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Sedimentary exhalative Pb-Zn deposit model of the Ban Lin – Phia Dam ore range, Vietnam

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Abstract

Purpose. The aim of this study is to construct a typical ore model for Pb-Zn ore range in Ban Lin – Phia Dam and to compare it with the existing ones. The model is constructed based on three main elements of the mineral generation process, such as formation environment, generated-ore fluid source, and deposited-ore mechanism. The obtained results are aimed at determining and predicting the resource of sedimentary exhalative (SEDEX) Pb-Zn ore deposit in Vietnam.

Methods. To comprehend the characteristics of the SEDEX Pb-Zn ore deposits in the Ban Lin – Phia Dam area, we employ a combination of approaches that include mineralography to determine the composition and tectonic structure of rocks and ore, inclusion analysis to determine the temperature and inclusion composition, Pb isotopic analysis and stable S isotopic analysis to explore the environment and sources of ore-forming materials.

Findings. The sedimentary exhalative (SEDEX) Pb-Zn ore deposit arises from the dissolution of metal-rich salt deposits due to heating at shallow depths (several kilometers). Subsequently, this fluid migrates through faults and fractures to preferred locations where galena and sphalerite precipitate alongside sedimentary basin deposition.

Originality. SEDEX ore deposits have been extensively studied in various regions of the world. Although there are multiple theories regarding their origin, including explosion, biological debris accumulation, and surface replacement, each model has its own distinct advantages and limitations in explaining the genesis and development of SEDEX ore deposits.

Practical implications. The acquired findings are intended to identify and predict the resources of sedimentary exhalative Pb-Zn ore deposits in Vietnam.

Keywords: *SEDEX, formation environment, generated-ore fluid source, deposited-ore mechanism*

1. Introduction

The sedimentary exhalative (SEDEX) ore deposits represent the largest Zn-Pb deposits in the world [1]. Their reserves comprise more than 50% of the world's Zn and Pb resources [2], with over 129 such deposits identified in sedimentary basins worldwide [3], [4]. Taylor R.D. et al. [5] demonstrate that SEDEX ore deposits are present in 25 sedimentary basins, with seven basins containing over 10 million metric tons (Mt) of combined Pb + Zn. These are primarily located in:

– the Mt. Isa-McArthur basins, Australia (7 deposits totaling 112 Mt of Zn + Pb metal);
– the Selwyn basin, Canada (17 deposits, 55 Mt);
– the Brooks Range, Alaska, United States (3 deposits, 40 Mt);
– the Rajasthan basin, India (5 deposits, 20 Mt);
– the Belt-Purcell basin, United States and Canada (1 deposit, 19 Mt);
– the Rhenish basin, Germany (2 deposits, 11 Mt).

In Vietnam, the SEDEX Pb-Zn ore deposit type has been studied by Do Quoc Binh et al. [6], Do Quoc Binh et al. [7], and Do Quoc Binh et al. [8]. Moreover, the SEDEX Pb-Zn deposit model of the Ban Lin – Phia Dam ore range is still under investigation. The purpose of the study is to develop a model of SEDEX Pb-Zn deposit type through data analysis of ore range structure, mineral ore textural and structural properties, mineralography, as well as analysis of radioactive Pb isotopes, stable S isotopes, and fluid inclusions.

The study area map is compiled based on 1:200000 geological map of the Khau Loc region. The map is modified from Dojikov [9] and Do Quoc Binh et al. [6]-[8], [10]-[12]. The study area is situated along the northeastern margin of the Lo-Gam Structural Belt, adjacent to the Song Hien Structural Belt [13]-[15]. Covering an approximate area of 15 km in length and 2 km in width, it extends in a northwest-southeast direction (Fig. 1). It includes:

The Lo-Gam Structural Belt. This structural belt belongs to the Phanerozoic structural series in northeastern Vietnam, representing essentially an early Paleozoic marginal marine structure. Available documents indicate that this structure has an ancient basement that was highly fragmented and altered initially during the dispersive inland rift phase in the late Neoproterozoic.

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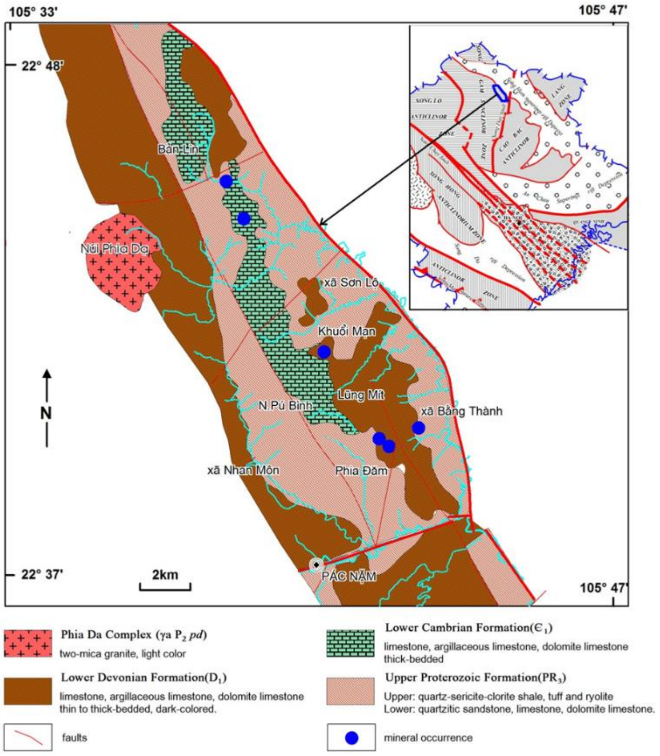

