Geology and ore genesis of the porphyry copper deposits in Baguio District, Luzon Island, Philippines (フィリッピン,ルゾン島バギオ地域の地質及び斑岩銅鉱床の研究)

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論 文 内 容 要 旨

Summary

This paper aims to define the geological environment, time of formation, nature and physico-chemical conditions of formation of the porphyry copper deposits in Baguio District, Luzon, Philippines that are relevant to the search for mineral deposits.

To this end, 1,480 square kilometers of surface was geologically mapped, 565 thin and polished sections were petrographically analyzed, 63 rock samples were analyzed for major elements, 117 samples were analyzed for minor elements, 9 samples were subjected to electron probe microanalysis and 76 samples were analyzed for their fluid inclusions, aside from other analyses made.

Baguio District is one of the most highly mineralized spots in the Philippines. Gold mining dates back to pre-colonial periods and the same spots mined by the old headhunting natives are still being mined by more sophisticated methods, for gold. Porphyry copper was first discovered in the district in 1955. Since then, a total reserve of 318 million tons of 0.35-0.49 % Cu has been discovered, and four companies are at present actively mining them. These mines are Western Minolco, Santo Nino, Kennon and Santo Tomas II. More copper deposits are expected to be present in Luzon Central Cordillera and their discovery can be enhanced by a thorough knowledge of the deposits now known in Baguio District.

The result of this study shows that Baguio District is in a calc-alkali magma province. Majority of rocks are products of magmatic intrusions and effusions generated from Eocene(?) to Pliocene/ Pleistocene. The porphyry copper deposits were formed

in Middle Miocene together with quartz phenocryst-bearing stocks of quartz diorite porphyry. At this time, Baguio District was, like at present, part of an intermittently rising orogenic mountain belt. This mountain belt was initially formed by inversion of an eugeosyncline during the early part of Early Miocene. Large-scale batholithic intrusions of dioritic rocks attended this orogenic inversion, thus forming Agno Batholith in Baguio District. The orogenic mountain belt, thus formed, which comprises the present Luzon Central Cordillera, is situated midway between two trench-arc systems related to opposite-dipping subduction zones now defined by Manila Trench and the northern extension of Philippine trench.

At first sight, the porphyry copper deposits and the gold deposits in the district seem to have been brought by intrusion of Agno Batholith. But, the present work proves that this batholith was not the ore-bringer. At least for the porphyry copper deposits, the ore-bringer was the Middle Miocene intrusions of silica-oversaturated magmas forming stocks of quartz dioritic to tonalitic porphyries characterized by phenocrysts of quartz. The texture of these porphyries indicates shallower intrusions than the older Agno Batholith. Intrusions later than the ore-bearing porphyries are of much shallower depths, thus, indicating continuous or intermittent rise of the cordillera from Early Miocene to Pliocene/Pleistocene. At present, Baguio District is a rejuvenated matureland and geomorphological analysis show that rejuvenation was caused by recent uplifts. The porphyry copper deposits are situated along the axis of an ancestral ridge with fairly smooth mature topography before the advent of the recent uplifts. At present this ridge (Halsema Ridge) has elevations of 1,500 to more than 2000 meters, but, before rejuvenation it could have been

about 500 meters lower.

The rock formations identified are:

1. Pugo formation/ Dalupirip schist -- Eocene(?) to early Lower Miocene
2. Agno Batholith -- early Lower Miocene
3. Zigzag formation -- Lower Miocene
4. Kennon formation -- Middle Miocene
5. Black Mountain Porphyry Complex -- late Middle Miocene
6. Balatoc Plug -- late Middle Miocene
7. Klondyke formation -- Upper Miocene
8. Late Intrusive Andesites -- Upper Miocene to Pliocene
9. Rosario formation -- Upper Miocene to Pleistocene
10. Alluvium and terrace gravels -- Pleistocene to Recent

Only BMI deposit of Kennon Mine reaches the stratigraphic level of Kennon formation. The other porphyry copper deposits reach only as far as Pugo formation or the lower part of Zigzag formation, in the case of Santo Tomas II deposit.

The porphyry copper deposits are vertical to moderately dipping pipes and funnels with diameters of 200 to 450 meters. At a cut-off grade of 0.3 % Cu, the volume of mineable reserves vary from 6.75 to 150.31 million tons. The average grades vary from 0.35 to 0.49 % Cu, with negligible to 8.73 grams per ton gold.

The major ore minerals are chalcopyrite, bornite, pyrite and magnetite. These minerals are distributed as fine disseminated grains in the host rocks and in a generally dense network of veinlets. Chalcopyrite and bornite usually occur as exsolution pairs in the central high-grade zones of the ore bodies.

Pyrite do not coexist in equilibrium with bornite. These two minerals are distributed in separate zones, with pyrite, associated with chalcopyrite and magnetite/hematite, occupying the peripheral zones. Native gold is present in the ore bodies with high gold values. Molybdenite is relatively abundant in ore bodies with low gold values.

