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The characteristics of lead-zinc metallization in the Ban Kep area, Bac Me District, Ha Giang Province

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Abstract

Purpose. This study aims to determine the origin and type of lead-zinc ore deposits in the Ban Kep area, Bac Me District, Ha Giang Province, based on mineral morphology, formation temperature, and isotopic characteristics. The results are intended to support the assessment and forecasting of sedimentary exhalative (SEDEX) Pb-Zn ore resources in Vietnam.

Methods. To investigate the characteristics of SEDEX Pb-Zn deposits in the Ban Kep area, a combination of methods was applied, including mineralographic analysis to determine the composition and tectonic structure of rocks and ores, fluid inclusion studies to constrain formation temperatures, and Pb isotopic analysis to evaluate the environment and sources of ore-forming materials.

Findings. The study shows that lead-zinc metallization in the Ban Kep area has a medium-temperature hydrothermal origin. Furthermore, the results indicate that the metallization shares key features with the SEDEX deposit type.

Originality. SEDEX deposits have been extensively studied worldwide, and multiple genetic models have been proposed, including explosive activity, accumulation of biological debris, and surface replacement. Each model has certain advantages and limitations in explaining the genesis and development of SEDEX deposits. The present study contributes new data from Vietnam, where this deposit type remains less understood.

Practical implications. The findings provide a scientific basis for identifying and evaluating Pb-Zn SEDEX resources in Vietnam, with potential applications in mineral exploration and resource forecasting.

Keywords: *lead-zinc, fluid inclusions, stable isotopes, hydrothermal, sedimentary exhalative (SEDEX)*

1. Introduction

In recent decades, geological and mineral resource studies in Northeastern Vietnam have garnered particular attention, as this region is home to a variety of economically valuable metallic mineral deposits. Among them, lead-zinc is one of the most important targets, not only because of its resource potential but also due to its scientific significance in understanding the geotectonic evolution and ore-forming processes of the region. The Lo-Gam Structural Belt, located in Northeastern Vietnam, has been identified as one of the most promising areas, where complex deformation and tectonic activities have created favorable conditions for the formation and concentration of mineral deposits, especially lead-zinc ores. Several SEDEX-type lead-zinc ore bodies and deposits have already been discovered in the area [1]-[6], opening new directions for research on ore-forming mechanisms and the potential distribution of this type of metallization throughout the regional structure. The study area is situated along the northeastern margin of the Lo-Gam Structural Belt located in the Tung Ba – Bac Me area.

The Lo-Gam Structural Belt: this structural belt belongs to the Phanerozoic structural series in northeastern Vietnam, essentially representing an early Paleozoic marginal sea structure. Available documents indicate that this structure has an ancient basement that was heavily fragmented and altered initially during the dispersive inland rift phase at the end of the Neoproterozoic and subsequently developed as a fairly stressed continental margin dynamic zone during the Cambrian and early Ordovician, involving deep-seated materials components of an ophiolite complex (ultramafic, mafic, and oceanic volcanic-sourced sediments). Orogenic structures emerged in the late Silurian to early Devonian in the form of molasse basins, thermally metamorphosed and granitized dome sequences, and characteristic mosaic patterns.

In the modern structural framework of the Lo Gam structure, several distinct constituent structures form a unique mosaic pattern. Notably, the residual fragments of the Precambrian folded basement of Luc Lieu – Lap Thach, as well as the concentric granite-metamorphic dome structures of Chiem Hoa, Cham Chu, and Bac Muc, also known as the granite-migmatite micro-domes, are particularly noteworthy.

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These structures are interconnected by the fold complexes of early Paleozoic oceanic-type structures surrounding the Song Chay microcontinent. Superimposed on these structures is the late orogenic Pia Phuong basin, which arose from the collision of microcontinents and the closure of oceanic structures in the late Silurian to early Devonian. The structural image of the Lo Gam belt, along with the formation characteristics, thickness, and deformation of pre-Devonian dynamo-tectonic complexes, suggests the formation of a structure resembling a conglomerate of microcontinents bonded by fold complexes of dynamic zones. This explains the uneven deformation and the specific facies-zone characteristics of the complexes forming them. Generally, such structural landscapes are familiar in marginal sea structures formed through dispersive rifting at the edges of mature continental crust structures. In a metaphorical sense, the early Paleozoic marginal sea of Lo Gam can be considered the ancient counterpart of the Cenozoic East Sea.

