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Genetic modeling and prospecting criteria: An example of syngenetic vs. epigenetic ore formation

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Генетично моделиране и критерии за търсене: един пример за сингенетично или епигенетично рудообразуване

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Abstract. The paper presents the importance of mineral deposit modeling, based on the elucidation of key elements of its origin, for the development of reliable criteria for prospecting of new deposits and orebodies of this type. On the example of the Kremikovtsi carbonate-hosted IF-barite-polymetallic deposit, it is shown that the adoption of a well-grounded syngenetic or epigenetic concept for its origin is crucial for successful prospecting activity. Based on the developed model for a sedimentary-exhalative (SEDEX) origin of the deposit (i.e. syngenetic to the carbonate host), the key factors controlling ore formation are specified, and an optimal strategy for future prospecting in the region is proposed.

Keywords: mineral deposit modeling, prospecting criteria, SEDEX, hydrothermal-metasomatic, Kremikovtsi IF-barite-polymetallic deposit.

Introduction

In recent years, the mineral deposits modeling has become increasingly important for the prospecting and exploration of new deposits and orebodies of any type. Moreover, it becomes a major challenge for economic geology in the century ahead (Skinner, 2005), and a key to successful prospecting and exploration in the future (Pohl, 2022). The enormous volume of data and scientific knowledge accumulated so far on a wide range of mineral deposits types, already allow the development of relatively reliable concepts (genetic models) for their formation conditions and geological evolution. The genetic model of mineral deposit should not be only the basic idea of its formation and classification type, but a logical construction based on a maximum set of facts, data and theory not contradicting each other and summarized in an integral scheme of numerous attributes, including: age, geodynamic setting, regional and local geological processes, sources of ore matter and ore solution, transport, deposition medium and ore-forming mechanisms, thermodynamic conditions, zonation, etc. (Damyanov, 2022).

A brief example on the crucial importance of the proposed genetic concept for mineral deposit formation on the selected prospecting and exploration strategy is presented in this paper. The object of study is the Kremikovtsi carbonate-hosted iron formation (IF)-barite-polymetallic deposit near Sofia, Bulgaria. This large Phanerozoic deposit was explored in 1953–1957 and mined for iron ores and barite for more than 50 years. After discovery of the deposit, all the prospecting and exploration activi-

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ties in the Kremikovtsi region and the surrounding area for 30 years were entirely based on the concept of its epigenetic hydrothermal-metasomatic origin. New research results in the last years, however, have provided strong evidence for a SEDEX origin (Damyanov, 1998), suggesting a completely different approach to the prospecting and exploration of similar types of deposits and orebodies.

Genetic models of ore formation

A detailed review of the genetic hypotheses for the origin of the Kremikovtsi deposit was made earlier (Damyanov, 1998). Two basic concepts ("epigenetic" and "syngenetic") have been an object of long-standing debates. The acceptance of one or the other viewpoint by the governing geological bodies

Table 1. Main genetic model attributes of the Kremikovtsi paleohydrothermal system

