

Results on mineralogy and geochemistry of rare earth elements in the Dong Pao deposit and the orientation of Vietnam's rare earth industry

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ABSTRACT

Dong Pao is one of the largest deposits in the Northern part of Vietnam with 60 orebodies of rare earths have been discovered. After 13 years since it was explored, the deposit has not yet come into operation. Meanwhile, the demand for the utilization of rare earth elements (REE) in green energy applications for sustainable development is increasing. This study provides some results about REE mineralogy and geochemical composition of REE ores in three large bodies, F.3, F.7, and F.9, and proposes strategies for developing Vietnam's rare earth industry. Samples were collected from three orebodies, including core and outcrop-vein samples. X-ray diffraction, Scanning Electron Microscopy with Energy Dispersive Spectroscopy, Electron Micro Probe Analyzer, and Inductively Coupled Plasma Mass Spectrometry were used to identify mineral assemblages and provided quantitative geochemical data for REE in each sample. Research results show that the main REE-bearing mineral in ore samples F.7 and F.9 is bastnasite, and the total concentrations of REE are 131,188 ppm and 39,700 ppm, respectively. The ore sample F.9 has a high concentration of heavy rare earth elements (up to 4,958 ppm). Synchysite is the main REE-bearing mineral in ore sample F.3, with 15,048 ppm of the total concentration of REE. These results are important data for further research to enhance effective mining in the future and management of mineral resources. Vietnam should focus on systematic exploration and value-added strategies in its REE industry, shifting from raw material exports to establishing an indigenous industry for REE intermediates and green energy products. To achieve this, Vietnam must invest in research and development, attract foreign investments and talent, and implement policies prioritizing domestic industries in the REE sector.

Keywords: Rare earth elements (REE); REE ores; REE industry; Dong Pao deposit; Lai Chau Province.

1. Introduction

We are confronted with significant global challenges, including climate change, environmental degradation, and the loss of biodiversity. These challenges underscore the necessity for forward-looking solutions in energy supply, storage, and the sustainable utilization of materials and resources. The prevailing development trajectory emphasizes the reduction of carbon emissions and pollution, coupled with preserving biodiversity. The global shift involves transitioning to clean energy, diminishing reliance on fossil fuels, and embracing technologies such as electric vehicles, renewables, and batteries (SDG, 2015; Katila et al., 2019). Concurrently, the advancement of science and technology heightens the demand for materials essential to electronic devices (Sachs et al., 2019; Bali Swain and Yang-Wallentin, 2020). Moreover, aligning with global development trends, there is an imperative to bolster national security and defense, propelling a nation toward becoming an advanced and secure entity.

REE plays a pivotal role in the production of various high-tech goods, including hybrid vehicles, mobile phones, computers, televisions, and energy-efficient lighting. Recognized for their strategic importance, rare earth elements are not only integral to vital components in rapidly growing consumer electronics and environmentally friendly products but are also critical defense equipment (Haxel, 2002; De Lima and Leal Filho, 2015). Consequently, the mastery of science, technology, and rare earth

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resources presents a significant opportunity for Vietnam to undergo rapid, robust, and sustainable development, propelling the nation toward the goal of becoming a developed country.

Dong Pao is one of the largest deposits in the Northern part of Vietnam (Khang, 2002; Bui Tat Hop et al., 2010). Which was investigated for the first time in 1971 by Geological Division No.35 discovered 60 orebodies of REE in different sizes (Nguyen Ngoc Anh and Duong., 1971). The deposit experienced two explorations. The first was in 1986, on the orebody F.3 was explored, documenting the reserve is 890,000 tons of T-RE₂O₃ with a grade better than 10% (JICA, 2002). The second is in 2011, the exploration project focused on estimating resources on seven orebodies F.04, F.07, F.09, F.10, F.14, F.16, and F.17, documenting the reserve is 2,552,852 tons of T-RE₂O₃ and the resource is 2,158,380 tons of T-RE₂O₃ (Du, 2010).

