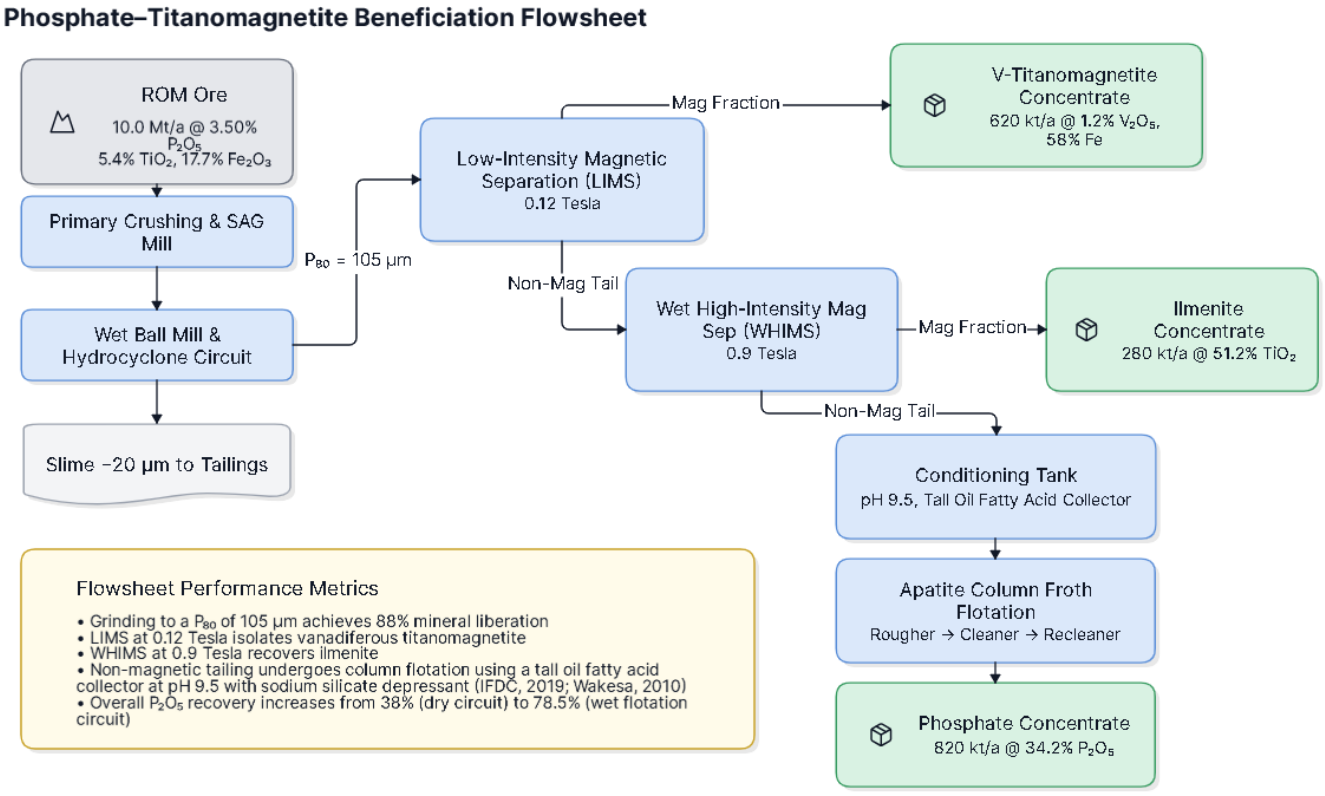

Figure 1. *Re-engineered wet beneficiation flowsheet for Ethiopian Fe–Ti–P–V ore, combining wet ball milling, low-intensity magnetic separation (LIMS), wet high-intensity magnetic separation (WHIMS), and multi-stage froth flotation (IFDC, 2019; Wakesa, 2010).*

