**Application of geometallurgical modeling in SICOMINES refractory copper–cobalt deposit in Congo (Kinshasa)**

WANG Ling1,2, DU Yuhang1, ZHAO Zhanfeng3, ZHANG Wenjuan1,2, MA Baozhong1,2, WANG Chengyan1,2\*

State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing, Beijing 100083, China1

School of Metallurgical and Ecological Engineering, University of Science and Technology Beijing, Beijing 100083, China2

China ENFI Engineering Co., Ltd., Beijing 100038, China3



|  |  |
| --- | --- |
| **ABSTRACT**  The SICOMINES Cu–Co ore deposit is located in southwest Kolwezi, Congo (Kinshasa), and is a typical deposit in the Katanga Copper Belt in central Africa. Dozens of Cu and Co minerals exist in the deposit as a result of the superposition and transformation of three complex ore-forming stages, including the sediment-hosted, hydrothermal, and oxidation periods; some of these minerals include heterogenite, carrollite, chalcocite, malachite, Co-containing malachite, spherocobaltite, Cu/Co-containing psilomelane, and Co-containing limonite. The mineralogy and processability properties among Co minerals differ considerably. The variability in Co minerals poses substantial challenges in establishing a universal beneficiation or extraction process that can accommodate all geometallurgical variations. The current Co-recovery process integrates flotation and magnetic separation techniques. However, the lack of fundamental knowledge about the spatial distribution of Co minerals and the poor adaptability of current Co-recovery processes to adapt to variable ores contribute to considerable Co losses in mine tailings. The recovery efficiency for Co is generally low, and the operational stability of the process is unstable. To address the issues, this study devised a geometallurgical model of Co in an ore body using Datamine and Leapfrog software for the first time. Initially, historical exploration data were collected, strata and mineralized domain models were developed, and the spatial variation in Co grade was preliminarily obtained. Subsequently, a sampling design was implemented to collect samples for process mineralogical research, effectively representing the Co-grade distribution within the strata and ore bodies. Furthermore, quantitative data of the mineral content and Co-occurrence state for each sample were obtained using a process mineralogical method, and these data were incorporated into the model using interpolation methods such as single-domain assignment and the distance inverse power ratio. As a result, five spatial beneficiation zones were obtained based on the spatial distribution of Co minerals with varying processability properties. These zones were classified as suitable for flotation (TYPE1), suitable for magnetic separation (TYPE2), suitable for combined magnetic separation and flotation (TYPE3), suitable for leaching (TYPE4), and difficult to recover (TYPE5); this classification resulted in the formation of a preliminary geometallurgical model. Finally, comprehensive samples were collected from the five beneficiation zones for the beneficiation experiments. The results revealed that the integrated magnetic separation and flotation process employed in the mine achieved varying Co-recovery efficiencies across the five beneficiation zones. This process proves applicable solely to the spatial domains of TYPE1, TYPE2, and TYPE3. The results also indicated that the classification of beneficiation zones in the geometallurgical model was within reason. Reasonable ore blending, based on the occurrence state of Co and the effective Co grade in the model, contributes to stabilizing current production and enhancing Co recovery. The developed geometallurgy model can be continuously optimized by adding sampling points or mineralogy parameters such as Co mineral particle size, mineral liberation degree, and Co-associated relationship with other minerals. The developed geometallurgy model serves as a valuable guide for the realization of classified mining and separation of Co ores in the SICOMINES mining region and for appropriate management. | **KEYWORDS:**  geometallurgy, SICOMINES mine, refractory Cu–Co ore, process mineralogy, spatial beneficiation zones, processability properties of mineral  Corresponding author: 1,2\* |

**1. Introduction**

Geometallurgy is a comprehensive discipline developed based on mining production. Its content involves multiple fields of mining production, including ore deposits, process mineralogy, mining, mineral processing, metallurgy and technical economics. Its purpose is to distinguish the spatial differences in the process mineral properties of ores, to achieve effective spatial ore separation and separation (metallurgy) and waste rock treatment, and to achieve reasonable planning of mine production in time, so as to achieve the best economic and social benefits [1- 3]. At present, geometallurgy is widely used in non-ferrous and ferrous metal mines [4- 10], and also has some applications in cobalt mines [11- 14]. It is mainly used to optimize the short-term mining process and ore distribution management of mines. With the continuous improvement of the automation and intelligence level of mines, the automation, standardization, precision and real-time maturity of the acquisition technology of mineral process parameters and rock mechanics parameters, and the continuous strengthening of the management level of mine safety and production technology modernization, geometallurgy has become a representative of modern mining new technologies, and more and more mines are trying to use it [15- 17].