Lead-Zinc metallization in the Tung Ba – Bac Me Area has long attracted the attention of many researchers. Recent detailed studies indicate that the southeastern part of the Tung Ba – Bac Me structural zone hosts a diverse range of endogenous ore formations, including iron, lead-zinc, lead-zinc-barite, polymetallic, and pyrite-pyrrhotite. These formations are commonly distributed along the margins of granitoid intrusions of the subvolcanic Tung Ba complex. They are influenced by vein-belt systems of diabase from the Cao Bang complex in the eastern part of the area. The study area lies within the Tung Ba – Bac Me structural block and covers approximately 10 km^2. The geological formations in the area are mainly composed of the Ha Giang Formation ($Є_2hg_1$; $Є_2hg_2$), which includes limestone, marble interbedded with calcareous clastic rocks, quartz-mica schist, and the overlying Tung Ba Formation (D1*tb*), comprising quartzite, quartz-mica schist, and foliated acidic volcanic rocks. Lead-zinc metallization in the area primarily occurs within the metamorphosed limestone of the upper member of the Ha Giang Formation ($Є_2hg_2$), and is concentrated in four ore bodies (BK1, BK2, BK3, BK4). The metallization is controlled by northeast- and southeast-trending fault systems, as well as northwest- and southeast-trending sub-meridional and sub-latitudinal faults, most of which are destructive and cause displacement of the ore bodies.

The study area, spanning approximately 10 km^2, is situated within the Ban Kep A – Ban Kep B region of Minh Son Commune, Bac Me District. It is bordered to the north by Du Gia Commune (Yen Minh District), to the east by Giap Trung Commune (Bac Me District), and to the west by the Suoi Thau area in Minh Son Commune (Fig. 1).

The main geological formations in the area include the Ha Giang Formation ($Є_2hg_1$ and $Є_2hg_2$), which constitutes the majority of the study area. It comprises limestone, calcareous interstitial marble, and mica-quartz schist. This formation serves as the host rock for lead-zinc metallization. The overlying Tung Ba Formation (D_1tb) consists of quartzite, quartz-mica schist, and foliated acidic volcanic rocks. It is distributed above the Ha Giang Formation and has not shown any association with metallization.

The study area features four fault systems: the northwest-southeast (NW-SE) fault system, the northeast-southwest (NE-SW) fault system, the sub-meridional fault system, and the sub-latitudinal fault system.

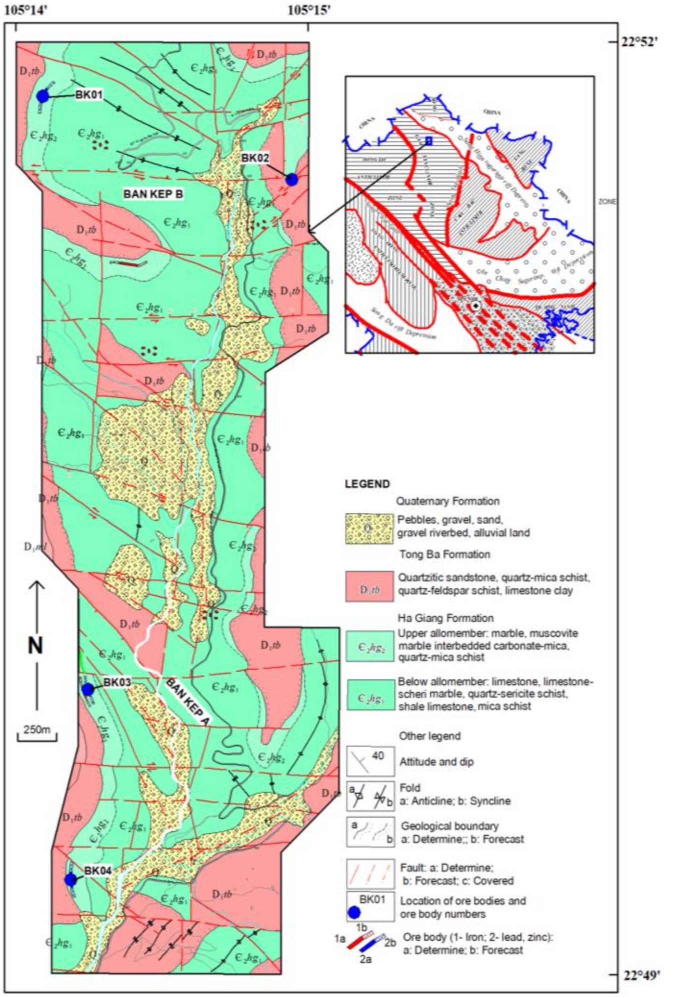

Figure 1. Geological map of the study area on the regional structural map [6], [7]

Among these, the NW-SE fault system is the oldest and most developed. It is classified as a medium-scale fault system and has a significant impact on the regional structural framework. The NE-SW fault system is less prominent, typically consisting of small to medium faults. These faults have large displacement amplitudes and are considered to be closely associated with metallization. The sub-meridional fault system includes medium to significant faults that dissect, slip, and complicate the ore zones. The sub-latitudinal fault system is relatively well-developed in the area, generally comprising small to medium-sized faults. These faults intersect the main structural trends and slip the pre-existing fault systems.

