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A geostatistical approach of ore grade modeling in combination with a physical law

Lei Lu*, Taiki Kubo*, Risa Uchikura*, Chunxue Liu**, Koki Kashiwaya*, Katsuaki Koike* and Ryoichi Yamada***

*Graduate School of Engineering, Kyoto University, C1-2-214, Kyoto Daigaku Katsura, Nishikyo-ku, Kyoto, Japan. E-mail: lu.lei.62a@st.kyoto-u.ac.jp
**School of Urban and Environment, Yunnan University of Finance and Economics, China
***Graduate School of Science, Tohoku University, Japan

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1. Introduction

Despite small sizes in ore productions, there were many, various kinds of metalliferous mines in Japan. In addition, potential mapping resource investigations had been conducted over Japan for a long period. To utilize such information on the closed mines and investigations can contribute to clarify the ore genesis mechanisms and control factors of metal deposits in Japan and furthermore, to resource exploration for the same type deposit such as volcanogenic massive sulfide (VMS) type over the world.

From a viewpoint of geological processes, four basic requirements are needed for ore deposits (McQueen, 2005): ore components source, process that transports ore components and removes non-ore components, depositional mechanism to fix the components, and geological setting that preserves ore deposit. The unifying characteristics of VMS deposit are associated with volcanic activity and mineralization by hydrothermal solutions at or near the seafloor. The key distinction is that VMS deposits were formed as seafloor massive sulfides from hydrothermal fluids driven by the magmatic heat. This mineralizing process may involve convecting seawater that evolves by water/rock interaction into a slightly acidic metalliferous fluid, which may contain a significant component of magmatic volatiles (Shanks, 2012).

Characterizing the ore deposits often involves imaging 2D and 3D structures, physical and chemical properties, and interactions of materials. In general, imaging techniques use irregularly-spaced data that have originated from field surveys, borehole investigations, well-logging, core tests, and laboratory analyses. However, these data are limited in quantity, sampling location, areal (or volumetric) distribution, and spatial and temporal resolution. In addition, geomaterials tend to have heterogeneous structures and properties and behave nonlinearly due to geological discontinuities such as faults and unconformities, and the limited local influence of many geological processes. Therefore, this study is aimed to develop a spatial modeling technique covering the heterogeneity and nonlinearity of ore grade data by combing geostatistics and a physical law of hydrothermal fluids flows for accurate imaging.

2. Methods

2.1 Review of previous studies

Early ideas about the origin of metal-rich submarine hydrothermal solutions and the formation of seafloor deposits were advanced by taking the role of thermal crack propagation into a heat source admitting seawater and establishing convective fluid flow (Corliss, 1971). Then, a simple numerical model was developed by describing the convection of hydrothermal fluids and leading to potential ore body formation (Cathles, 1977). A general descriptive model of kuroko massive sulfide by Franklin (1981) is shown in Fig. 1.

A more comprehensive modeling approach was taken by Cathles (1983), who studied fluid flow requirements for several deposit settings. A more recent study used a basic single-pass model by employing expression of conservation of mass and momentum, and integrating version of Darcy's law to model fluid flow of VMS deposit (Lowell et al., 2008). A recent noteworthy study like surface-based model or process-based model, by reproducing the deposit genesis, provides realistic representation of the subsurface structures (Bertoncello et al., 2013).

Although the results from those studies have been used successfully to investigate a number of important aspects such as rock permeability, the role of basement relief and heat source, or the importance of fault structures, few studies have integrated all these features. Moreover, traditional methods focus only on analyzing and processing the deposit geometry as they exist at the end of sedimentation process. However, the emergence of specific deposit structures is driven by complex physical processes, such as ejected metal solution by an advection-diffusion process near the seafloor, that occur both in space and time. By neglecting the advection-diffusion (reaction-advection-diffusion) process, traditional modeling methods fail to reproduce the complex interactions of topography, flow, deposition, and erosion.

