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Paleostress and fluid-pressure regimes inferred from the orientations of Hishikari low sulfidation epithermal gold veins in southern Japan

Guillaume D. Faye[a,*], Atsushi Yamaji[b], Kotaro Yonezu[a], Thomas Tindell[a], Koichiro Watanabe[a]

[a] Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395 Japan
[b] Division of Earth and Planetary Sciences, Graduate School of Sciences, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan

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ABSTRACT

The orientation distribution of dilational fractures is affected by the state of stress around the fractures and by the pressure of the fluid that opened the fractures. Thus, the distribution can be inverted to determine not only the stress but also the pressure condition at the time of vein formation. However, epithermal ore veins that we observe today are the results of a great number of intermittent upwelling of overpressured fluids with different pressures. Here, we define driving pressure index (DPI) as the representative non-dimensionalized fluid pressure for the fluids. We collected the orientations of ~1000 ore veins in the Hishikari gold mine, which were deposited at around 1 Ma, in southern Kyushu, Japan. It was found that the majority of the veins were deposited under an extensional stress with a NW-SE-trending σ_3-axis and a northeasterly-inclined σ_1-axis with relatively high stress ratio. The representative driving pressure ratio was ~0.2. Data sets obtained at different depths in the mine indicated a positive correlation of representative driving pressure ratios with the depths. The correlation suggests repeated formation and break of pressure seals during the mineralization. Our compilation of the Pliocene–Quaternary stress regimes in southern Kyushu, including the result of the present study, suggests that epithermal gold mineralization was associated with distributed extensional deformations in southern Kyushu, and strain localization into an intra-arc rift seems to have terminated the mineralization.

1. Introduction

The understanding of fluid transport through the crust is an important issue today. Tectonic deformations interplay with the transport and pressurization of fluids at depths (e.g., Sibson, 1987, 1996, 2001; Austrheim, 2013). In addition, the behaviour of fluids has great relevance to resource exploration, deep geological disposal of radioactive waste and carbon dioxide. Impermeable layers seal overpressured fluids at depths in oil fields to form pressure compartments, and fluid has a hydrostatic pressure gradient in each of the compartments (Cathles and Adams, 2005). High fluid pressures in the compartments can be preserved for hundreds of millions of years in interior basins (Al-Shaieb et al., 1994). A different scenario is possible in lode deposition, where overpressured ore fluids can breach pressure seals, but hydrothermal ore mineralization seals fracture networks. As a result, the pressure compartments between seals are formed and broken countless times in the lifetime of ore mineralization in the deep crust (Cox, 2005). The observation of hydrothermal ore systems in a mine provides a unique opportunity for us to study such dynamic processes at different depths.

Here, we show that dynamic processes took place in the shallow hydrothermal system that resulted in the Pleistocene epithermal gold veins of the Hishikari Mine in southern Kyushu, Japan (Fig. 1). This type of lodes was deposited at depths of ~1 km or less (Simmons et al., 2005). The paleostress analysis of vein orientations determines not only paleostresses, but also gives a clue to fluid pressure (Baer et al., 1994; Jolly and Sanderson, 1997; Yamaji et al., 2010). That is, the advancement in the stress inversion of dilational fractures has enabled us to determine not only the stress condition, but also the driving pressure ratio,

$$p = (p_f - \sigma_3) / (\sigma_1 - \sigma_3), \quad (1)$$

from the orientations of dilational fractures, where p_f is fluid pressure, and other symbols in the right-hand side of this equation stand for the principal stresses. In this article, compression is treated as positive stress, and the principal stresses are assumed to satisfy $\sigma_3 \le \sigma_2 \le \sigma_1$.

Plio-Pleistocene, low-sulfidation, epithermal gold veins are abundant in the southern Kyushu island, Japan, including the world-class Hishikari deposit (Feebrey et al., 2001). Their coherent NNE-SSW to NE-SW trends (Fig. 1) emphasize the role of regional stress field on the

* Corresponding author.
E-mail addresses: guillaume@mine.kyushu-u.ac.jp (G.D. Faye), yamaji@kueps.kyoto-u.ac.jp (A. Yamaji), yone@mine.kyushu-u.ac.jp (K. Yonezu), tindell-tom@mine.kyushu-u.ac.jp (T. Tindell), wat@mine.kyushu-u.ac.jp (K. Watanabe).