In the study area, the geological formations have undergone multiple phases of tectonic activity, resulting in deformation and folds of various scales. Most of these folds are small and short, exhibiting nearly symmetrical or asymmetrical shapes, with fold axes trending NW-SE, NE-SW, or sub-latitudinal. These folds are often incomplete and truncated by faults. However, they are generally associated with the activities of the NW-SE and NE-SW fault systems.

Overall, the main structural feature of the study area is a complex anticlinal zone trending sub-meridionally, which the sub-meridional Po Pieng fault zone has disrupted with two relatively wide limbs (3-5 km). In the eastern limb, the rocks dip east, east-northeast, or east-southeast; in the western limb, they dip west, west-northwest, or west-southwest, with gentle dip angles ranging from 5 to 30°.

Overall, the understanding of the origin and characteristics of lead-zinc metallization within the Lo-Gam Structural Belt remains limited and subject to debate:

– there is no consensus regarding the ore-forming mechanisms and their relationship to the sedimentary – tectonic setting;

– detailed analytical data on ore material composition, associated minerals, and characteristic geochemical signatures are lacking;

– the scale, distribution patterns, and relationships of SEDEX-type ore bodies across the entire structural zone have not yet been clarified.

These shortcomings highlight the urgent need for this study, which aims to:

– supplement and improve the geological mineral resource database of the area;

– identify genetic features and ore-forming conditions of selected lead-zinc ore bodies within the Tung Ba – Bac Me area;

– propose new criteria to guide exploration targeting in the Khau Loc area and adjacent regions.

The results of this research are expected not only to enhance the understanding of the geological-mineral evolution of Northeastern Vietnam, but also to contribute to the assessment of resource potential and to the rational orientation of future exploration and exploitation of lead-zinc deposits.

2. Methodologies

The general characteristics of SEDEX deposits worldwide suggest that they are sulfide deposits formed within a sedimentary basin through the submarine venting of hydrothermal fluids, with sphalerite and galena as the primary ore minerals. SEDEX deposits exhibit intermediate characteristics between Volcanogenic Massive Sulfide (VMS) and Mississippi Valley Type (MVT) ores [8]-[13].

To distinguish these ore types from others, they exhibit three unique features. Firstly, SEDEX ores form within sedimentary basins, typically spanning tens to hundreds of square kilometers. They occur within geological formations that contain specific sedimentary rocks, often displaying stratification that conforms to the surrounding rocks. Secondly, the primary mineralized ores are sphalerite and galena, which distinguishes them from ore deposits containing "nonsulphide" minerals formed in seabeds, such as barite, iron, and manganese, as well as from VMS deposits, where chalcopyrite is predominant. The presence or absence of chalcopyrite serves as an indicator of the primary product of hydrothermal activity, directly reflecting the temperature of the hydrothermal fluid. Thermal measurements of inclusions indicate a temperature range of 150 to 300°C for SEDEX hydrothermal fluids, whereas VMS temperatures exceed 300°C. Thirdly, SEDEX ores form from erupting hydrothermal fluids in seabed craters, emphasizing their syngenetic nature beneath the seafloor. This depositional environment serves as a crucial criterion for distinguishing them from MVT ore types, which are epigenetic and exhibit significant differences in ore mineral age compared to their host rocks [13], [14].

To understand the nature of SEDEX Ban Kep Pb-Zn ore deposits, we employ a combination of methods, including mineralography, inclusion analysis, ICP-MS, and S stable isotopes. These methodologies are outlined below.

2.1. Research samples

The materials used for this paper are derived from all previous studies. In addition, the authors conducted further analyses on 15 microsection samples, 15 polished samples, six chemical composition samples, 20 ICP-MS samples, five inclusion samples, and two sulfur isotope samples. The authors collected these from geological formations and iron, lead, and zinc ore bodies within the study area.

2.2. Methodologies

2.2.1. Methods and data compilation

Based on previous publications on lead-zinc metallization characteristics in the study area, as well as the research results of the authors, the compiled, processed, and analyzed data contribute to clarifying the origin and metallization characteristics of the region.

2.2.2. Petrographic method

Petrographic samples were collected from the study area, prepared, and analyzed at the Vietnam Institute of Geosciences and Mineral Resources. The samples were examined using an Axioskop optical microscope to study their mineral composition, texture, structure, and classification, and to interpret the origin of the rocks.

2.2.3. Metallization method

Ore samples were collected from ore bodies within the study area, prepared, and analyzed at the Vietnam Institute of Geosciences and Mineral Resources. The samples were examined by an Axioskop optical microscope to study ore textures and structures, distinguish metallization stages, identify mineral assemblages, and determine their paragenetic sequence.