All the above reports are not publicly available. Currently, after 14 years of exploration, the Dong Pao deposit has not come into a mining operation, and no further scientific studies have been published about REE minerals in the Dong Pao deposit. In this study, we clarify the characteristics of REE minerals that occur in ore veins in Dong Pao deposits, which are the scientific basis for further research in the future, and give recommendations for the REE industry in Vietnam.

2. Sampling and Analytical Methods

Samples were collected at three large orebodies F.3, F.7, and F.9 in the Dong Pao deposit from outcrop and drill cores, including 01 core sample in orebody F.3, 01 core sample in orebody F.7, 01 outcrop-vein sample in orebody F.9.

The Assemblage analytical methods used comprise X-ray diffraction (XRD), Scanning Electron Microscopy-Energy Dispersive Spectroscopy (SEM-EDS), Electron Micro Probe Analyzer (EPMA), and Inductively Coupled Plasma Mass Spectrometry (ICP-MS). XRD and SEM are analytical methods to identify the minerals assemblage, and XRF, ICP-MS, and EPMA are used for geochemistry study, providing the quantitative information of the REE ore and the characteristics of the REE component in each sample.

Samples were pulverized for XRD and ICP-MS analyses and were used to make thin section samples for observation under microscope, SEM-EDS, and EPMA. Only ICP-MS analyses were conducted at the Activation Laboratories, situated in Ontario, Canada. Another was conducted at Akita University, Japan, as well as preparing samples. Analyses using The Rigaku D/Mac-RC instrument for XRD employing Cu K α 1 radiation with conditions: a voltage of 30 kV, a beam current of 16 mA, a scanning rate of 8 degrees per minute, and DS (divergent slit) and SS (scattering slit) set to 1 degree. Using JEOL JSM-IT300 scanning electron microscopy (SEM) equipped with an Oxford Instruments X-Max 50mm² energy dispersive spectroscopy (EDS) attachment, calibration was done using pure cobalt standard. The elemental composition of minerals was identified using electron microprobe (EMPA), JXA-8230 EPMA model.

3. Results

3.1. Mineralogical characterization

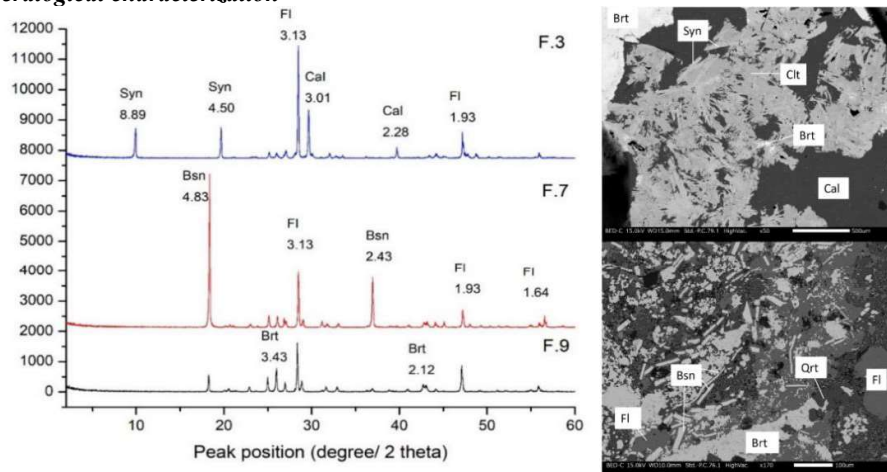


Figure 1. XRD patterns of ore samples in orebodies F.3, F.7, F.9. And back-scattered electron images of REE and gangue minerals FI = fluorite, Brt = barite, Cal = calcite, Syn = synchysite, Bsn = bastnasite. Clt = celestine, Qtz = quartz.