2.2 Proposed method for ore grade modeling

The proposed modeling workflow consists three parts, geological structure modeling, ore grade estimation, and

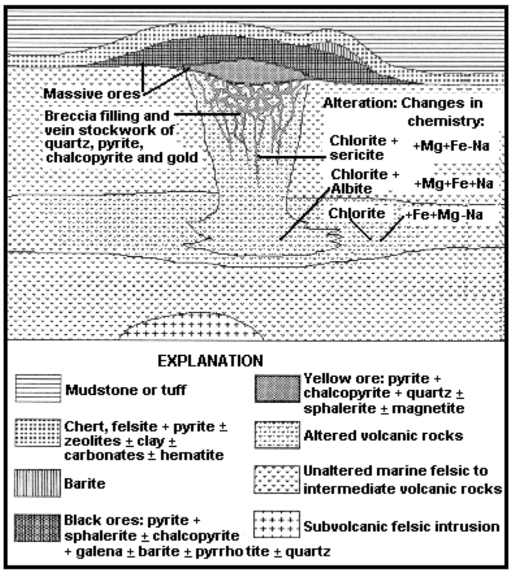

Figure 1. Kuroko massive sulfide deposit model, modified from Franklin et al. (1981).

physical-based convection-diffusion model.

The vast majority of fluid compositions in the modern and ancient VMS deposits indicate that seawater or evolved seawater was the dominant source of mineralizing fluids. The resulting convection system produces compositionally evolved seawater following reactions with host rocks along the flow path and the hydrothermal vent site on the seafloor (Shanks, 2012).

The convection–diffusion equation is a combination of the diffusion and convection (advection) equations, and describes physical phenomena where particles, energy, or other physical quantities are transferred inside a physical system by diffusion and convection. The general convection–diffusion equation is expressed as:

$$\frac{\partial c}{\partial t} = \nabla \cdot (D\nabla c) - \nabla \cdot (\vec{v}c) + R$$

where c is variable of interest, D is diffusivity, $\vec{v}$ is average velocity, R describes "sources" of quantity c, ∇ represents gradient, and $\nabla \cdot$ represents divergence.

3. Ongoing case study of kuroko deposits

The Hokuroku basin in Akita Pref., northern Japan, is a volcano sedimentary basin that was developed within the rift graben and designated as the most important kuroko ore field in Japan. The Matsumine deposit of the Hanaoka mine, found in 1963, is the largest kuroko deposit, located in the western margin of the Hokuroku basin. For considering the boreholes distribution with dense record data, 77 boreholes were chosen for an ore grade analysis in this study. Lithology record in the boreholes contains clay, tuff, mud stone, rhyolite, siliceous ore, yellow ore, kuroko, dolerite, gypsum, and pyrite.

The ore grades of three principal metals, Cu, Zn, and Pb were estimated by kriging. Cross-section comparison between the Cu grade and geological model suggests that the high concentration of Cu has a coherent distribution with kuroko and yellow ores (Fig. 2).

Next, the advective velocities and the diffusion coefficients were calculated at each grid point by a combination of the ore grade model and the convection–diffusion equation. The advective velocities are mainly directed upward and the grid points with this direction are continued in the distributions of silicious ore and rhyolite. This may imply the main paths of ore solutions.

4. Concluding remarks

The importance of considering hydrothermal fluids flow for VMS ore grade modeling was summarized with a case study. Our next step is to improve the grade model by incorporating the convection–diffusion equation into kriging system. The authors wish to express their gratitude to Dowa Metals & Mining Co., Ltd. and Hanaoka Eco-System Co., Ltd. for providing the precious drilling investigation materials.

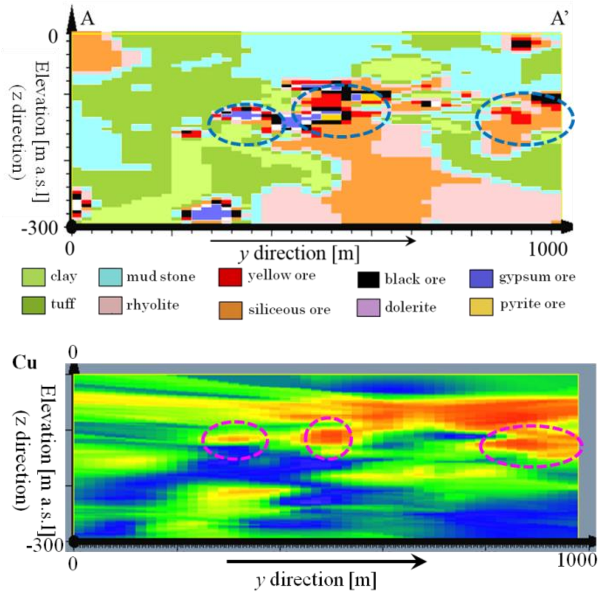

Figure 2. Relationship between grade distribution (Cu) and geological models. Grade increases from blue to red colors.

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