Figure 1. Geological map of Pb-Zn ore range area in Ban Lin – Phia Dam

It was 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. Particularly notable are the residual fragments of the Pre-Cambrian folded basement of Luc Lieu – Lap Thach and the concentric granite-metamorphic dome structures of Chiem Hoa, Cham Chu, and Bac Muc, also known as granite-migmatite micro-domes. These structures are interconnected by folded complexes of Early Paleozoic oceanic-type structures surrounding the Song Chay microcontinent. These structures are superimposed by the late orogenic Pia Phuong basin, which arose from the collision of microcontinents and closure of oceanic structures in the late Silurian to early Devonian. The structural pattern of the Lo Gam belt, along with the characteristics of formation, thickness, and deformation of pre-Devonian dynamo-tectonic complexes, suggests the formation of a structure resembling a conglomerate of microcontinents bound by folded dynamic zone complexes. This explains uneven deformation and specific facies-zone characteristics of the complexes forming them. Generally, such structural landscapes are common in marginal marine structures formed as a result of dispersive rifting at the edges of mature continental crust structures. In a metaphorical sense, the early Paleozoic marginal marine zone of Lo Gam can be considered the ancient counterpart of the Cenozoic East Sea.

The Song Hien Structural Belt. The fundamental formation characteristics of the Song Hien structure include the widespread development of Lower to Middle Triassic sedimentary and volcanic deposits, which exhibit uneven deformation and contain numerous ultramafic and mafic bodies along their boundaries and within some higher-order structures. The initiation of the Song Hien belt coincides with the global thermal activation period and the breakup of Pangea II (Late Paleozoic), while simultaneously aligning with the collision and overthrust activities during the final phase of Hercynian margin structures in the Southeast China Coastal region. Along the destructive boundary lines, contrasting volcanic rocks emerged. By the early Late Triassic, this structure underwent compression and uplift; however, no orogenic complexes have been identified within this structure scope to date. The geodynamic regime characteristics and the material-structural complexes formed here allow us to consider the Song Hien structure as an inverted aulacogen. The precursor of the Song Hien aulacogen includes rift-like structures that appeared behind the Phu Ngu overthrust zone and the Hercynian fold belt of the Southeast China Coastal region. This Early Mesozoic rift did not evolve into secondary oceanic structures, but remained as an intraplate destructive-superimposed structure.

The geological background of the study area comprises sedimentary rocks dating from the Neoproterozoic to the Early Paleozoic [6]-[8], [10]-[12]. The general stratigraphy of the basin can be delineated from bottom to top as follows: the lower section consists of Neoproterozoic formations characterized by predominantly metamorphic terrigenous and terrigenous sediments, including schist, quartz-sericite-chlorite, sandstone, and quartzite sand interbedded with marblized-limestone lenses. These formations are primarily concentrated in the central area under study.

The middle section comprises early Cambrian metamorphic sedimentary formations composed of quartz-sericitization and marblized-limestone, dolomite. The upper portion consists of Ordovician formations composed of quartz-sericite-schist rocks infiltrated by Pb-Zn mineralization. These Ordovician formations are overlain by Ordovician ryolite, which is overlain by compressed schist layers infiltrated with Pb-Zn mineralization, predominantly distributed in the north-northwest of the study area. The uppermost layer comprises Devonian formations consisting of limestone, limestone-dolomite, and silic limestone infiltrated by Pb-Zn mineralization, distributed mainly in the south and center of the study area. These formations together form a unified structure, inclined to the west and southwest. The ore range boundary is delineated by the northwest-southeast fault and northeast-southwest fault.

The Lo Gam structural belt is an area rich in various minerals such as Sn, Hg, Pb, Zn, Ag, Au, Bz, Sb, and Fe. Lead-zinc minerals predominate among them, with significant potential. The lead-zinc minerals in this belt originate from various sources, including hydrothermal, VMS, and SEDEX. Of these, the SEDEX-origin lead-zinc minerals are a new target and, to date, their origin and formation mechanisms have not been thoroughly studied. Research to develop a model of lead-zinc minerals in the study area will serve as a basis for a more detailed assessment and prediction of the lead-zinc mineral potential in the region.

2. Methodologies

The general characteristics of SEDEX deposits worldwide indicate that they are sulfide deposits formed in a sedimentary basin by submarine venting of hydrothermal fluids, and the primary ore minerals are sphalerite and galena. SEDEX deposits exhibit intermediate characteristics between Volcanogenic Massive Sulfide (VMS) and Mississippi Valley Type (MVT) ores [16], [17].

