Structural and Thermal Controls on the Formation of the Hishikari Epithermal Gold Deposit, Japan

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論文題名　：　Structural and Thermal Controls on the Formation of the Hishikari Epithermal Gold Deposit, Japan（菱刈浅熱水金鉱床生成における構造・熱規制に関する研究）

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論 文 内 容 の 要 旨

Epithermal deposits form at shallow depths as a result of hydrothermal activity, which involves fluid circulation through fractures, powered by a heat anomaly. This makes the fluid paths a key factor in the formation process of this type of ore deposit. The heat source is the driving force of the system and in some cases, its emplacement creates the fractures that become fluid paths. Thus, it is also an important part of the system. Therefore, for a better understanding of the mineralization at the Hishikari deposit, it is important not only to investigate the paleostress and fluid pressure regimes, but also to study the actual effect of the basement uplift on the occurrence of the fractures hosting the veins. The latter requires to constrain the position, temperature, shape and overpressure of the heat source. In this thesis, I unravel the structural controls of the Hishikari low sulfidation epithermal deposit and I put constraints on the heat source of its mineralizing hydrothermal system.

Firstly, Chapter 1 introduces the deposit geology and provides all the background information on stress inversion and the methods used for the paleostress analysis. Hishikari is part of the Hokusatsu gold district, located in southern Kyushu (Japan) where previous research revealed that veins could be hosted in both conjugate faults (e.g. Kushikino) and tensile fractures (e.g. Hashima). In Hishikari, the presence of ENE-WSW to NW-SE-trending normal faults were recognized in previous studies. Moreover, in the northern part of the Honko sub-deposit, fault gauge, pull-apart structures and drag folds were reported and the conclusion was further made that the local basement uplift was responsible for the formation of the veins. However, the reported structures placed only a weak constraint on the paleostress conditions as assumptions and particular situations were needed to explain their occurrence by normal faulting. On the other hand, horizontal strain rate calculation suggested that regional extensional movements in southern Kyushu were responsible for the mineralization at Hishikari; but the study did not further constrain the stress tensor. A question arises as to whether the veins at Hishikari resulted from local or regional movements and left hanging the topic of the paleostress conditions that prevailed during the mineralization. Moreover, the orientations of the veins show spatial variations between the Honko-Sanjin sub-deposit (N50°E-70°NW to 90°) and the Yamada sub-deposit (N50°E-70°NW to 90° and N30°E-80°NW to 90°). Furthermore, structural differences (strike, dip, and width) between early and late veins might suggested a temporal variation of the stress conditions. Thus, spatio-temporal variations of the paleostress conditions under which the Hishikari deposit formed are to be expected. The software GArcmB, implementing the method of Yamaji (2016) for fitting orientation data to a mixed Bingham distribution is used in this study. The principles of stress inversion in general and of this technique in particular are also detailed in Chapter 1.

In Chapter 2, the results of the paleostress analysis of the Hishikari deposit are presented. Vein orientations (strike and dip) were collected at the Hishikari mine, along with their respective widths and gold grades. The results reveal that 98% of the veins at Hishikari were formed under extensional stress with a NW-SE-trending horizontal σ_3-axis and a northeasterly-inclined σ_1-axis with a relatively high stress ratio. The high stress ratio explains the ease of

rotation of the σ1- and σ2-axes, leading to a mean stress regime intermediate between normal faulting and strike-slip faulting. This stress condition is consistent with the regional stress field that was present in southern Kyushu at the time of the mineralization, suggesting that regional tectonics controlled the deposition of almost all the veins in Hishikari. The remaining veins were formed under an axial compression stress condition that could be related to local perturbations.

Chapter 3 details the fluid pressure regimes in the Hishikari deposit during mineralization. The Driving Pressure Index (DPI) is defined as the 95 percentile point of normal stresses on the wall of the fracture. It is considered as the representative driving pressure ratio *p*. The calculation of *p* during the formation of the veins gives a result of ~0.2. Moreover, *p* is determined at various depths in the mine and its variation with depth studied. Whereas it is demonstrated that *p* has a negative correlation with depth in hydrostatic pressure conditions regardless of the stress regime, a positive correlation between *p* and depth is found at Hishikari. This suggests that pressure compartmentalization occurred in Hishikari, with pressure compartments bound by pressure seals that were repeatedly broken and re-created. Moreover, the driving pressure ratio was higher in the Honko-Sanjin sub-deposits (0.24) than in the Yamada sub-deposit (0.19). This could be explained by a higher fluid pressure in the Honko-Sanjin sub-deposits, which is consistent with the fact that the main fluid conduit was located in Sanjin, suggested by previous research. Finally, it is found that in the Yamada sub-deposit, the veins having a gold grade higher than 100 g/t have higher driving pressure ratios (0.24) than the rest of the veins (0.19). This indicates that higher driving pressure was associated with higher gold grades during the mineralization at Hishikari, and that fluid pressure controlled gold grade.

In Chapter 4, physical and geometric constraints are put on the heat source of the Hishikari mineralizing hydrothermal system, by means of 1D steady-state heat conduction modeling. Stratigraphic columns were made from drillholes (outside the mine) and cross sections (inside the mine) taken from a geothermal research report by NEDO (1991). The depth of the heat source is varied between 2 km and 10 km with a step of 1 km and the temperature of the heat source was varied between 250 °C and 1200°C with a step of 50 °C. Hence, 180 models were run for each stratigraphic column. The temperature was calculated along the stratigraphic column every 10 m using the software OpenGeoSys (OGS). The calculated temperatures were then compared to the fluid inclusion homogenization temperatures by the calculation of the root mean square error (RMSe) of each model, the best fit model being the one with the lowest RMSe. This gives the depth and the temperature of the heat source. Using the depth and rock densities, the lithostatic pressure (P_l) was calculated. On the other hand, the total pressure (P_t) was obtained using the temperature and Al-in hornblende geobarometer. The subtraction of P_l from P_t gives the overpressure in the magma chamber. From a discussion involving the Mogi spherical point source model, the tectonic regime and the absence of ring fault, the shape of the magma chamber was inferred. The depth of the Shishimano Dacite magma chamber, considered as the heat source, was estimated at ~9 km. The magma had a temperature of ~1075-1200°C at the onset of the mineralization, and seems to have cooled down to a temperature of ~300-500°C after the mineralization. The estimated excess pressure within the magma chamber is high and the shape of the magma chamber is likely prolate ellipsoidal.

Chapter 5 provides an overall discussion of the results that summarizes contribution to the understanding of the mineralization in Hishikari, as well as the remaining challenges. The potential contribution of the basement uplift to the mineralization is addressed and the hypotheses include the weakening of host rocks, the creation of faults, and the apparition of 5% of the veins in the Yamada sub-deposit. The other point of discussion is related to the possible causes of pressure sealing and the hypotheses include the self-sealing by the precipitation of the vein-forming minerals, sealing by the clay-rich alteration halo and capillary sealing by the gases released during boiling process.

Finally, Chapter 6 gives a recapitulation of the main conclusions of these study.