2.2.4. Fluid inclusion method

The fluid inclusion samples consist of carbonatite rocks mineralized within the ore bodies of the study area. Fluid inclusion analysis helps determine the temperature of hydrothermal fluids during different metamorphic stages. The fluid inclusion samples were analyzed using equipment from Linkam (UK), including a TH-600 heating stage, TSM-90 temperature controller, and a microscopy imaging system. The temperature analysis range extends from -195°C to 600°C, with an accuracy of ±1°C (Vietnam Institute of Geosciences and Mineral Resources). The analysis results help distinguish the metallization stages and the formation temperatures of hydrothermal fluids at each stage.

2.2.5. Inductively coupled plasma mass spectrometry analysis method (ICP-MS)

Trace element samples were collected from ore outcrops and surrounding host rocks within the study area to identify other valuable elements in the lead-zinc ores. The samples were analyzed using an Agilent 7900 Inductively Coupled Plasma Mass Spectrometer (ICP-MS) system at the Geological Survey of Vietnam's Rare Earth and Radioactive Elements Division.

2.2.6. Sulfur isotope analysis method

Two lead-zinc ore samples were collected from minera-lized ore bodies within the study area. The samples were analyzed at Jisuo Lusheng Technology Services Co., Ltd. (Tianjin, China). The analysis results provide the stable sulfur isotope ratio $^{34}S/^{32}S$, expressed as $\delta^{34}S$ (‰). The $\delta^{34}S$ values for each ore sample were compared with sulfur isotope data from various known mineral deposits worldwide, aiding in the interpretation of the sulfur sources in the mineralized zones of the study area.

3. Results and discussion

3.1. Characteristics of metallization distribution

Lead-zinc ьetallization in the study area is typically distributed within the carbonatite and marble units of the upper Ha Giang Formation ($Є_2hg_2$). Four mineralized ore bodies have been identified in the study area. The Ban Kep B area contains two ore bodies (ore body BK01-ĐKS.BK1200; ore body BK02-ĐKS.BK317), while the Ban Kep A area includes two ore bodies (ore body BK03-ĐKS.BK13; ore body BK04-ĐKS.BK1227).

3.2. Morphological characteristics of ore bodies

The morphology of lead-zinc ore bodies in the study area is generally quite simple. They mainly occur as pseudostratiform bodies developed intercalated within the carbonatite-bearing units of the upper Ha Giang Formation. At the outcrops, ĐKS.BK13 and ĐKS.BK1227, lead-zinc ores generally occur in stratiform bodies (Fig. 2a, b) hosted within calcite marble and tremolite-bearing marble formations. The rocks are primarily composed of crystalline calcite with equigranular to irregular grains, ranging in size from 0.1 to 0.5 mm. Intergrown with calcite are abundant tremolite crystals occurring as plates, prisms, rods, or fine grains of various sizes, arranged in a disordered manner without a clear orientation. The rock-forming mineral assemblage consists of: calcite (60-95%); tremolite (0-30%); quartz (5-7%); feldspar (1-3%); biotite (minor); sphene (minor); ore minerals (trace-10%) (Fig. 3a, b).

Four ore bodies have been identified in the study area (BK01, BK02, BK03, BK04), predominantly oriented northwest-southeast with dip angles ranging from 15 to 25°. Among them, ore bodies BK01 and BK03 are small-scale with low grades and relatively thin thicknesses (usually less than 0.5 m). Ore bodies BK02 and BK04 are thicker, ranging from 1 to 3 m, with Pb + Zn grades varying between 0.14% and 11.68%. The Pb/ (Pb + Zn) ratio ranges from 0.19 to 0.89, which falls within the typical range reported for SEDEX-type lead-zinc deposits worldwide (Table 1).

3.3. Characteristics of metallization

3.3.1. Composition of ore minerals

The composition of ore minerals in the polished samples from the study area is relatively simple. It mainly includes primary ore minerals: pyrite, sphalerite, galena, and, less commonly, chalcopyrite. Secondary minerals present are goethite, melanterite, and anglesite. Gangue minerals include quartz and calcite. Hydrothermal alteration minerals include quartz, calcite, and dolomite.

(a) (b)

***Figure 2.** Lead-zinc ore bodies in banded, pseudostratiform form within altered carbonatite units: (a) ore body BK03 in unit ĐKS. BK13; (b) ore body BK04 in unit ĐKS. BK1227. Photos by Ta Dinh Tung*

(a) (b)

