Mineralogical constraints on critical elements recovery from Moroccan carbonatites and implications for processing strategies

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Abstract

Carbonatite-hosted ores are promising sources of critical elements, yet their beneficiation is strongly controlled by mineralogical complexity. This study evaluates a complex carbonatite ore containing rare earth elements (REE), Nb and Fe, using a process mineralogy approach with emphasis on mineralogical constraints affecting apatite and associated REE recovery. The ore is dominated by quartz, hematite, goethite, and apatite, while REE are mainly hosted by monazite. Monazite occurs as fine-grained particles (P80≈24µm) and exhibits limited liberation (~43.7% below 38µm) due to extensive locking with apatite and Fe oxides/hydroxides. Although apatite reaches ~62.4% liberation at −250µm, composite particles remain significant. Flotation tests conducted at a grinding size of P80=50µm indicate that monazite reports primarily to the apatite concentrate, demonstrating that mineralogical coupling governs recovery behavior. These results indicate that selective REE flotation is unlikely and that flowsheet strategies should integrate mineralogical constraints favoring combined apatite–REE recovery and tailored downstream separation strategies.

Keywords: Process mineralogy, TIMA, Flotation, critical minerals

Introduction

The rising demand for critical raw materials, driven by the expansion of high-technology applications and the global shift towards low-carbon energy systems, requires more efficient utilization of critical mineral resources (European Commission. Directorate General for Internal Market, Industry, Entrepreneurship and SMEs., 2023; Grandell et al., 2016; Watari et al., 2020). Carbonatite-hosted deposits are among the few geological settings in which critical elements such as phosphorus (P), rare earth elements (REEs), and niobium (Nb) occur together at economically significant concentrations, making them a globally important source of critical

and strategic raw materials (Simandl and Paradis, 2018). Despite this coexistence, beneficiation flowsheets for carbonatite ores are typically designed around a single principal commodity, most often REE, so that potentially valuable co-products are frequently rejected to tailings or dispersed among intermediate process streams, limiting the overall resource efficiency and economic value that can be extracted from the ore (Berger et al., 2009; Jin et al., 2025).

The beneficiation of such multi-commodity carbonatite ores is inherently challenging because the P-, REE-, and Nb-bearing mineral phases differ in abundance, grain size, texture, surface properties, and response to separation processes (Antoniassi et al., 2020; Ersoy et al., 2023; Hong et al., 2021). These constraints are particularly relevant in multi-commodity ores, where beneficiation of one valuable phase may influence the recovery or rejection of other critical elements. Process mineralogy can therefore provide a basis for identifying element hosts and establishing relationships between mineral texture, liberation, and metallurgical response.

This study investigates a complex carbonatite ore from southern Morocco, with particular emphasis on apatite and associated REE mineralization. The objectives were to identify the mineral hosts of P, REE, and Nb; quantify their grain size, associations, and liberation characteristics; and relate these features to the flotation response of apatite and REE-bearing phases.

Methodology

The ore was initially crushed to 100% passing 2 mm and characterized to assess its mineralogical composition and liberation characteristics. Following the limited liberation observed at this size, a representative subsample was wet ground to 100% passing 250 µm for detailed automated mineralogical characterization. Bulk chemical composition was determined by ICP-OES and ICP-MS following lithium borate fusion and acid dissolution.

Quantitative mineralogical characterization was performed by enhanced SEM analysis with Tescan TIMA, providing modal mineralogy, mineral grain size, elemental deportment, mineral associations, and liberation data. Size-resolved mineralogical characteristics were additionally evaluated using TIMA-derived virtual size classes. As virtual sizing is based on equivalent spherical diameter and is affected by particle statistics and volume-to-weight conversion, these size-resolved results were treated as indicative rather than equivalent to physical sieve fractions. LA-ICP-MS (Laser Ablation - Inductively Coupled Plasma - Mass Spectrometry) analyses were performed on selected mineral grains to investigate the mineral-scale distribution of REE, Nb,

Ta, Th, U, and other trace elements and to refine the characterization of mineral phases that could not be unambiguously differentiated by TIMA.