The proposed circuit processes 10.0 Mt/a of run-of-mine (ROM) ore through wet SAG and ball milling, grinding to a P_{80} of 105 μm to achieve 88% mineral liberation. Low-Intensity Magnetic Separation (LIMS at 0.12 T) first isolates vanadiferous titanomagnetite (620 kt/a @ 1.2% V_2O_5, 58% Fe). The non-

magnetic tailings pass to Wet High-Intensity Magnetic Separation (WHIMS at 0.9 T) to recover ilmenite (280 kt/a @ 51.2% TiO_2). Finally, the WHIMS non-magnetic tail is conditioned at pH 9.5 using tall oil fatty acid collectors and sodium silicate depressants, undergoing rougher-cleaner-recleaner froth flotation (IFDC, 2019; Wakesa, 2010). This increases overall P_2O_5 recovery from 38% (dry circuit) to 78.5%, producing 820 kt/a of premium phosphate concentrate @ 34.2% P_2O_5.

5. Economic & Comparative Evaluation

A comparative financial analysis demonstrates the economic transformation achieved by transitioning from single-commodity dry processing to the multi-commodity wet circuit [3, 13] (Table 3). Igneous phosphate deposits globally (e.g., Siilinjärvi, Palabora) rely on co-product credit revenues to ensure commercial viability [1, 14].

Table 3. *Comparative economic and operating metrics for the historic dry processing route versus the re-engineered multi-product wet recovery route.*

Economic & Operating Metric	Historic Dry Route (P-Only)	Re-Engineered Wet Route (Co-Product)
ROM Processing Rate	10.0 Mt/a	10.0 Mt/a
Phosphate Recovery (%)	38.0% (39% tailings loss)	78.5%
Annual Products Produced	490 kt/a Phosphate Concentrate	820 kt/a P_2O_5 + 280 kt/a Ilmenite + 620 kt/a V-Magnetite
Initial CAPEX	US$ 247.7 Million	US$ 385.0 Million
Annual Gross Revenue	US$ 20.6 Million/a	US$ 254.3 Million/a
Net Present Value ($NPV_{10\%}$)	-US$ 142.0 million	+US$ 385.4 million
Internal Rate of Return (IRR)	< 0% (Unviable)	24.6% (Payback: 3.8 Years)

6. Conclusions

Neoproterozoic magmatic Fe–Ti–P–V intrusions in Ethiopia represent major multi-commodity mineral deposits when evaluated within an integrated petrogenetic and metallurgical framework. Replacing historic dry pneumatic classification with a wet ball-milling, magnetic separation, and froth flotation flowsheet recovers fine-grained apatite (78.5% recovery) and unlocks high-value ilmenite and vanadiferous titanomagnetite co-products. This shifts project economics from a negative NPV (-US$ 142M) to a highly profitable asset (+US$ 385.4M $NPV_{10\%}$), establishing a robust domestic foundation for agricultural fertilizer production and industrial metallurgy in East Africa.

Abbreviations

BLGC	Bikilal Layered Gabbro Complex
CAPEX	Capital Expenditure
Cd	Cadmium
EPMA	Electron Microprobe Analysis
Fe_2O_3tot	Total Ferric Oxide
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
IRR	Internal Rate of Return
JORC	Joint Ore Reserves Committee
LIMS	Low-Intensity Magnetic Separation
LREEs	Light Rare Earth Elements
Mt	Million Tonnes
NPV	Net Present Value
OK	Ordinary Kriging
P_{80}	80% Passing Particle Size (Grind Size)
pH	Potential of Hydrogen (Measure of Acidity/Alkalinity)
REE	Rare Earth Elements
ROM	Run-Of-Mine (Raw Extracted Ore)
SAG	Semi-Autogenous Grinding (Milling Process)
T	Tesla (Unit of Magnetic Flux Density)
TREE	Total Rare Earth Element
US$	United States Dollar
WHIMS	Wet High-Intensity Magnetic Separation
µm	Micrometers (Microns)

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Author Contributions

Gutema Mekonen: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Writing – original draft

Data Availability Statement

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

Conflicts of Interest

The author declare no conflicts of interest.

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