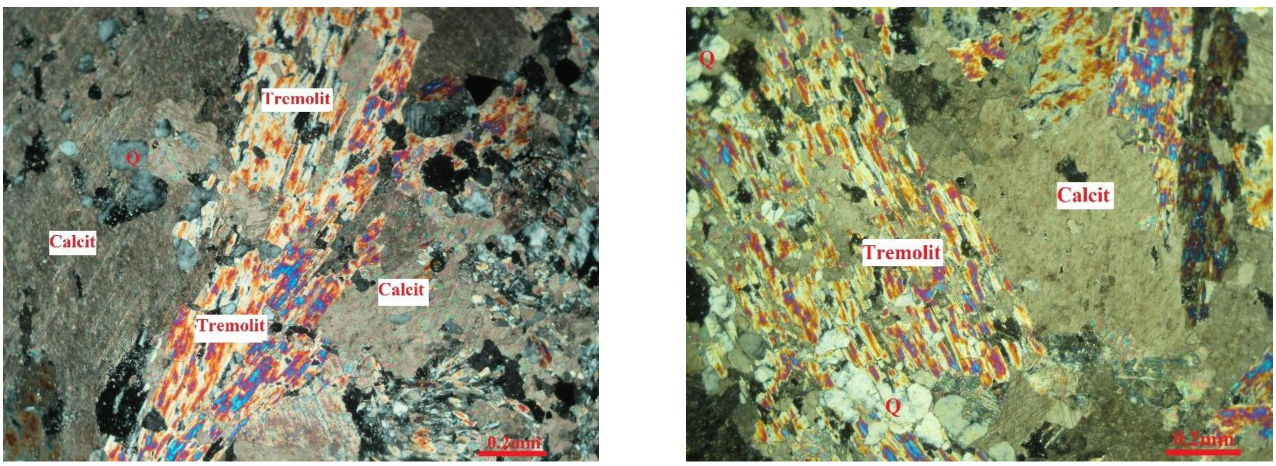

***Figure 3.** Marble with tremolite from the upper unit of the Ha Giang Formation containing lead-zinc metallization: (a), (b) ore body BK04 at survey point BK.1227/2*

Table 1. Chemical analysis results of ore samples from the study area

No.	Sample	Analyte concentration (%)				(Pb + Zn)	Pb/ (Pb + Zn)
		Pb	Zn	TFe	S	(%)	ratio
1	BK 317-R (BK02)	2.21	9.47	17.57	15.79	11.68	0.19
2	BK 1227-R/1 (BK04)	1.21	1.40	4.02	2.07	2.61	0.46
3	BK 1227-R/2 (BK04)	2.76	0.35	6.65	1.41	3.12	0.89
4	BK 1227-R/3 (BK04)	5.00	1.54	5.21	2.46	6.55	0.76
5	BK 1227-R/4 (BK04)	0.08	0.06	3.74	0.03	0.14	0.55

3.3.2. Texture and structure of the ore

Microscopic examination of polished thin sections from samples in the study area reveals that the lead-zinc ores (BK01, BK02, BK03, BK04) are characterized by banded structures, with banded disseminations, and occasionally intergrowth textures. The ore mineral architecture is typically subhedral to anhedral, with occasional colloform textures (Fig. 4a, b, Fig. 5a, b).

3.3.3. Chemical composition characteristics of the ore

Chemical analysis results show that, besides the main ore-forming elements Zn and Pb, there are also several associated valuable elements. The Zn content ranges from 0.06 to 9.47%. The Pb content ranges from 0.08 to 5%. The combined ICP-MS analysis results indicate that, in addition to the main elements Zn and Pb, the ore also contains associated elements such as Ba, Cu, Mn, Sb, Ag, and As. The most notable associated elements are copper (Cu) and silver (Ag). Specifically, Cu shows a high concentration of 0.33% in the lead-zinc ore sample from ore body BK02. Ag values range from 23 to 94 ppm in ore bodies BK2 and BK4, potentially making these elements recoverable in the lead-zinc concentrate.

3.4. Formation temperature characteristics

The analysis results of the inclusion samples in the lead-zinc ore samples show that they are mainly liquid-gas inclusions, which are typically small in size and have low density. Based on the presence of inclusions in the samples and the homogenization temperatures of their phases, the following general characteristics are observed (Table 2).

(a) (b)