Age of ore formation	• Contemporaneous to the host carbonate rocks, determined by dating of fossil remains in the siderite IF: early Anisian (Aegean + Bithynian) Substage of Middle Triassic
Geodynamic setting	• *Intracontinental rift* setting at the beginning of Triassic epicontinental transgression, located along the border of early Paleozoic block accreted to the Moesian platform margin
Geological processes producing ore formation	• *Triassic upper mantle basaltic magmatism* – tectonomagmatic and heat flow activator of long-lived recycling paleohydrothermal system • *Hydrothermal sedimentation* – mixing of hydrothermal fluids with seawater and chemical precipitation of bedded IFs and barite into seafloor depressions near contemporaneous activated basement faults • *Hydrothermal replacement* and *cavity-filling* – contemporaneous epigenetic fault-fissure-controlled barite-sulfide and vein barite mineralizations deposited in the basement rocks and stratiform orebodies • *Diagenetic alteration* - low-grade sulfide mineralization formed under the control of the fissure-porous permeability of host carbonate rocks and ores during the transitions limestone → dolomitic limestone → dolomite and lower Mg-Mn siderite → higher Mg-Mn siderite
Sources of ore matter	• *Paleozoic basement rocks:* – Exogenic nature, continental crust origin and Paleozoic model age (310 Ma, middle/late Carboniferous) of Pb isotopes in barite and galena – Well-homogenized Pb and Sr isotope data; uniform exogenic source of Sr in barite, siderite and ankerite – Stable isotope data of siderite implying biogenic source of carbon – High contents of ferrous and base metals in Paleozoic basement rocks from the region
Sources of ore solution	• Modified *Middle Triassic seawater* sinking down along the graben faults, heated by magmatic activity, enriched in biogenic carbon and metal components from Paleozoic basement rocks and lifted up in the rift zone
Ore-forming solution	• *Red Sea-type* acid chloride Na > K fluids
Transport mechanism	• *Recycling thermal convection* of Middle Triassic seawater driven, heated and metals-exchanged in the upper crust by the magmatic activity in depth
Ore deposition medium	• SEDEX – stratified low energy brine seawater in seafloor depressions mixed with hydrothermal fluids • Epigenetic – Middle Triassic carbonate and Paleozoic basement rocks
Ore zonation	• Lateral zoning: pyrite → siderite → barite → Fe dolomitic limestone with Pb orebodies → hematite → hematitized Middle Triassic dolomitic limestone • A gradual decrease of Cu/(Cu+Pb+Zn) and Pb/Zn ratios upwards and NW • Lack of primary overlying geochemical halo and large underlying one
Thermodynamic conditions	• Oxic, postoxic, anoxic, sulfidic and sulfatic environments of sedimentary-hydrothermal precipitation/diagenesis; epigenetic hydrothermal replacement and cavity-filling
Post-ore alterations and deformations	• Diagenetic/epigenetic alteration of host carbonate rocks and ores: hydrothermal recrystallization, chloritization, ferroan dolomitization and ankeritization • Post-Middle Triassic tectonic events – Kremikovtsi thrust and several fault systems
Comparison with other deposits	• *No full analogue*; similar deposits: – SEDEX Pb-Zn-barite deposits – Atasu-type in Kazakhstan (SEDEX Fe-Mn pyrite-barite-polymetallic deposits in flysch) – Metalliferous sediments in modern rifts – Fe-Mn-Ba deposit in the Afar Rift, barite-polymetallic deposits in the marginal parts of the Red Sea

largely determines the development of successful strategy for prospecting and exploration of new orebodies and deposits of this type in the region. Therefore, the clarification of the key ore-controlling factors and their combination in a reliable genetic model is of great importance for the future geological activity.

Due to the level of knowledge and research methods in economic geology in the past (1950–1980), the concept of ***epigenetic hydrothermal-metasomatic origin*** of the Kremikovtsi deposit was adopted and used for the prospecting-exploration activities in the region. No genetic models in detail have been developed, but several basic postulates of this concept can be summarized: (i) fluids from unknown magmatic source (telethermal, amagmatic) or Tithonian basin dewatering system metasomatically replaced the host carbonate rock; (ii) the Kremikovtsi thrust is the main ore-controlling structure (thrust age determination is crucial for the ore formation timing); (iii) different ages of ore deposit formation (Late Jurassic (Tithonian), Late Cretaceous, Oligocene (Late Alpine)) related to basic geological events in the region; (iv) epigenetic nature of barite mineralization formed after metasomatic IFs (no relation to any tectonomagmatic activity has been assumed).

The analysis of huge amount of data and the numerous new facts about the mineralogical, geochemical and geological characteristics of the Kremikovtsi primary ores gave a strong reason to propose the concept of ***syngenetic SEDEX origin*** and to develop a new genetic model of ore formation (Damyanov, 1996, 1998). According to that model (Table 1), Kremikovtsi is a zonal deposit of SEDEX-type hosted by Middle Triassic carbonate rocks. It consists of three facies of ore formation: (i) *distal facies* – Mg-Mn siderite and hematite IFs with low-grade disseminated, rarely strata-bound sulfide mineralization formed in oxic, postoxic and anoxic environments; (ii) *intermediate facies* – generally stratiform pyrite and barite mineralizations in sulfidic and sulfatic environments; (iii) *proximal facies* – stockwork, vein and veinlets-disseminated siderite-barite-sulfide mineralization in the underlying rocks and ores. The Kremikovtsi deposit is generally the result of two-stage (hydrothermal-sedimentary and hydrothermal-epigenetic) Middle Triassic metallogenesis. The paleohydrothermal system of recycling type is located in a graben-shaped structure along the border of early Paleozoic block accreted to the Moesian platform margin. It operates in an extensional intracontinental rift setting characterized by a high geothermal gradient, perme-