Batch flotation tests were subsequently performed on material ground to a P_{80} of approximately 50 µm using a 500 mL mechanical flotation cell at 20 wt.% solids and pH 9. Fatty acid-based collectors were evaluated for apatite recovery in the presence of corn starch and sodium silicate as gangue depressants.

Results and discussion

The ore is characterized by a complex assemblage dominated by quartz (39.3 wt.%), hematite (14.7 wt.%), Fe oxide/hydroxide–silicate intergrowths (18.9 wt.%), and apatite (13.1 wt.%). An additional 4.4 wt.% occurs as apatite–Fe oxide/hydroxide intergrowths. Monazite accounts for 0.68 wt.% of the sample, whereas Nb-bearing phases represent approximately 0.10 wt.%. The abundance of pre-existing Fe oxide/hydroxide–silicate and apatite–Fe intergrowths indicates that mineralogical complexity is not restricted to simple particle locking but is partly inherent to the ore texture.

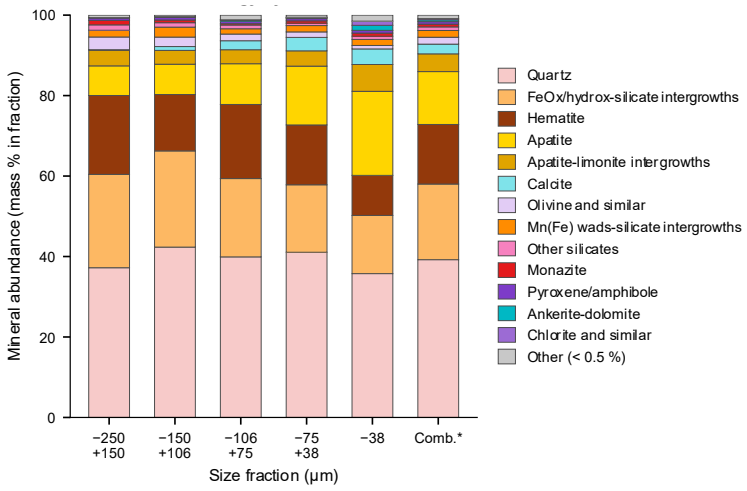

Figure 1- Modal mineralogy of the sample by virtual size fractions

Apatite and monazite display markedly different grain-size characteristics. Monazite is finely disseminated, with a P80 of approximately 24 µm, whereas apatite occurs over a broader and comparatively coarser size range. Size-resolved TIMA data further show that the nature and extent of mineral associations vary with particle size. Monazite is principally associated with apatite, Fe oxide/hydroxide phases, and silicates, while apatite also exhibits extensive associations with Fe-bearing phases and quartz. These textures result in incomplete liberation even after substantial size reduction. Monazite liberation reaches only approximately 43.7% in

the <38 µm fraction, whereas apatite exhibits a higher degree of liberation, approximately 62.4% in the material characterized at <250 µm.