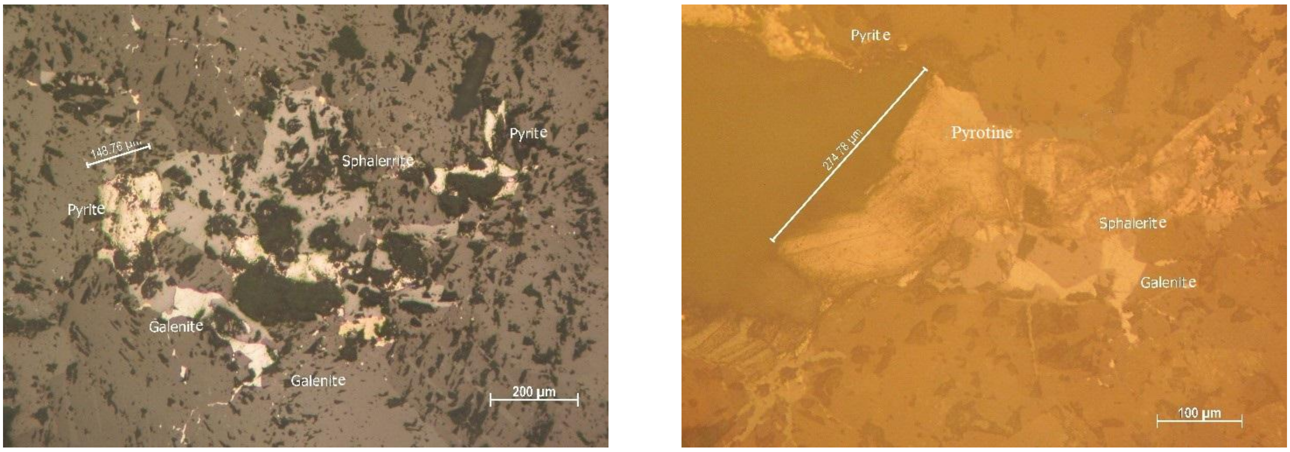

Figure 4. Disseminated banded assemblages of pyrite, galena, and sphalerite in weakly altered limestone matrix, sample BK.1227 from ore body BK04: (a) irregular grains within the matrix; (b) pyrrhotite partially altered to melanterite. Photos by Ta Dinh Tung

(a) (b)

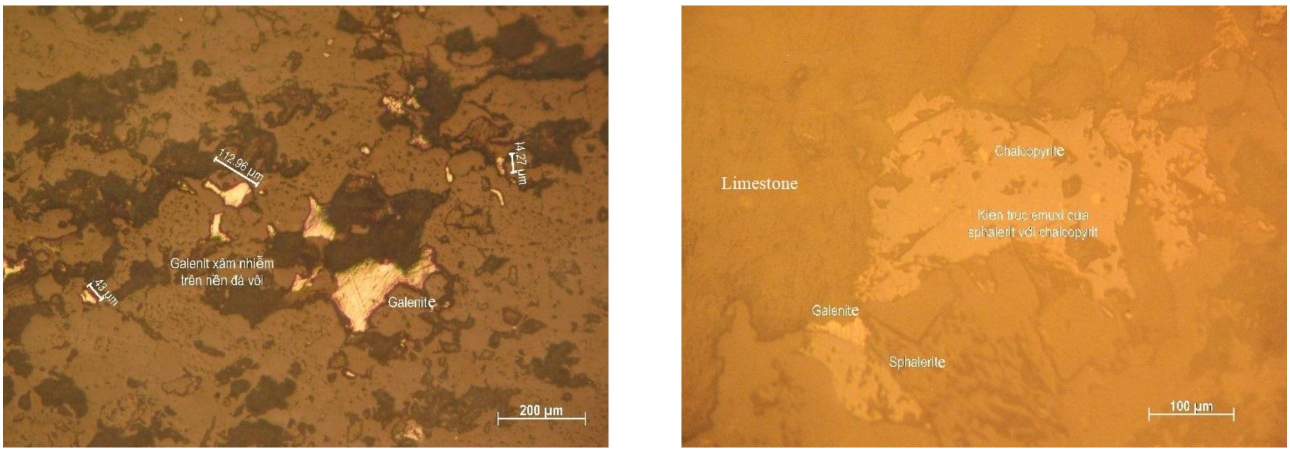

Figure 5. Disseminated metallization in limestone matrix, sample BK.13 from ore body BK03: (a) galena disseminated in limestone; (b) galena, sphalerite, and chalcopyrite assemblage in weakly altered limestone. Photos by Ta Dinh Tung

Table 2. Results of fluid inclusion sample analysis

No.	Sample	Type of inclusion (composition)	Shape	Size, μm	Homogenization temperature, °C
1	BK13/1 (BK03)	Liquid-gas (80-90% liquid, 10-20% gas)	oval, polygonal, elongated tubular	2-3	210-295
2	BK28 (BK04)	Liquid-gas (80-90% liquid, 10-20% gas)	oval, polygonal	2-3	207-290
3	BK28/1 (BK04)	Liquid-gas (80-90% liquid, 10-20% gas)	oval, polygonal, droplet	2-3	205-290
4	BK28/2 (BK04)	Liquid-gas (80-90% liquid, 10-20% gas)	oval, polygonal, droplet	2-3	208-292
5	BK1227/2 (BK04)	Liquid-gas (80-90% liquid, 10-20% gas)	oval, polygonal, droplet	2-3	215-293

Liquid-gas inclusions are commonly oval, polygonal, or droplet-shaped, with lengths ranging from 2 to 3 μm. Their phase composition consists of 80-90% liquid and 10-20% gas. The inclusions occur at a low density (< 50 inclusions/mm^2) and exhibit homogenization temperatures ranging from 205 to 295°C. Based on the presence of inclusions and their homogenization temperatures, the minerals in the inclusion samples formed at medium temperature ranges.