To distinguish these ore types from others, they exhibit three unique features. Firstly, SEDEX ores are formed in sedimentary basins [18], typically spanning tens to hundreds of square kilometers. They occur in geological formations containing specific sedimentary rocks, often exhibiting stratification consistent with the surrounding rocks. Secondly, the primary mineralized ores are sphalerite and galena [18], which distinguishes them from ore deposits containing "non-sulfide" 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, while VMS temperatures exceed 300°C. Thirdly, SEDEX ores are formed from erupting hydrothermal fluids in seabed craters [18], emphasizing their syngenetic nature beneath the seabed. This depositional environment serves as a crucial criterion for distinguishing them from MVT ore types, which are epigenetic, exhibiting significant differences in ore mineral age compared to their host rocks.

To understand the nature of SEDEX Ban Lin – Phia Dam Pb-Zn ore deposits, we employ a combination of methods including mineralography, inclusion analysis, radioactive Pb isotopes, and stable S isotopes. These methodologies are outlined below:

Field Survey Method: Field survey routes are conducted throughout the ore zone area, with a focus on surveying and collecting various samples at locations where lead-zinc ore has been encountered. Additionally, we create structural cross-sections to illustrate the overall structure of the study area. In important regions, we conduct surveys at a scale of 1:5000. During the survey, we collect various samples, including petrology, mineralogy, inclusions, and isotopes.

2.1. Mineralography

Mineralography is used to determine the origin of ore generation, that is, the processes controlling mineral formation, such as metamorphism, replacement-exchange, weathering, differential magma, or agglomeration-sedimentation. Mineralized samples are collected from ore bodies, treated, and analyzed at the Vietnam Institute of Geosciences and Mineral Resources. These samples are examined under an optical microscope to identify ore texture and structure to identify different ore mineral generations and symbiotic mineral assemblages.

2.2. Inclusion analysis

Inclusion analysis is conducted to determine the properties of inclusions, such as the formation temperature and salinity of hydrothermal fluids at each stage of mineralized formation, using six samples. The mineralized samples are analyzed at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). Among the six analyzed inclusions from the mineralized samples, properties of two inclusions are determined. The samples are analyzed using the Linkam THMS 600 combined with FLUID INC (USA) to measure temperature. The THMS600 has a temperature range of < -120 to -70°C with a precision of ±0.5°C, -70 to +100°C with a precision of ±0.2°C, and 100 to 500°C with a precision of ±2°C. To accurately record temperature changes during the measurement of fluid inclusions, the temperature rate ranges from 0.2 to 5°C/min. For inclusions containing CO_2 in solid form, the temperature rate decreases to 0.2°C/min. For precise measurement of phase change, the temperature rate increases from 0.2°C to -0.5°C/min when the inclusions contain water at the freezing point.

The NaCl salinity in CO_2 inclusions is estimated using the method outlined in [19]. The composition of each inclusion is analyzed using Raman spectroscopy with 2000 Renishaw system model, equipped with [1] Ar ion laser (wavelength of 514 nm). Raman spectra are collected at room temperature within the range of 100-4000 cm^{-1}. The inclusion analysis results aim to identify the mineralization stages, composition of inclusions, formation temperature, and hydrothermal fluid salinity. Specifically, the hydrothermal fluid temperature and salinity are crucial proofs for determining the environmental conditions of mineralization.

2.3. Radioactive Pb isotope

Four ore mineral samples collected from the ore seams and bodies are analyzed at the IGGCAS to identify the radioactive isotopic Pb ratios ($^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$). The age of the ore minerals is determined based on these isotopic ratios. In combination with inclusion analysis, the origin of the ore minerals is interpreted.

2.4. Stable S isotope

Six ore mineral samples were collected from the ore seams and bodies. Three of these samples were analyzed at the IGGCAS, while the remaining three were analyzed at the University of Saskatchewan, Canada. The obtained results of the stable isotopic S ratio are combined with the radioactive isotopic Pb ratio to interpret the origin and phase of deposited-ore formation.

3. Results and discussion

3.1. Structural and textural characteristics

The ore mineral range is distributed throughout two areas: Ban Lin – Lung Thom and Khuoi Man – Phia Dam. The Pb-Zn ore deposits of Ban Lin – Lung Thom are located in the northwestern part of the ore mineral range and are mainly found in early Cambrian formations. Similarly, the Pb-Zn ore deposits of Khuoi Man – Phia Dam are situated in the southeastern part of the ore mineral range and are predominantly found in Devonian formations [6]-[8], [10]-[12].

The structural and textural characteristics of the ore deposits are crucial for identifying the SEDEX type [16], [18], [20], [21]. The parallel stratigraphic textures, formed by the sandwiching of ore mineral lamination with sedimentary rocks, provide important evidence supporting the co-sedimentation process (Fig. 2a, 2b). Additionally, there are other types of disseminated textures (Fig. 2c, 2e) and nodular forms (Fig. 2d), which may result from the deposition of previous sulfide debris.

The main ore mineral composition includes barite, sphalerite and galena, while the minor ore mineral composition comprises pyrrhotite, chalcopyrite, and arsenopyrite. These minerals are found in the form of pseudo-colloforms and pseudo-fossils, as illustrated in Figures 3a, 3b [6]-[8], [10]-[12]. Such characteristics are typical of Pb-Zn SEDEX ore deposits [22], [23].