Fluid inclusion studies revealed that the bulk of mineralization in Santo Tomas II Mine was formed at about 525 ^{o}C, 500 bars and 2 km depth from the surface. The average salinity of ore solutions was about 54 wt. % NaCl equivalent. Those of Santo Ninon Mine were formed at about 516 ^{o}C, 475 bars, 1,900 meters depth from the surface and 52 wt. % salinity of ore solutions. Lobo ore body in Western Minolco Mine was formed at about 497 ^{o}C, 410 bars, 1,640 meters depth and 49 wt. % NaCl equivalent salinity of ore solutions. Boneng ore body, also of Western Minolco Mine, was formed at about 505 ^{o}C, 430 bars, 1,720 meters depth and 53 wt. % NaCl equivalent salinity of ore solutions.

The BMI ore body of Kennon Mine was formed much different conditions. The temperature was about 433 ^{o}C; pressure, about 275 bars; depth, about 1,100 meters; and salinity of ore solutions; about 42 wt. % NaCl equivalent.

Coexisting pyrrhotite-sphalerite geothermometry and geobarometry, revealed that the contact metasomatic deposit at the border between limestone and the porphyry copper ore-bearing quartz diorite porphyry in Kennon Mine, was formed at about 430 ^{o}C, 300 bars and 1,200 meters depth. Sulfur fugacity was $10^{-6.5}$ atm. and FeS activity was about 0.5.

Integrating the data from fluid inclusions and pyrrhotite-sphalerite compositions, the thermochemical conditions of ore formation in all the deposits studied are determined. The border zones of the porphyry copper deposits have lower sulfur

fugacities than the cores, at certain temperature conditions. The bulk of ore mineralization in Kennon Mine ranges from 392 to 433 ^{o}C and sulfur activities of $10^{-6.5}$ - 10^{-5}. On the other hand, that of the other mines ranges from 497 to 525 ^{o}C and sulfur activity of 10^{-2} to 10^{-4}. The big difference in sulfur activity, is explained by the fact that limestone is present in Kennon, while such highly reactive strata which oxidizes sulfur by reaction with CO_2, is absent in the other deposits.

The differences in temperature, pressure and depth of formation between BMI deposit of Kennon Mine and the other deposits are explained by the fact that Kennon Mine occur at a much higher stratigraphic level than the other deposits.

The result of this study further show that porphyry copper mineralization in the district was controlled by the presence of irregular stocks of quartz phenocryst-bearing quartz diorite porphyry, intersecting NE and NW faults related to the Philippine fault and, negatively, by the presence of limestone which favored contact metasomatic deposits at the expense of porphyry copper. Exploration for porphyry copper deposits in Luzon Central Cordillera should, therefore, be geared towards discovering the locati of quartz phenocryst-bearing quartz diorite porphyry stocks and intersecting NE and NW faults. Sphalerite, chalcopyrite and pyrite bearing veins at the borders of the porphyry copper deposits establish a link between porphyry copper and vein gold mineralization in the district.

論文審査の結果の要旨

本論文で研究している斑岩銅鉱床は日本にはまだ見つかっていないが，東南アジアとくにフィリッピンでは重要な銅資源として知られている。しかし，この鉱床の生成機構およびその成因についてはいまだ十分にわかっておらず，世界的に一層の研究が望まれている。本論文はこのような斑岩銅鉱床の研究に関する状勢下で，フィリッピン，ルソン島における主要な斑岩銅床地帯であるバギオ地方の鉱床について詳細な地質調査と室内実験の資料から，斑岩銅鉱床の地質的環境，関係火成岩，鉱床生成の時期，その機構および条件など，鉱床の成因に関する諸問題を明らかにしている。

Balceはまず野外における詳しい地質調査の資料からバギオ地方の地質および層序，火成岩の迸入関係を知り，斑岩銅鉱床が新第三紀中新世中部の時期に活動したシリカ過飽和のカルク・アルカリマグマより生じた石英閃緑斑岩を運鉱岩とし，その内部に鉱染状および網状をなして発達した塊状鉱体であることを明らかにする一方，この鉱化作用を，豊富な資料にもとづいて，この地域の活火成活動史および構造発達史の中で関係ずけ，鉱床形成に関する地質的因果関係を論じている。さらに鉱床生成の物理的あるいは化学的条件を詳らかにするため，鉱石中の石英などにみられる液体包有物多数について高温顕微鏡による加熱実験を行ない，その結果から鉱床の生温度は250°～500℃，生成圧270～500気圧とかなり広い範囲にわたり，また鉱液中のNaCl相当濃度も1.0wt％以下のものから30～60wt％と高い値を示すものまで広範囲に存在する，などの事実を見い出している。また鉱物共生，とくに磁硫鉄鉱・黄鉄鉱と組み合う閃亜鉛鉄のFeS濃度をEPMAで分析し，その値からこれら鉱物共生の生成温度を430℃，鉱液中の硫黄活量を10^{-65}と決定し，さらにこれらの値をScottおよびBarnesによる閃亜鉛鉱地質圧力計に適用し，これらの生成圧として500気圧以下という値を出している。これらの値は斑岩銅鉱床生成の条件を示す新しい資料となる。

上記のように本論文は斑岩銅鉱床の形成に関する地質的環境，関係火成岩，鉱床生成の機構とその条件などについて，多くの新しい事実を提供しており，自立して研究活動を行なうに必要な高度の研究能力と学識を有することを示している。よってGuillermo Rasca Balceの論文は理学博士の学位論文として合格と認める。