3.5. Sulfur stable isotope characteristics

The results of stable sulfur isotope analysis on two disseminated lead-zinc ore samples from the study area (BK.11) and the southeastern part of the study area (BK.1073), as shown on the diagram (Fig. 6), indicate that the $\delta^{34}S$ (‰) values of the study area and the Ban Lin – Phia Dam ore belt suggest that the sulfur source in the ore samples is primarily related to evaporite sedimentary deposits. Additionally, there is evidence of input from volcanic SO_2 and H_2S sources. This indicates that the ore-forming fluids are closely related to, and consistent with, sedimentary exhalative (SEDEX) lead-zinc deposits within the study area and more broadly within the Khau Loc structural subzone [1]-[6].

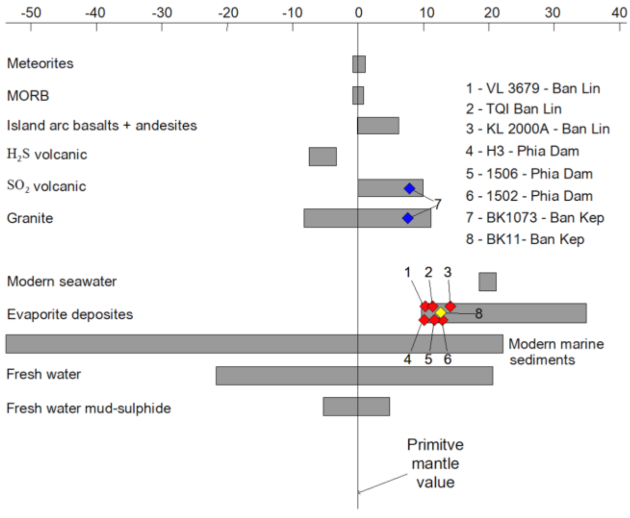

Figure 6. Diagram showing $\delta^{34}S$ (‰) isotope values of the study area and the Ban Lin – Phia Dam ore belt (compiled by [6], [15])

A study on the characteristics of lead-zinc metallization in the Ban Kep area, Bac Me, Ha Giang, shows that the lead-zinc Metallization has a medium-temperature hydrothermal origin. Additionally, the authors suggest that the lead-zinc Metallization in the study area shares similarities with the SEDEX deposit type, with the following main features:

– the lead-zinc metallization occurs within a sedimentary basin area belonging to the Khau Loc structural subzone;

– the lead-zinc metallization typically has a banded, strati-form morphology; this natural foliated texture is consistent with a low-energy environment provided by an evaporitic source;

– the Pb/(Pb+Zn) ratio (Table 1) ranges from 0.19 to 0.89, which is a standard range in previously studied SEDEX deposits [16], [17];

– the mineral formation temperature range is from low to medium (in this study, from 205 to 295°C);

– the $\delta^{34}S$ (‰) isotope ratio values of the study area are 7.63 and 12.75 (Table 3), indicating that the sulfur source in the ore samples is mainly related to evaporite deposits, with additional contributions from volcanic SO_2 and H_2S sources (Fig. 6).

Table 3. $\delta^{34}S$ (‰) isotope values of the study area

No	Sample	$\delta^{34}S$, ‰	Sampling location	Note
1	BK.11	7.63	Southern Ban Kep	The samples were processed and analyzed at Jisuo Lusheng Technology Services Co., Ltd. (Tianjin), China
2	BK.1073	12.75	Southeastern Ban Kep	

These values are consistent with those from SEDEX deposits of the Ban Lin – Phia Dam ore belt and the Khau Loc structural subzone [1]-[6]. According to [17], a compilation of known SEDEX deposits worldwide shows that $\delta^{34}S$ values typically range from -8 to +30‰, with concentrations commonly found between +10 and +15‰.

3.6. Perspectives for further research

Although the current research results have initially confirmed the presence and outlined the genetic characteristics of lead-zinc metallization in the study area, many scientific aspects remain unresolved. First, geochemical, isotopic, and mineralogical data are still limited to a basic level, which is insufficient to clearly determine the ore-forming environment, the sources of ore materials, and the relationship between tectonic–hydrothermal activities and metallization processes. In addition, the spatial distribution patterns of SEDEX-type lead-zinc metallization across the entire Lo-Gam Structural Belt have not yet been fully characterized, thereby complicating the prediction of mineral resource potential.

Therefore, further in-depth studies should focus on several main directions:

– supplementing data through advanced analytical methods such as Pb/Pb isotopes, stable isotopes (O, S), fluid inclusion composition, and trace-element analyses in minerals (EPMA), to clarify the ore-forming environment and evolutionary processes;

– integrating geophysical methods and 3D modeling to identify deep anomalies, thereby defining ore-forming models and the subsurface extent of ore bodies;

– comparing with typical SEDEX deposits both regionally and globally to highlight similarities and differences, which would enhance both the scientific understanding and practical implications for mineral exploration.