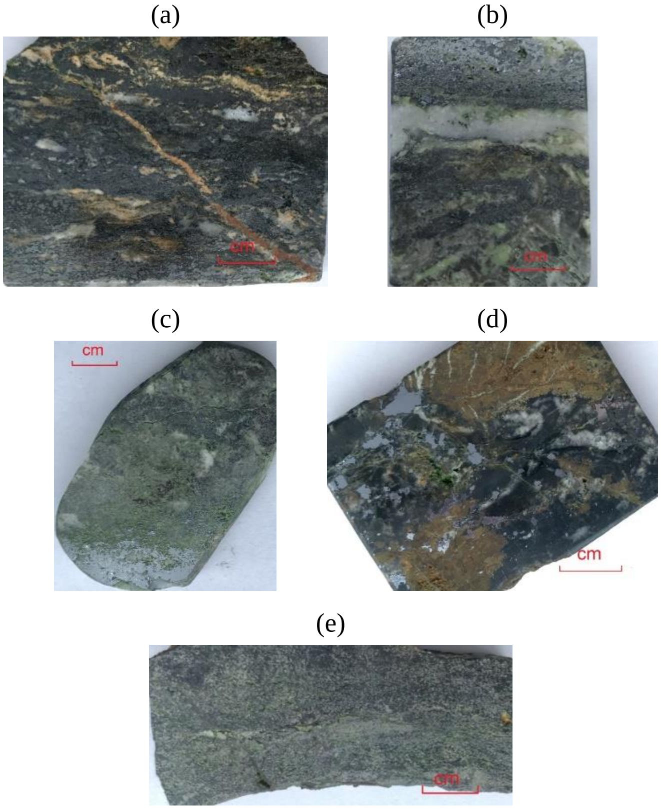

Figure 2. Photographs of samples illustrating the diversity of SEDEX ore textures collected in the Ban Lin – Phia Dam range: (a) light to dark gray sulfide ore mineral lamination in Ban Lin (dark gray galena and light gray sphalerite); (b) light to dark gray sulfide ore lamination and vents at Phia Dam (dark gray galena and light gray sphalerite); (c) light to dark gray sulfide ore infiltration and lamination at Phia Dam (dark gray galena, light gray sphalerite, and light-yellow pyrite); (d) light to dark gray sulfide ore infiltration and nodule at Khuoi Man (dark gray galena and light gray sphalerite); (e) light to dark gray and yellow infiltrated sulfide ore lamination at Khuoi Man (dark gray galena, light gray sphalerite, and light-yellow pyrite)

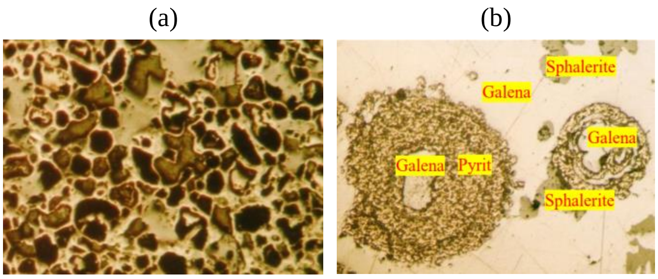

Figure 3. Photographs of mineralographic samples illustrating the diversity of SEDEX ore textures in the Ban Lin – Phia Dam range: (a) disguised colloforms of galena and sphalerite; (b) disguised fossil forms of galena and pyrite (photographs are taken by Do Quoc Binh et al. [7])

The presence of crystallization of pseudo-colloform and metamorphic colloidal remnant of pyrite suggests that the sulfur source of ore minerals originates from deep hydrothermal fluid and an external source, possibly due to reduction caused by bacterial activity in sulfate, leading to the initial formation of pyrite and subsequent generation of metamorphic colloidal pyrite post-textures. SHRIMP analysis indicates that both the pre- and post-crystallization phases of pyrite were formed from the same sulfate group as a result of decontamination by bacterial activities. However, the sulfide ore was formed from a single source of sulfide [24], [25].

3.2. Characteristics of environmental mineralization formations

3.2.1. Gas-fluid inclusion composition

In the pre-generated ore stage, microscopic examination reveals primary inclusions with a round shape and small size (< 0.5 μm). These inclusions form prior to the ore formation stage and consist of a high proportion of liquid and gas, with at least 50% being pure gas. Temperature spectrum analysis indicates that CO_2-containing inclusions have a low amount of H_2O. The solid melting point ranges from -53.2 to -49.9°C, with a clathrate melting temperature ($T_{m\,(clath)}$) of 5.3-8.3°C. The average temperature in the gas phase ranges from 13.0 to 15.8°C, and the equilibrium temperature in the gas phase ranges from 321 to 392°C, corresponding to a salinity of the liquid phase of $NaCl_{cq}$ = 5.51 – 3.33% (Table 1).