The mineralogy of ore samples was determined by XRD analysis, the results show major minerals in three ore samples. F.3 ore sample is dominated by fluorite (CaF_2), synchysite ($\text{Ca}(\text{REE})(\text{CO}_3)_2\text{F}$), calcite (CaCO_3), and barite (BaSO_4). F.7 and F.9 ore samples have similar peak intensities dominated by fluorite, barite, and bastnasite ($(\text{REE})\text{CO}_3\text{F}$). Synchysite and bastnasite are the two main REE minerals in these samples. The SEM and EPMA investigation verified the presence of the primary minerals and detected additional minerals, celestine (Cel) and parisite (Par) (Fig.1 and Table 1).

Table 1. Compositions of representative main REE-bearing minerals in three ore samples F.3, F.7, F.9, the Dong Pao REE deposit.

Ore body	F.7	F.9	F.3	F.7	F.9	F.3	F.9	F.3
Mineral	Bsn	Bsn	Bsn	Par	Par	Par	Syn	Syn
F	9.5	8.1	6.4	13.0	12.4	7.6	12.3	5.3
CaO	0.5	1.1	0.5	5.8	4.2	7.6	18.2	17.4
La_2O_3	26.8	16.0	22.6	22.1	13.3	20.6	6.1	15.1
Ce_2O_3	32.0	38.5	28.8	27.0	34.1	27.2	18.8	24.4
Nd_2O_3	4.3	8.9	4.4	3.3	8.9	4.9	6.4	6.0
Sm_2O_3	0.0	0.3	0.3	0.0	1.3	0.4	0.0	0.6
Eu_2O_3	0.5	0.9	0.0	0.4	1.4	0.0	0.0	0.0
Gd_2O_3	4.7	5.5	0.1	3.8	5.6	0.1	1.2	0.1
Y_2O_3	0.0	0.4	0.1	0.0	4.1	0.0	5.5	0.1
Pr_2O_3	2.1	3.3	1.6	1.4	3.2	1.8	1.9	1.9
Tb_2O_3	0.1	0.1	0.0	0.1	0.2	0.0	0.0	0.0
Er_2O_3	0.0	0.0	0.0	0.0	0.5	0.0	1.0	0.0
ThO_2	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0
UO_2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Total	76.6	79.7	62.9	71.6	84.6	68.0	68.7	68.8
CO_2 Cal	18.8	19.7	15.6	13.6	9.8	17.8	28.6	27.3
F Cal	5.5	4.7	3.7	7.5	7.2	4.4	7.1	3.1
Total Cal (%)	95.4	99.3	84.7	85.2	94.4	85.8	96.8	96.1
$\Sigma \text{REE}_2\text{O}_3$	70.5	73.9	57.9	58.1	72.1	55	39.9	48.2

4.2. Geochemical characterization

Ore sample in F.3 orebody has high concentrations of Sr (59,370 ppm), Ba (32,920 ppm), and ΣREE (15,048 ppm). Ore samples in F.7 and F.9 orebodies have high concentrations of Sr (4,876; 3,914 ppm), Ba (213,900; 175,000 ppm), ΣREE (131,188; 37,700 ppm), respectively.

Table 2. Trace element (including REE) compositions of ore samples F.3, F.7, F.9, Dong Pao deposit.

Orebody	F.3	F.7	F.9
Cs	< 0.5	< 0.5	< 0.5
Rb	< 2	< 2	< 2
Ta	0.70	0.60	0.80
Nb	15.00	50.00	21.00
Be	2.00	8.00	11.00
V	17.00	36.00	51.00
Sr	59,370.00	4,876.00	3,914.00
Zr	24.00	12.00	12.00
Ba	32,920.00	213,900.00	175,000.00
La	5,100.00	57,200.00	8,100.00
Ce	6,890.00	58,700.00	18,200.00
Pr	585.00	4,000.00	1,730.00
Nd	1,790.00	9,570.00	5,300.00
Sm	210.00	623.00	1,080.00
Eu	49.50	125.00	332.00
Gd	96.80	246.00	669.00
Tb	10.70	28.40	85.70
Dy	42.50	94.00	383.00
Ho	6.60	14.60	61.80