These directions will not only help overcome current limitations but also open up prospects for a more comprehensive assessment of lead-zinc potential within the Lô Gâm structural zone, while providing a scientific basis for sustainable management, exploration, and utilization strategies of the region's mineral resources.

4. Conclusions

The study results on the characteristics of lead-zinc metallization in the Ban Kep area, Bac Me district, Ha Giang province, allow for the following conclusions:

Lead-zinc metallization in the study area commonly occurs as banded, disseminated bands within carbonated formations that have undergone silicification and dolomitization, belonging to the upper sequence of the Ha Giang Formation. The northeast-southwest fault system is related to the metallization.

The ore mineral composition is relatively simple, mainly consisting of pyrite, sphalerite, and galena. The common ore texture in samples is banded and disseminated banded. The ore mineral architecture is typically subhedral to anhedral, occasionally exhibiting a colloform texture.

The sulfur source involved in ore formation in the study area is mainly related to evaporate deposits, with additional contributions from volcanic SO_2 and H_2S sources.

The ore genesis is attributed to medium-temperature hydrothermal fluids and shares several characteristics with the SEDEX deposit type known in the Khau Loc structural subzone and worldwide.

Overall, the preliminary results suggest that the Ban Kep area, Bac Me District, Ha Giang Province, has favorable geological conditions for the formation of SEDEX-type lead-zinc mineralization. The discovered and studied ore bodies show a close relationship with carbonate formations and tectonic activities in the region. However, current studies still have certain limitations, particularly the lack of in-depth data on geochemistry, fluid inclusions, mineralogy, isotopes, and 3D modeling. Therefore, future research should focus on integrating methods such as electron probe microanalysis (EPMA), fluid inclusion studies, stable isotope analyses, and 3D structural modeling to clarify better the distribution patterns and resource potential of lead-zinc metallization in the area. These results will not only contribute to advancing the scientific understanding of SEDEX ore-forming processes in the study area but also provide practical significance for prospect prediction, exploration targeting, and the sustainable exploitation of lead-zinc mineral resources in Vietnam.

Author contributions

Conceptualization: TDT; Data curation: TDT, NTQ; Formal analysis: TDT; Funding acquisition: TDT; Investigation: TDT, DQB, HST; Methodology: TDT, DQB, HST; Project administration: TDT, LCT; Resources: TDT, LCT, DQB, HST, NTQ; Software: TDT, NTQ; Supervision: TDT, LCT; Validation: TDT, LCT; Visualization: TDT, LCT; Writing – original draft: TDT, LCT; Writing – review & editing: TDT, LCT, DQB, NTQ. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare that they have no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Характеристика свинцево-цинкового оруднення в районі Бан Кеп, повіт Бак Ме, провінція Хазянг

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Мета. Дослідження спрямоване на визначення походження та типу свинцево-цинкових родовищ у районі Бан Кеп, повіт Бак Ме, провінція Хазянг, на основі вивчення морфології мінералів, температури утворення та ізотопних характеристик. Отримані результати мають слугувати підґрунтям для оцінки й прогнозування ресурсів свинцево-цинкового типу SEDEX у В’єтнамі.

Методика. Для дослідження характеристик родовищ SEDEX Pb-Zn району Бан Кеп було застосовано комплекс методів, зокрема мінералографічний аналіз для визначення складу та тектонічної будови порід і руд, вивчення включень у флюїдах для встановлення температур формування, а також аналіз ізотопів свинцю для оцінки середовища та джерел рудоутворювальних матеріалів.

Результати. Встановлено, що свинцево-цинкове оруднення в районі Бан Кеп має середньотемпературне гідротермальне походження. Крім того, встановлено, що воно демонструє ключові риси, характерні для родовищ типу SEDEX.

Наукова новизна. Родовища SEDEX широко вивчаються у світі, і для них запропоновано кілька генетичних моделей, зокрема пов’язаних із вибуховою активністю, накопиченням біогенного матеріалу та поверхневими процесами заміщення. Кожна з моделей має свої переваги та обмеження у поясненні генезису й розвитку таких родовищ. Представлене дослідження доповнює наявні дані новими матеріалами з В’єтнаму, де цей тип родовищ досі недостатньо вивчений.

Практична значимість. Отримані результати формують наукове підґрунтя для виявлення та оцінки свинцево-цинкових ресурсів SEDEX у В’єтнамі та можуть бути використані в геологічній розвідці та прогнозуванні ресурсного потенціалу.

Ключові слова: *свинець-цинк, флюїдні включення, стабільні ізотопи, гідротермальний, осадовий ексгалятивний SEDEX*

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