Geometallurgy modeling is the use of Datamine, Surpac, Micromine, Vulcan, Three-dimensional mining software such as Leapfrog, 3Dmine and Dimine, based on the traditional three-dimensional modeling of strata and ore bodies, give the block model of the ore body information related to production, so that the block model not only contains geological information such as strata and grade, but also contains information such as minerals, rock mechanical properties, mining methods, mineral processing technology and technical economy [18], [19]. Common assignment methods include single domain assignment method, nearest distance method, inverse distance power method, Kriging method and multiple regression method [20- 22]. The single domain assignment method is often used for spatial body assignment such as strata; interpolation methods such as nearest distance method, inverse distance power method and Kriging method are suitable for spatial point assignment such as grade and mineral content; multiple regression method is suitable for multiple spatial point data assignment with strong correlation.

The SICOMINES copper-cobalt mine in the Democratic Republic of the Congo is located at the western end of the famous Zambia-Congo (DRC) mineralization belt in Africa. It is a typical deposit in the Katanga copper belt. The mineralization process has undergone sedimentation, tectonic hydrothermal superposition and oxidation leaching 3 The main mineralization stages [23- 25]. The multiple stages of mineralization formed a complex mineral assemblage. The copper minerals are mainly malachite and chalcocite, followed by chrysocolla, copper-containing manganese oxide minerals, cuprite, pseudomalachite, azurite, and a small amount of bornite, covellite, chalcopyrite, clinoselite, pyrocobaltite, phosphate copper, black copper, hydrovanadium copper, hydroxyvanadium copper lead, vanadium calcium copper and native copper. The cobalt minerals and cobalt-containing minerals are mainly hydrocobaltite and cobalt-containing manganese oxide minerals, followed by pyrocobaltite, cobalt-containing malachite, cobalt-containing dolomite, cobaltite, cobalt-containing chalcocite, cobalt-containing chalcocite and cobalt-containing limonite. Different deposit genesis forms different mineral assemblages, and the mineral assemblage determines the choice of beneficiation and smelting process. Since copper is a typical sulfur-loving element, although the types of copper minerals are complex, they all have good natural hydrophobicity. The beneficiation and smelting processes of the main copper minerals malachite and chalcocite are relatively mature. Therefore, the copper recovery indicators of the mine are relatively stable and ideal.

However, since cobalt has both oxygen- and sulfur-loving geochemical characteristics, the complex and diverse ore deposit genesis has formed a cobalt mineral assemblage with many types and great differences in dressing and smelting processes. The cobaltite and cobalt dolomite formed by early deposition need to be recovered by leaching, the cobalt sulfide ore, cobalt sulfide arsenic ore, copper sulfide cobalt ore and cobalt sulfide antimony ore enriched by late hydrothermal transformation can be recovered by flotation, and cobalt minerals such as hydrocobaltite, cobalt-containing manganese oxide and cobalt-containing limonite formed in the supergene oxidation stage are more suitable for enrichment by magnetic separation or combined dressing and smelting methods. At present, due to the unclear distribution of cobalt mineral assemblage in the ore body, the mixed mining and mixed selection used in production have led to problems such as low cobalt recovery rate, large fluctuations in indicators and high production costs in the mine. In order to improve the recovery of cobalt, this paper, based on an in-depth study of the geology of the ore deposit, collected spatially representative samples for process mineralogy research, and for the first time used the geological metallurgical concept to establish a three-dimensional model of the mineral, and divided different spatial domains according to the dressing and smelting characteristics of copper and cobalt minerals to achieve separate mining and separation (metallurgy), improve the cobalt recovery rate and production stability, and reduce production costs.