In the major-generated ore stage, microscopic examination reveals primary forms with irregular shapes (Fig. 4a). The gas-liquid inclusions are relatively small, ranging from 10% to a maximum of about 30%. Results obtained from laser electronic spectroscopy show that the minerals are mainly quartz, with minor peaks of CH_4 (1915 cm^{-1}) and H_2O (Fig. 4b). Temperature measurements of the inclusions indicate a solid melting point ranging from -88.7 to -86.9°C, a temperature equilibrium of 11.1-12.5°C, and full temperature equilibrium in the liquid phase ranging from 148 to 195°C. Based on these results, this process primarily occurs under relatively low-temperature conditions with an enrichment in CH_4-H_2O.

In the post-generated ore stage, inclusions primarily originate from primary inclusions. Results obtained from laser electronic spectroscopy analysis show that the inclusion compositions mainly consist of small amounts of CH_4 or large amounts of H_2O. The freezing temperatures measured range from -1.8 to 0°C, with equilibrium temperatures in the liquid phase ranging from 102 to 168°C, and the salinity of the liquid ($NaCl_{cq}$) ranging from 3.06 to 0.0%. This indicates that during the post-ore formation stage, relatively low sulfur salts were formed through a mixture with surface water under low-temperature conditions.

The analysis of inclusion composition and temperature confirms that the mineralized ore environment is related to the seabed environment, characterized by enrichment of H_2O, CH_4, and CO_2 and low formation temperatures.

Table 1. The result of analyzed inclusions and division of ore mineral phases

Order generated ore	Inclusion types	Melting point of the CO_2-contained inclusion, $T_{m\,(car)}$ / °C	Equilibrium temperature, $T_{h\,(car)}$ / °C	Contained inclusion, $T_{m\,(clath)}$ / °C	Melting point of mixture, $T_{m\,(ice)}$ / °C	Fully equilibrium temperature, $T_{m\,(hot)}$ / °C
Pre-generated ore	CO_2-H_2O	-58.1～-6.9	13.0～15.8	5.3～8.3		321～92
Initial-generated ore	CO_2-CH_4-H_2O	-61.5～-8.9	-14.5～-3.1	7.2～12.6		256～39
Major-generated ore	CH_4-H_2O	-88.7～-6.9	-58.1～-6.9	11.1～2.5		148～95
Post-generated ore	H_2O				-1.8～0	102～68

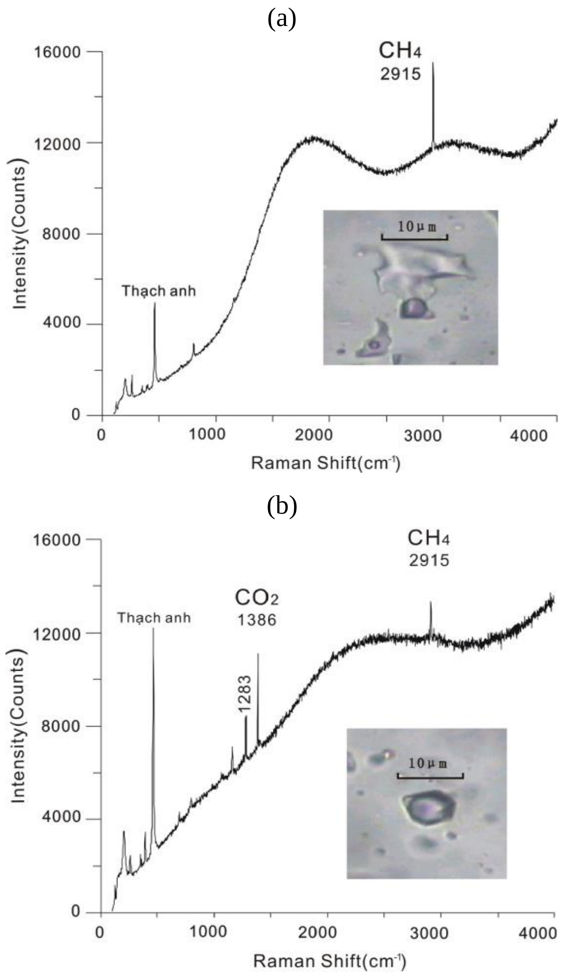

Figure 4. Raman laser spectrum of CO_2-CH_4-H_2O-enriched inclusions in Ban Lin: (a) inclusion #1 – H6R2 sample; (b) inclusion #2 – H6R2 sample

The salinity of the liquid phase is higher than that of seawater, consistent with previous models of SEDEX-type ore deposits. According to a previously published model [1], the salinity of the hydrothermal fluid in SEDEX ore deposits is two to four times higher than that of seawater. The salinity of the hydrothermal fluid in the quartz inclusion sample from the Ban Lin ore deposits is shown in Figure 5.

