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学位論文題目（英文）	ボツワナ北東部、Matsitama 片岩帯、Mowana 銅鉱床の多段階 Cu 鉱化作用 (Multi-stage Cu Mineralization of the Mowana Copper Deposit, Matsitama Schist Belt, NE Botswana)
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論文内容の要旨

The Mowana hydrothermal Cu deposit is located within the Matsitama-Motloutse Complex in the southwestern part of the Zimbabwe Craton in the northeastern part of Botswana. The deposit is in the northern-most flank of the Matsitama Schist Belt, which makes one of the four granite-greenstone belts of north-eastern Botswana. It is poorly understood and has received less documentation since its discovery, by comparison to other ore deposits in the same area. Mowana deposit is unique from other Archean greenstone belt vein deposits in the sense that instead of Au mineralization it is rather dominated by Cu mineralization. There is a large inferred time gap between rock formation and mineralization. The deposit is hosted by the NNE-striking and nearly vertically dipping (70-80°) Bushman Lineament (shear zone) within the graphitic schist lenses in the carbonaceous and argillaceous metasedimentary rocks of the Neoproterozoic to Paleoproterozoic Matsitama Sedimentary Group. Within the Matsitama Sedimentary Group, the Mowana deposit is hosted by rocks belonging to the Bushman Mine group, a sedimentary fining upward sequence. The Matsitama Sedimentary Group is enclosed within the foliated granitoids of the Matsitama-Motloutse Complex. The ca. 0.2 Ga Phanerozoic Karoo Supergroup overlies these units.

The host metasedimentary rocks: limestone, argillite, and graphitic schist, as well as the surrounding granites, suffered from hydrothermal alteration. The hydrothermal alteration is characterized by silicification, chloritization, epidotization, sericitization, hematite, and carbonate alterations. Based on the alteration mineral assemblage, the main mineralization

stage is attributed to near-neutral pH fluids at temperatures between ~ 200 °C and ~ 340 °C. The temperatures obtained from the chlorite geothermometry of the Type 1 veins coincides with the above temperature in the range 340-400 °C and a modal temperature of 370-380 °C.

The base metal mineralization of the Mowana deposit evolved in at least two hydrothermal vein types. The first mineralization type, represented by the quartz+calcite \pm K-feldspar veins and breccias, is characterized by the precipitation of principal chalcopyrite with pyrite, minor bornite and trace amounts of galena. The Type 2, represented by quartz+calcite \pm fluorite veins, hosts appreciable amounts of galena. The supergene mineralization is widely distributed in the shallow levels (up to 70 m below the surface) of the deposit. Supergene enrichment is manifested by the significant presence of chalcocite, bornite, covellite and anglesite. Oxidation is characterized by Fe-oxides and Cu carbonates: malachite, goethite, and hematite. The ore mineral assemblage of pyrite+chalcopyrite+bornite paired with the temperature obtained from the chlorite geothermometry from the Type 1 veins was used to determine the sulfidation state of the Mowana deposit. The ore mineral assemblage of the Type 1 veins lies on the pyrite+chalcopyrite+bornite buffer line at a temperature of 340 to 400 °C indicating that the Type 1 veins evolved under a transition between intermediate and high sulfidation state.

Chalcopyrite is the principal Cu-bearing mineral, which also contains an average 67.4 ppm of Ag which may be due to incorporation of Ag in the Cu site. Galena from the Type 2 veins has high contents of Se with an average of 1231 ppm, possibly incorporated as PbSe. The average Ag content in galena from the Type 2 veins is 58.9 ppm. The average Co, Ni, and As contents in pyrite are 143 ppm, 33.6 ppm, and 107 ppm, respectively.

Fluid Inclusion analysis was also conducted. Two-phase (liquid and gas) fluid inclusions were observed in the mineralized quartz veins. However, the fluid inclusions were too small to perform microthermometry.