Table 2. Prospecting criteria for new IF-barite-polymetallic deposits of SEDEX type in carbonate host

REGIONAL CRITERIA (indicative of potential mineralization)	
Paleotectonic	• Intracontinental rift-related second-order graben-shaped basins in the Middle Triassic epicontinental sea • Local fault-related third-order depressions with low energy and high salinity sedimentary environment
Paleostructural	• Early-Mesozoic Oboriste lithosphere cryptorupture covered under the Mesozoic–Cainozoic sediments of the Sofia graben and not activated during the Alpine events • Parallel to the Oboriste cryptorupture second-order and contemporaneous-activated basement faults from the marginal parts of the basin
Stratigraphic	• Low levels of the Iskar Carbonate Group (from the highest Lower Triassic to the lowest parts of lower Anisian)
Lithologic/ Facial	• Shallow-water shelf-sea dark-grey dolomitic limestone and dolomite • Abrupt local changes in sedimentary facies and rock thickness near contemporaneous graben faults
Magmatic	• Negligible manifestations of Triassic K-alkaline bimodal volcanism • Fine volcanic interbeds within the host carbonate rocks
LOCAL CRITERIA (indicative of the presence of mineralization)	
Mineralogical/ Petrographic	• Presence of interbeds, lenses and nests consisting of barite, chert, Fe(±Mn)-bearing carbonates, pyrite (±other sulphide minerals) and hematitized carbonate rocks • Wall-rock alterations: Fe dolomitization-ankeritization, silicification, baritization, chloritization, hydrothermal recrystallization • Zonal distribution of metalliferous carbonate facies and IF occurrences
Geochemical	• Primary lateral halo of Mn, Fe, Ba, Si, Mg, Pb, Zn, Hg in host sedimentary rocks • Lateral and downward zonation of Ba, ferrous and base metals • Homogeneous non-radiogenic Pb isotope compositions of barite and galena
Geophysical	• Anomalies created by hidden Fe-Mn and barite-sulfide orebodies • Anomalies related to deep-penetrating basement faults

able fault-disturbed basement rocks, arid climate at the beginning of marine transgression, and depressions on the epicontinental seafloor (Damyanov, 1998). Ore and geochemical zonation of that powerful paleohydrothermal system gives a strong reason Kremikovtsi in its current (tectonically formed) boundaries to be considered as a distal/intermediate fragment of richer proximal sulfide (Pb-Zn-Cu) mineralization at depth.

Prospecting criteria

In the past (1960–1990), on the basis of the accepted viewpoint of epigenetic hydrothermal-metasomatic origin of the Kremikovtsi deposit, the corresponding strategy for prospecting and exploration was developed with several key elements: similar tectonic structures (Kremikovtsi thrust, block structure, and several fault systems) considered to be preexisting and ore-controlling, carbonate host rocks favorable of metasomatic replacement, and related to them geochemical and geophysical anomalies. This approach greatly expands the range of possible ore-forming settings in the region, and new deposits of this type and scale have not been discovered, despite efforts made.

Based on the proposed syngenetic SEDEX model of ore formation, a new set of prospecting criteria for such type of ore deposits in the region is proposed (Table 2). The most suitable prospecting strategy should have the following sequence: lower levels of Middle Triassic Iskar Carbonate Group → facies of shallow-water dolomitic limestones precipitated into fault-bounded graben basins with low energy and partly evaporate environment → wallrock alterations; primary and secondary lateral dispersion haloes of Fe, Mn, Ba, Si, Pb, Zn, Cu, Ag, Hg; geophysical anomalies of magnetic, gravitational or electric fields; low-grade oxide/carbonate or barite-sulfide ore occurrences → drill intersection of ore horizons and determining the type and economic perspectives of ore mineralizations.

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