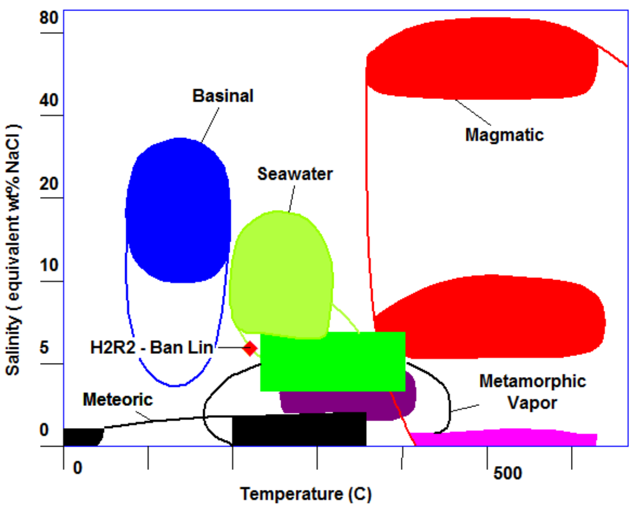

Figure 5. Schematic representation shows salinity in hydrothermal fluid in the Ban Lin ore deposits (modified from Wilkinson, J.J. [26])

The salinity of the ore-forming solution during the main ore-forming stage (5.51-3.33%) and after the ore-forming stage (3.06-0.0%) suggests that there was a dissolution of evaporites during ore formation (similar to the results of sulfur isotope source comparisons – Figure 6). As shown in Figure 5, the salinity in the hydrothermal fluid of the Ban Lin ore deposits corresponds to that of SEDEX ore deposits.

3.2.2. Characteristics of generated-ore fluid source and deposit mechanism

The results of stable isotope of sulfur ($\delta^{34}S$, ‰) of the Ban Lin – Phia Dam ore mineral range are shown in Table 2.

The $\delta^{34}S$ (‰) for the Ban Lin – Phia Dam ore deposit range (Fig. 6) falls into the field of sedimentary exhalative, salt deposits (evaporite). This proves that the ore deposit seam is SEDEX [24], [26].

Table 2. Isotopic ratio of sulfur ($\delta^{34}S$, ‰) of deposited ore seams of the Ban Lin – Phia Dam ore mineral [6]-[8]

No. sample	$\delta^{34}S$ (‰)	Sample location	Sample analysis place
VL 3679*	11.1	Seam I – Ban Lin	University of Saskatchewan, Canada
H3-R3	9.5	Seam II – Phia Dam	
H2-2.5 A	9.0	Seam II – Phia Dam	
KL. 2000 A	13.632	Northern seam Ban Lin – Lung Thom	IGGCAS, China
KL. 1502	12.703	Khuoi Man – Bang Thanh	
KL. 1506	11.678	Seam of lower part of Phia Dam: barite-Pb-Zn	

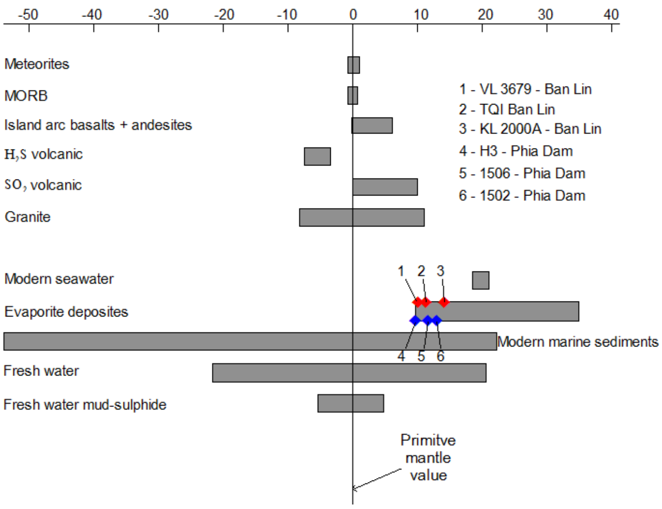

Figure 6. Scheme showing isotopic values $\delta^{34}S$ (‰) of the Ban Ban – Phia Dam [28] ore range compared to the research of Rollinson, H.R. [29]

SEDEX types of the Ban Lin – Phia Dam ore deposits are interpreted based on Pb isotopes in galena of the Ban Lin – Phia Dam ore deposits and combined with a "Plumbotectonics" model [30]. The Pb sources may result from a complex process related to a mixture and assimilation of Pb from many heterogeneous sources, including crustal remelting, sediment modification, and sediment extraction. Pb exists in the form of compounds circulated by hydrothermal fluid system and transported to favourable sites for ore deposition [30]. The results of Pb isotopic ratios of the Ban Lin – Phia Dam ore mineral range are shown in Table 3.

Table 3. The results of Pb isotopic ratios of the Ban Lin – Phia Dam ore mineral range [6]-[8]

No. sample	Sample location	$^{206}Pb/^{204}Pb$	Error (2s)	$^{207}Pb/^{204}Pb$	Error (2s)	$^{208}Pb/^{204}Pb$	Error (2s)
KL2000A	Ban Lin	17.8908	0.0012	15.6785	0.0013	38.5320	0.0042
VQI	Phia Dam	18.1073	0.0012	15.7526	0.0007	38.8136	0.0032
TQII	Phia Dam	18.6012	0.0011	15.7733	0.0009	39.1024	0.0026
TQIII	Ban Lin	18.3106	0.0014	15.772	0.0014	38.9714	0.0013

The results of Pb isotopic ratios (Fig. 7), displayed on the "Plumbotectonics" model [30], indicate that Pb isotopic source in the Ban Lin – Phia Dam ore deposit range is located between the two continental crusts and closer to the lower crust, probably related to the intracontinental activities.