**2. Conclusion**

In order to solve the problems of complex cobalt dressing process, unstable production and low recovery rate in SICOMINES copper-cobalt mine, this paper selected 105 samples representing the spatial distribution of cobalt grade in the mining area for process mineralogy research based on the modeling of the strata and ore bodies in the mining area. Based on the quantitative parameters of cobalt mineral content and occurrence state, the main cobalt-containing minerals were divided into 4 categories according to the dressing process. In combination with the symbiotic relationship between cobalt minerals, 5 types of dressing space domains were divided in the mining area, and the geological metallurgical model of the mining area was constructed as the main parameters. Finally, comprehensive samples were collected in the 5 dressing space domains, and the model was verified. The conclusions were drawn:

1. There is a certain correspondence between the spatial distribution law of cobalt grade of 105 samples and the spatial distribution law of cobalt minerals. The cobalt grade in the ore body fluctuates mainly in the range of 0.1% to 0.7%, among which the cobalt grade is higher (>0.3%). The area with low cobalt content (<0.3%) corresponds to the cobalt minerals formed by late hydrothermal transformation and surface oxidation, mainly hydrocobaltite, sulfide copper cobaltite, cobalt-containing manganese oxide and cobalt-containing limonite; the area with low cobalt grade (<0.3%) corresponds to the cobalt minerals of primary sedimentary origin, mainly carbonate minerals such as cobalt dolomite or cobalt-containing dolomite.
2. According to the process performance of cobalt minerals, the cobalt minerals in the mining area are divided into four categories: easy flotation, easy magnetic separation, easy leaching and difficult recovery. According to the spatial distribution characteristics of the four types of minerals, the mining area is divided into five types of beneficiation and smelting space domains, corresponding to easy flotation (TYPE1), easy magnetic separation (TYPE2), magnetic flotation combined (TYPE3), easy leaching (TYPE4) and difficult recovery (TYPE5) recovery processes. The existing magnetic flotation combined process flow of the mine can process ores in the corresponding space domains of TYPE1, TYPE2 and TYPE3; TYPE4 The cobalt minerals in the middle are mainly cobalt dolomite and cobalt-containing dolomite minerals. Under the current technical conditions, wet acid leaching technology is required for recovery.
3. Based on the beneficiation experiments of the comprehensive samples in the five beneficiation domains, it is verified that the division of the spatial domain in the model is basically in line with expectations. When carrying out production matching, we do not simply pursue the stability of the cobalt grade in the mixed sample, but according to the spatial distribution law of different cobalt minerals in the geological metallurgical model of the ore body, we match the effective cobalt grade that can be floated and magnetically separated, which can stabilize production and improve the cobalt recovery rate and production efficiency. In future work, by adding the process mineralogical parameters of the sampling points or samples, such as the particle size of the cobalt mineral, the degree of monomer dissociation, and the co-existence relationship with other minerals, the geological metallurgical model of the mine will be further optimized to improve the refined management of the mine.

**3. References**

[1] Lund C, Lamberg P. Geometallurgy-A tool for better resource efficiency. Eur Geol, 2014, 37: 39

[2] Dominy S C, O′Connor L, Parbhakar-Fox A, et al. Geometallurgy—A route to more resilient mine operations. Minerals, 2018, 8(12): 560 doi: 10.3390/min8120560

[3] Lund C, Lamberg P, Lindberg T. Development of a geometallurgical framework to quantify mineral textures for process prediction. Miner Eng, 2015, 82: 61 doi: 10.1016/j.mineng.2015.04.004

[4] Bhuiyan M, Esmaeili K, Ordóñez-Calderón J C. Evaluation of rock characterization tests as geometallurgical predictors of bond work index at the Tasiast Mine, Mauritania. Miner Eng, 2022, 175: 107293 doi: 10.1016/j.mineng.2021.107293

[5] Liu L H, Chen J, Zhou T F, et al. The new application of geometallurgy in deportment of gold and critical metals studies. Acta Petrol Sin, 2021, 37(9): 2691 doi: 10.18654/1000-0569/2021.09.06

[6] Tiu G, Ghorbani Y, Jansson N, et al. Tracking silver in the Lappberget Zn–Pb–Ag–(Cu–Au) deposit, Garpenberg Mine, Sweden: Towards a geometallurgical approach. Miner Eng, 2021, 167: 106889 doi: 10.1016/j.mineng.2021.106889

[7] Dzvinamurungu T, Viljoen K S, Knoper M W, et al. Geometallurgical characterisation of merensky reef and UG2 at the marikana mine, bushveld complex, South Africa. Miner Eng, 2013, 52: 74 doi: 10.1016/j.mineng.2013.04.010