The carbon isotopic composition of graphite from graphitic schist are from -21.0 to -29.8 ‰ (average -26 ‰) indicating a biogenic origin, possibly from cyanobacteria living in shallow water. The $\delta^{13}\text{C}$ values of the metacarbonates range from 6.05 to 6.89 ‰ which is higher than the global trend at the time of deposition and rarely observed in Archean carbonates. These heavier values may be explained by diagenetic carbonate precipitation during which dissolved inorganic C is enriched in ^{13}C by methanogenic processes, or alternatively by burial of reduced carbon in an isolated basin at that time, with the residual dissolved carbon being enriched in ^{13}C . The carbon isotopic compositions of the calcite of Type 1 veins ranging from 0.46 to 0.53 ‰ could indicate derivation from a mixed source including C from both host rock types. The $\delta^{18}\text{O}$ of the quartz is in the range 9.25 to 10.30 ‰ relative to Standard Mean Water Ocean Water (SMOW). The $\delta^{18}\text{O}$ values of calcite range from -12.42 to -22.34 ‰ with respect to Vienna Pee Dee Belemnite (VPDB). The calculated temperature from the co-existing mineral pairs of quartz and calcite in equilibrium range between 250 to 360 °C.

Sulfur isotopic ratios determined on the sulfides from Type 1, Type 2 and diagenetic

pyrite help to understand the evolution of the hydrothermal system. The sulfides, chalcopyrite, chalcocite and galena from Type 1 and Type 2 veins, recorded isotopic compositions $\delta^{34}\text{S}$ in the range -5‰ to $+4\text{‰}$. These values may indicate a magmatic sulfur source of S and/or leaching of the host metasedimentary rocks. However, $\delta^{34}\text{S}$ of diagenetic pyrite disseminated in silicified limestone and pyrite from a quartz+calcite±K-feldspar vein recorded sulfur isotopic values of $+15.4\text{‰}$ and $+18.0\text{‰}$. The values can be explained by closed system reduction of seawater sulfate, followed by remobilization of the $\delta^{34}\text{S}$ rich diagenetic pyrite during brecciation as the possible sources of S.

論文審査結果の要旨

The Doctoral thesis, thesis abstract, and list of publications and conference presentations were examined by a committee composed of four members. A paper directly related to this study was recently accepted for publication in the Journal Resource Geology, published by the Society of Resource Geology. After detailed examination, the documentation was deemed to be complete and of sufficient quality for the Doctorate to be approved.

The thesis examines the mineralogical and geochemical characteristics of Mowana Cu deposit of northern Botswana, for which only very limited studies have previously been conducted. This ore deposit is hosted by strongly deformed metasedimentary rocks belonging to the Matsitama greenstone belt, for which Neoproterozoic ages have been previously proposed. In particular, the Cu-mineralisation is associated with a large-scale fault zone, the Bushman Lineament, that extends north-northeast and displaced rocks of the Matsitama greenstone belt.

At the mine scale, Cu-mineralisation is hosted by argillite, graphitic schist, and limestone, all of which have been affected by deformation and hydrothermal alteration. This alteration is characterized by addition of silica minerals, chlorite, epidote, sericite, hematite, and carbonate. Two types of veins have been identified. The first type is composed of quartz–calcite–K-feldspar and contains an ore mineral assemblage composed of predominant chalcopyrite and minor pyrite, bornite and galena. The second type of veins is composed of quartz–calcite–fluorite and contains galena.

The temperature of ore deposition was estimated based on the alteration assemblage (which provide a temperature range of 200-340 °C), chlorite chemical composition (340-400 °C) and O-isotope fractionation between carbonate and quartz (250-360 °C).

The source of mineralizing fluids was assessed using analyses of stable isotopes of S, C and O measured in minerals associated with Cu sulfides. The limestone has C-isotope compositions $\delta^{13}\text{C} = 6.0 - 6.9\text{‰}$, and the graphitic schist $\delta^{13}\text{C} = 29.8 - -21.0\text{‰}$, whereas the vein carbonate associated with mineralisation has intermediate and relatively scattered $\delta^{13}\text{C} = -12.0 - 0.5\text{‰}$. Sulfur isotope compositions of sulfide minerals chalcopyrite, chalcocite and

galena from mineralised veins have most $\delta^{34}\text{S}$ values between -5 and +4 ‰, compatible with re-mobilisation of S from the volcano-sedimentary succession. However, one sample of vein pyrite and one sample of disseminated diagenetic pyrite have much higher $\delta^{34}\text{S}$ values of 15.4 and 18.0 ‰.

The study revealed the characteristics of mineralisation in the Mowana copper deposit from the viewpoints of the mineralisation stage and paragenesis, petrography, hydrothermal alteration, mineral chemical compositions, ore-forming temperature and S, O and C stable isotopes, which provides new insights in the exploration of copper deposits in greenstone belts. Since the achievement is worthy of a doctoral degree, the panels of final examination judged that the Doctoral thesis of Amogelang Kooganne is acceptable.