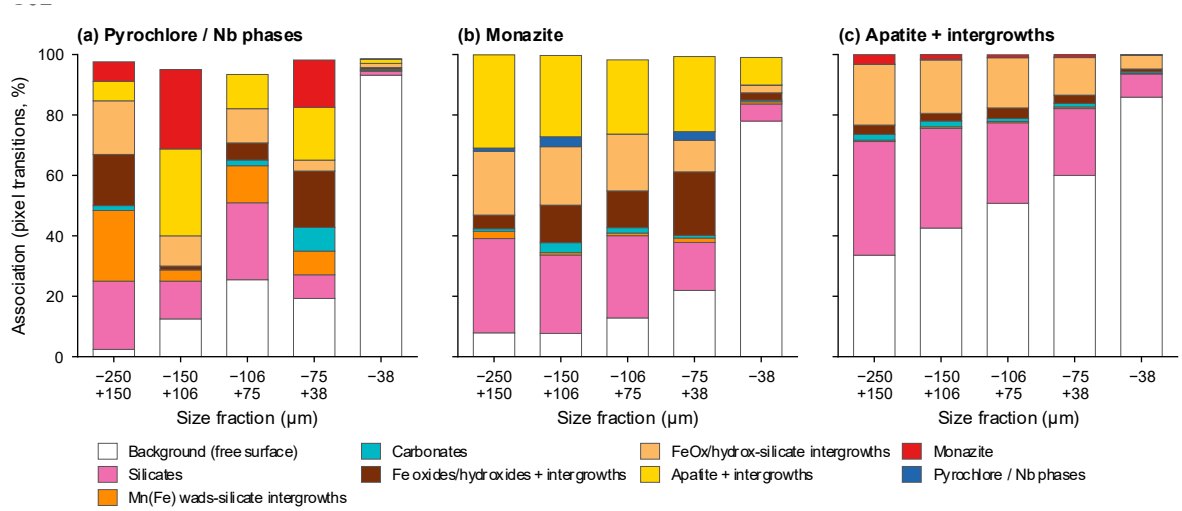

Figure 2- Mineral associations of pyrochlore/ Nb phases, monazite and apatite by virtual size fractions

Element deportment confirms monazite as the principal REE host, with a smaller contribution from apatite. La, Ce, and Nd show broadly similar deportment toward monazite; however, a larger fraction of Nd is associated with apatite. LA-ICP-MS mineral chemistry supports this distinction: monazite contains approximately 44.8 wt.% ΣREE, whereas apatite contains approximately 0.30 wt.% ΣREE, with measurable La, Ce, and Nd. This demonstrates that REE recovery is controlled by both discrete monazite and REE incorporated within apatite.

Flotation tests were conducted on material ground to a P80 of 50 µm using a fatty acid-based collector. Rougher flotation resulted in the simultaneous enrichment of P and REE. The P_2O_5 grade increased from 7.31 wt.% in the feed to 21.56 wt.% in the rougher concentrate, while REE increased from 0.37 to 0.92 wt.%, corresponding to an REE recovery of 66.89%. Subsequent cleaning improved phosphate concentrate quality, increasing the P_2O_5 grade to 34.97 wt.%. The REE grade was maintained and slightly increased during cleaning, reaching 0.97 wt.% in the cleaner concentrate.

The simultaneous enrichment of P_2O_5 and REE is consistent with the process mineralogical characteristics of the ore. Tescan TIMA analysis showed that REE are hosted by fine-grained monazite, which is closely associated with apatite. Monazite has a P80 of approximately 24 µm and remains poorly liberated, reaching only ~43.7% liberation in the <38 µm fraction. At the flotation grind of P80=50 µm, a significant proportion of monazite is therefore expected to occur within composite particles. Its recovery to the phosphate concentrate can consequently be attributed, at least partly, to the flotation of monazite-bearing apatite composites. LA-ICP-

MS additionally identified minor REE concentrations within apatite itself, providing a second contribution to REE reporting with the apatite-rich product.

Conclusion

This study demonstrates that the beneficiation of the investigated Moroccan carbonatite is strongly controlled by its mineralogical and textural complexity. Apatite is the main P-bearing phase, whereas REE are hosted by fine-grained monazite, with a minor contribution from apatite. Monazite has a P80 of approximately 24 µm and reaches only ~43.7% liberation in the <38 µm fraction, illustrating the limitations of attempting its independent physical separation. Despite these constraints, flotation successfully concentrated both P and REE. REE grade increased from 0.37 wt.% in the feed to 0.92 wt.% in the rougher concentrate at 66.89% recovery, while subsequent cleaning produced a concentrate containing 34.97 wt.% P_2O_5 and 0.97 wt.% REE. The parallel enrichment of P and REE is consistent with the close association of fine-grained monazite with apatite and the minor occurrence of REE within apatite identified by LA-ICP-MS. Overall, the results indicate that the mineralogical complexity of this ore can be considered not only as a constraint but also in defining an integrated recovery strategy. Rather than targeting independent REE flotation, co-concentration of apatite and associated REE followed by downstream recovery may provide a more appropriate route for the simultaneous valorization of P and REE, while Nb- and Fe-bearing phases represent additional potential streams requiring dedicated separation strategies.

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