Orebody	F.3	F.7	F.9
Er	15.90	41.10	140.00
Tm	1.71	3.93	14.50
Yb	8.70	20.70	69.40
Lu	1.08	2.79	8.01
Hf	0.60	0.40	0.80
Y	240.00	519.00	3,527.00
Sc	3.00	28.00	9.00
Th	11.50	499.00	210.00
U	10.90	103.00	60.50
ΣREE	15,048.49	131,188.52	39,700.41
LREE	14,624.50	130,218.00	34,742.00
HREE	423.99	970.52	4,958.41
LREE/HREE	34.49	134.17	7.01

5. Discussion

5.1. REE-minerals

The primary REE-minerals have been detected in ore samples of orebody veins in the Dong Pao deposit. The main REE-bearing minerals are bastnasite (Ce) and synchysite (Ce). Based on the mineral assemblage, the F.3 ore sample is clearly distinguished from the F.7 and F.9 ore samples. While synchysite is the main REE mineral that occurs with barite, fluorite, celestine and calcite within the F.3 sample. Bastnasite is the main REE mineral that occurs with barite, fluorite, and quartz within F.7 and F.9 samples (Fig.1).

The analysis of bastnäsite, parisite, and synchysite minerals reveals a conspicuous prevalence of light rare earth elements (LREE), particularly in the abundance of La_2O_3 , Ce_2O_3 , and Nd_2O_3 . Ce_2O_3 content is the highest in three samples compared to other REE oxides. Relative to parisite and synchysite, the concentration of $\Sigma\text{REE}_2\text{O}_3$ in bastnasite mineral is higher (up to 73.9%). The highest concentration of Ce_2O_3 is observed in bastnäsite from sample F.9, with a value of 38.5%. The bastnäsite minerals found in ore body F.7 demonstrate the greatest content of La_2O_3 , measuring at 26.8%. This observation indicates that the distribution of REE in ore samples obtained from orebodies exhibits variations.

5.2. REE geochemistry

The ICP-MS data are consistent with the data above, confirming a notable enrichment of LREE in the three samples. particularly La_2O_3 , Ce_2O_3 , and Nd_2O_3 , are significantly higher, with La at 57,200 ppm, Ce at 58,700 ppm, and Nd at 9,570 ppm in sample F.7. Sample F.9, while showing lower LREE concentrations compared to F.7, still maintains a high level of LREE enrichment with La at 8,100 ppm, Ce at 18,200 ppm, and Nd at 5,300 ppm, alongside a noticeable amount of HREE (4,958 ppm). Sample F.3 displays the lowest LREE concentrations among the three samples, with La at 5,100 ppm, Ce at 6,890 ppm, and Nd at 1,790 ppm. F.7 ore sample has the highest concentration of ΣREE (130,218 ppm). The concentration of ΣREE in F.9 ore sample is much less than that of F.7 with (39,700 ppm). The least is F.3 ore sample (15,048 ppm).

The study compares to prior research (Khang, 2002; Bui Tat Hop et al., 2010). The study has provided empirical evidence of the chemical composition and primary REE-bearing minerals by data and images of analysis results. The study outlines the different attributes of the distribution of REE components in minerals and the geochemistry of ore samples from orebodies F.3, F.7, and F.9. The study offers a framework for further research aimed to comprehending the spatial distribution of REE within each orebody, as well as the specific potential of each REE within Dong Pao deposit. This data serves as a foundation for mining, mineral processing, and the management of REE resources. Because each REE possesses distinct and unique applications for the advanced modern industry.