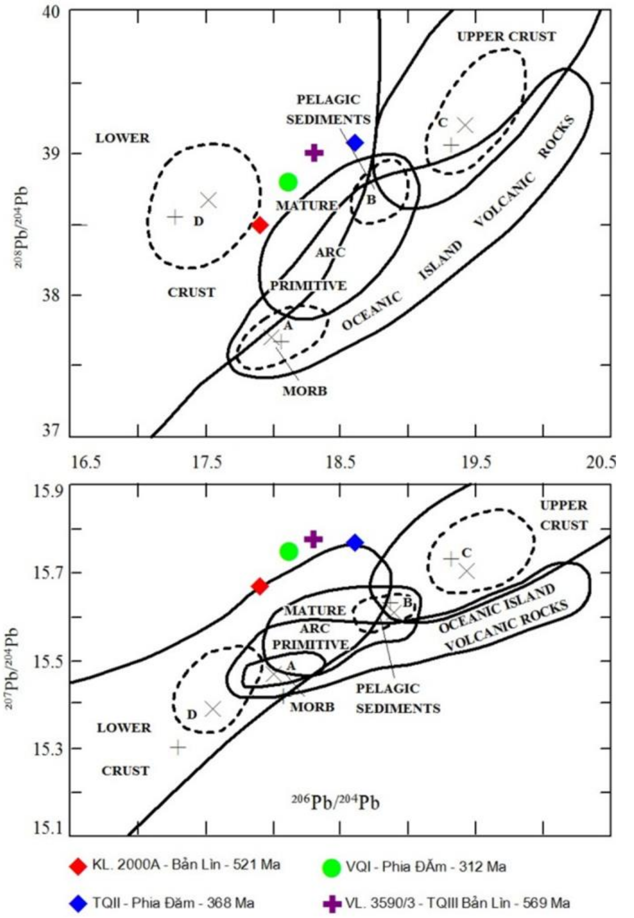

Figure 7. Pb isotope source in the Ban Lin – Phia Dam ore deposit range constructed based on the "Plumbotectonics" model [30]

From above results, the SEDEX ore deposit model of the Ban Lin – Phia Dam ore range is constructed (Fig. 8).

According to this model, the ore-forming fluids of the SEDEX ore deposits originate from fluid sources such as salt deposits (evaporites), containing metals. The anomalous geothermal gradient (up to 70°C/km) resulting from tectonic activities beneath the area probably heats the fluids to temperatures of 200°C [21], [26]. These fluid layers are located in highly porous rock formations covered by a clay layer. The clay layer, with its poor permeability, acts as a cap, preven-ting the movement of fluid and heat through it, thereby facilitating mineral deposition. In addition to the favorable stratigraphic conditions, tectonic activities such as faults and fractures play crucial roles as conduits for transporting and distributing mineralized fluids in sedimentary basins.

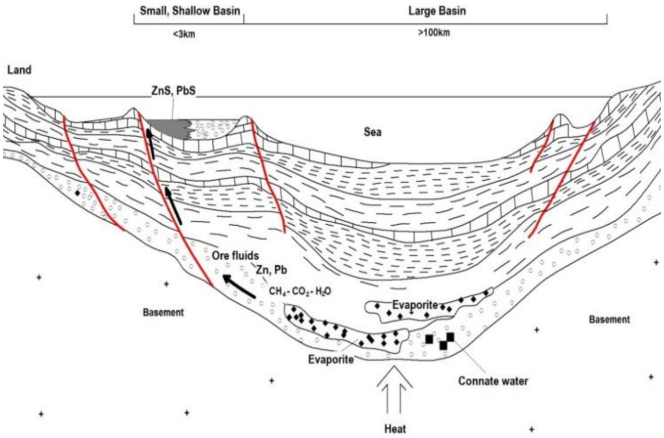

Figure 8. Model of mineralized ore formation of the Ban Lin – Phia Dam SEDEX ore deposit

These tectonic structures, including co-sedimentary faults and fractures, are formed during the early stages of sediment formation. SEDEX ore deposits have been modeled in various locations worldwide. Despite numerous theories regarding their mineralization origin, such as explosion [31], biological debris accumulation [16], and surface replacement [18], each model has its advantages and limitations in explaining the origin and formation of SEDEX ore deposits. In this study, our model primarily addresses key characteristics of SEDEX ore deposits.

– ore minerals are formed in co-sedimentary environment of sedimentary basin;

– seam lamination nature is consistent with low enthalpy environment, supplied by hydrothermal fluids of salt evaporation basin;

– the sedimentary texture of ore deposits occurs both at the initial stage and post-stage. The post-stage texture is the result of psue-morphology in the initial sediment;

– sulfur source is originated from salt deposits. Experimental results show that the fluid salinity at five times seawater salinity can carry millions of Pb, Zn and sulfide molecules in chemical equilibrium ratio to form sphalerite and galena at temperatures above 200°C [26].