[8] Boisvert J B, Rossi M E, Ehrig K, et al. Geometallurgical modeling at Olympic Dam Mine, South Australia. Math Geosci, 2013, 45(8): 901 doi: 10.1007/s11004-013-9462-5

[9] Amer T E, El Assay I E, Rezk A A, et al. Geometallurgy and processing of North Ras Mohamed poly-mineralized ore materials, South Sinai, Egypt. Int J Miner Process, 2014, 129: 12 doi: 10.1016/j.minpro.2014.04.005

[10] Zhou Y Q. Gold geometallurgy and its application. Gold Sci Technol, 2013, 21(5): 76

[11] Dehaine Q, Tijsseling L T, Glass H J, et al. Geometallurgy of cobalt ores: A review. Miner Eng, 2021, 160: 106656 doi: 10.1016/j.mineng.2020.106656

[12] Lutandula M S, Kitobo W S, Kime M B, et al. Mineralogical variations with the mining depth in the Congo Copperbelt: Technical and environmental challenges in the hydrometallurgical processing of copper and cobalt ores. J Sustain Mining, 2020, 19(2): 4

[13] Dehaine Q, Tijsseling L T, Rollinson G K, et al. Geometallurgical characterisation with portable FTIR: Application to sediment-hosted Cu–Co ores. Minerals, 2021, 12(1): 15 doi: 10.3390/min12010015

[14] Mambwe P, Shengo M, Kidyanyama T, et al. Geometallurgy of cobalt black ores in the Katanga copperbelt (Ruashi Cu–Co deposit): A new proposal for enhancing cobalt recovery. Minerals, 2022, 12(3): 295 doi: 10.3390/min12030295

[15] Parian M, Lamberg P, Möckel R, et al. Analysis of mineral grades for geometallurgy: Combined element-to-mineral conversion and quantitative X-ray diffraction. Miner Eng, 2015, 82: 25 doi: 10.1016/j.mineng.2015.04.023

[16] Wang L, Zhao Z F. Application and difficulties of process mineralogy in geometallurgy modeling. Multipurp Util Miner Resour, 2020(2): 37 doi: 10.3969/j.issn.1000-6532.2020.02.006

[17] Nwaila G T, Manzi M S D, Zhang S E, et al. Constraints on the geometry and gold distribution in the black reef formation of South Africa using 3D reflection seismic data and micro-X-ray computed tomography. Nat Resour Res, 2022, 31(3): 1225 doi: 10.1007/s11053-022-10064-5

[18] Escolme A, Cooke D, Hunt J, et al. Ore characterisation and geometallurgy modelling: Productora Cu–Au–Mo deposit, Chile // GEOMET 2014 2nd International Seminar on Geometallurgy. Santiago, 2014: 1

[19] Schouwstra R, De Vaux D, Muzondo T, et al. A geometallurgical approach at Anglo American Platinum's Mogalakwena operation // The Second AUSIMM International Geometallurgy Conference. Brisbane, 2013: 85

[20] Montoya P A, Keeney L, Jahoda R, et al. Geometallurgical modelling techniques applicable to prefeasibility projects – La Colosa case study // The First AUSIMM International Geometallurgy Conference. Brisbane, 2011: 103

[21] Parian M, Lamberg P, Rosenkranz J. Process simulations in mineralogy-based geometallurgy of iron ores. Miner Process Extr Metall, 2021, 130(1): 25

[22] Pownceby M I, Johnson C. Geometallurgy of Australian uranium deposits. Ore Geol Rev, 2014, 56: 25 doi: 10.1016/j.oregeorev.2013.07.001

[23] Chen X H, Liu Y J, Yang Y, et al. Geological characteristics and genesis of SICOMINES copper–cobalt deposit in D. R. Congo. Nonferrous Met, 2012, 64(6): 31

[24] Duan H C, Liu Y J, Zhang Y J, et al. Geological characteristics and prospecting criteria of SICOMINES copper–cobalt deposit in Congo. Miner Depos, 2014, 33(S1): 5 doi: 10.16111/j.0258-7106.2014.s1.005

This work is licensed under a Creative Commons Attribution Non-Commercial 4.0 International License.