5.3. Rare earth industry of Vietnam

China is a typical example of building the country into a developed country and is currently the world's second-largest economy, which is achieved through science-technology development and taking advantage of abundant mineral resources, including REE (Mancheri et al., 2013; Van Gosen et al., 2014). China has been the number one supplier of REE to the world over the past three decades, currently accounting for 70%. China's REE reserves are 44 million tons, the largest in the world. Vietnam's REE

reserve ranks second position with 22 million tons. In 2022, Vietnam had produced 4,300 tons of REE ore, increasing nearly 11 times compared to 2021 with 400 tons (USGS, 2023).

In the report published in April 2023 by the Japan Oil, Gas and Metals National Corporation (JOGMEC), Vietnam has not appeared as a REE mining country in the global rare earth supply chain. But along with China, Vietnam is the country that currently has rare earth metal factories supplying to two large consumer markets China and Japan (JOGMEC, 2023). This shows that Vietnam has many opportunities for economic development following China's economic development strategy to develop the REE industry.

For Vietnam to catch up with advanced economies, it needs to make simultaneous advancements on multiple fronts. An exemplar of an advanced economy, China, has already achieved maturity in the evolution of its REE industrial ecosystem. This implies that China has successfully gone through the incubation phase, the diversity phase, and the growth phase before reaching the maturity phase in the REE industry life cycle. Therefore, addressing gaps in technology needs to be a concern; Vietnam has to master technology, products, and markets. To develop the Vietnam rare earth industry, we propose some ideas:

- Continue the systematic exploration program to thoroughly understand the characteristics of REE minerals as well as the ore quantity and resources of REE in Vietnam territory prioritized known deposits such as Dong Pao and Yen Phu. Vietnam is the second-largest REE reserve in the world. This has the potential to be a valuable source of competitive and strategic advantage. The mining and export of REE materials as a part of the development becomes important. Concurrently, there is a recognition that adding value to raw materials could yield substantial economic and strategic benefits, constituting a long-term strategy. Active engagement in every part of the value chain, from research and development (R&D) through mining to the production of intermediate and final products, is essential. Achieving this value addition requires a combination of indigenous capabilities in integrating R&D with products and imports of critical technology.

- Shift focus from solely exporting raw materials to establishing an indigenous industry for the production and export of key REE intermediates, particularly magnets, and products for green energy, aligning with a national REE strategy.

- Establish a dedicated REE industrial zone in Lai Chau to attract foreign investments in REE-related facilities, forming part of the government's initiatives to bridge the technology gap.

- Take proactive measures in researching and acquiring rare earth mining and refining technologies. Attract talents and high-quality human resources to Vietnam to contribute to advancements in the rare earth industry.

- Implement a rationing system for REE materials that favors domestic companies over exports, ensuring that the country's rare earth resources contribute significantly to the growth and sustainability of its domestic industries.

6. Conclusion

This study has shown that REE concentrations in three ore samples from three orebodies of the Dong Pao deposit (Lai Chau, Viet Nam), are related to the presence of the major REE-bearing minerals bastnasite, synchysite, and parasite. The main gangue minerals are barite and fluorite.

The mineral assemblage in F.7 and F.9 ore samples is REE-fluorite-barite-quartz. Bastnasite is the main REE-bearing mineral. The mineral assemblage in F.3 ore sample is REE-fluorite-barite-calcite-celestine, and synchysite is the main REE-bearing mineral. LREE is dominant in all samples. F.7 ore sample has the highest Σ REE concentration (130,218 ppm). While F.9 ore sample has the highest HREE concentration (4,958 ppm).

Vietnam has rare earth potential and has enough conditions to develop the rare earth industry. This is an opportunity to develop the country's economy to become a developed country by 2050. Vietnam's vision involves a comprehensive and sustainable approach to development, strategically harnessing REE resources, investing in critical technologies, and actively participating in the REE global marketplace. These give Vietnam a great position as a dynamic and forward-thinking nation on the world stage, with a clear focus on both economic prosperity and environmental responsibility.

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