The constructed model still has some limitations, such as the small number of inclusion analysis. Additional analytical data about inclusion can help make our model understandable and our arguments convinced.

The Ban Lin – Phia Dam ore range is a small area in the Lo Gam structural belt. Our research has initially identified the origin and formation conditions, aiming to provide a general ore formation model for mines in this area. However, the results are limited and not fully representative of the entire structural belt. Therefore, to better understand the origin and formation conditions and to predict the potential of SEDEX lead-zinc minerals throughout the entire structure, the key task for future research is to expand studies on SEDEX lead-zinc mineral deposits in the Lo Gam structural belt.

The specific objectives are as follows:

– to provide a typical model for the mineralization process of the entire structural zone;

– to predict areas with high potential for SEDEX lead-zinc minerals.

4. Conclusions

This study has contributed to clarifying the characteristics, origin, and formation conditions of SEDEX lead-zinc minerals in the Ban Lin – Phia Dam area. The main results are as follows:

1. Lead-zinc ores are characterized by banded forms developed in sedimentary formations dating from Cambrian to Devonian periods.

2. The mineralization occurs at low temperatures (256-95°C), suggesting that the heat source in this region may be influenced by an anomalous geothermal gradient due to ongoing tectonic activity.

3. The presence of colloform pseudomorphs and altered pyrite relics indicates that the sulfur isotope source for mineralization is not only supplied by deep-seated hydrothermal solutions, but also due to bacterial sulfate reduction creating primary pyrite, leading to the development of the altered pyrite structure.

4. The mineralization environment is related to a marine sedimentary setting with fluid inclusions comprising H_2O, CH_4, CO_2, low formation temperatures, and a higher salinity compared to seawater. Comparison with sulfur isotope analysis suggests that the sulfur source and hydrothermal solution environment may be related to evaporite deposits.

5. The primary Pb source is probably from the lower crust, suggesting that lead-zinc supply may originate from relatively shallow sources and continental crust.

Overall, the model for the formation of lead-zinc ores proposed by the authors is as follows:

1. The sources of lead, zinc, and sulfur are believed to originate from evaporite deposits.

2. Heating caused by high geothermal gradients (up to 256°C) may be due to the fact that the layer is located in a porous rock unit, covered by a clay layer, which forms a seal preventing heat dissipation from the hydrothermal source, allowing high temperatures to accumulate.

3. Tectonic activity plays a crucial role in the formation and development of mineralization, creating faults that act as channels for the migration and distribution of mineralization in sedimentary basins. These faults are sediment-hosted and characteristic of the early stages of rock formation, replacing fine-grained sediment layers with hydrothermal veins, leading to the formation of SEDEX lead-zinc deposits in the Ban Lin – Phia Dam study area.

Author contributions

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

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Conflicts of interests

The authors declare 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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Модель осадово-ексгалятивних свинцево-цинкових родовищ рудного масиву Бан Лінь – Пхіа Дам, В'єтнам

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Мета. Побудова типової моделі свинцево-цинкової руди родовищ рудного масиву Бан Лінь – Пхіа Дам та порівняння її з існуючими моделями.

Методика. Для розуміння характеристики осадово-ексгалятивних (SEDEX) свинцево-цинкових рудних родовищ у районі Бан Лінь – Пхіа Дам використано комбінацію підходів, що включають мінералографію для визначення складу та тектонічної структури гірських порід і руди, аналіз включень для визначення температури й складу включень, ізотопний аналіз свинцю та аналіз стабільних ізотопів сірки для вивчення навколишнього середовища і джерел рудоутворюючих матеріалів. Модель побудована на основі трьох основних елементів процесу мінералоутворення, таких як середовище формування, джерело флюїду, що утворюється при рудоутворенні, та механізм відкладення руди.

Результати. Детально досліджено та роз'яснено характеристики, походження і умови утворення свинцево-цинкових мінералів SEDEX в районі греблі Бан Лінь – Пхіа Дам. Виявлено механізм формування досліджуваного осадово-ексгалятивного (SEDEX) свинцево-цинкового родовища. Встановлено, що родовище виникає в результаті розчинення багатих на метали родовищ солей внаслідок нагрівання на невеликих глибинах (кілька кілометрів), а згодом ця рідина мігрує через розломи та тріщини у сприятливіші місця, де галеніт і сфалерит осаджуються разом із відкладеннями осадового басейну.

Наукова новизна. Свинцево-цинкові рудні родовища ретельно досліджуються в різних регіонах світу, хоча і існує безліч теорій щодо їхнього походження, включаючи експлозію, накопичення біологічного сміття та заміщення поверхні, кожна модель має свої власні переваги й обмеження у поясненні генезису та розвитку осадово-ексгалятивних рудних родовищ.

Практична значимість. Отримані результати призначені для виявлення та прогнозування ресурсів осадово-ексгалятивних свинцево-цинкових рудних родовищ В'єтнаму.

Ключові слова: *SEDEX (осадово-ексгалятивний тип родовищ), середовище формування, джерело флюїду, що утворюється при рудоутворенні, механізм рудоутворення*

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