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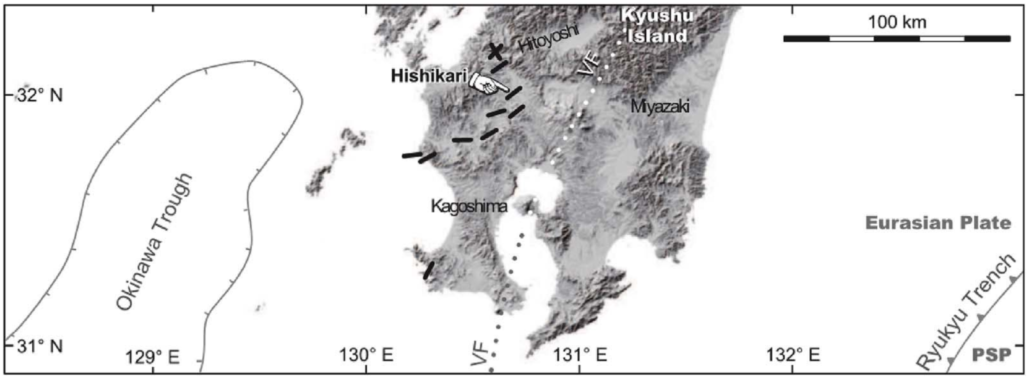

Fig. 1. The trends of representative Plio-Pleistocene ore veins (bars) in southern Kyushu, Japan (Urashima et al., 1981; Izawa, 2004). PSP = Philippine Sea Plate; VF = Present volcanic front.

mineralization (Izawa and Urashima, 2001; Izawa, 2004). However, the stress regime during their mineralization is not well understood. Recent advancements in paleostress analysis techniques allowed us to determine stress regimes directly from vein orientations (Baer et al., 1994; Jolly and Sanderson, 1997; Yamaji et al., 2010; Yamaji and Sato, 2011). The understanding of paleostress is essential to study paleo pressures of ore fluids.

In this study, we analyzed the orientations of some 1000 ore veins in the Hishikari Mine to understand the stress conditions and the driving pressure ratio during vein formation using the fuzzy clustering technique of Yamaji and Sato (2011). We had the opportunity to collect orientation data at different depths in the mine in order to find the variation of the fluid pressure ratio with depth, which suggested that pressure seals were brought about and broken repeatedly, probably by overpressured ore fluids and faulting during mineralization. Finally, we discuss the stress history with reference to lode deposition in southern Kyushu.

2. Method

2.1. Bingham distribution

In this study, we used the software GArcmB (Yamaji, 2016), which implements the method for dealing with the orientations of dilational fractures that were formed during polyphase tectonics (Yamaji and Sato, 2011). The method can separate stresses from a mixture of data corresponding to different stress conditions. It is assumed that a group of veins were formed intermittently when p_f was in excess of σ_3 (Fig. 2), while the stress orientations and stress ratio, $\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$, were unchanged. We use the term, "a stress condition", to refer to the states of stress that have the same principal axes and stress ratio whether or not they have different stress magnitudes. Neglecting the magnitudes, a stress condition is denoted by the reduced stress tensor,

$$\boldsymbol{S} = \boldsymbol{Q}^{\mathrm{T}}\mathrm{diag}(1,\ \Phi,\ 0)\boldsymbol{Q}, \tag{2}$$

where $\boldsymbol{Q}$ is the 3×3 orthogonal matrix indicating the principal stress orientations, and diag(1, Φ, 0) stands for the diagonal matrix with the diagonal components, 1, Φ and 0.

Veins are formed only along the fractures with the normal stress, σ, satisfying $\sigma < p_f$ because fluid pressure overcomes the normal stress to open the fractures. Since the plane perpendicular to the σ_3-axis has the minimum σ, the fluid with p_f smaller than σ_3 cannot form veins. So, the condition about the driving pressure ratio (Eq. (1)), $p > 0$, should be met to form them. Fractures nearly perpendicular to the σ_3-axis readily satisfy the condition, $\sigma < p_f$. Thus, those are favourably oriented fractures to be dilated by overpressured fluids (Fig. 2). In contrast, those nearly perpendicular to the σ_1-axis are the most unfavourably oriented ones.

Fluid pressure is assumed to have fluctuated with stress condition unchanged during the mineralization of Hishikari veins (Fig. 2a), which lasted for 6×10^5 years (Izawa et al., 1993a; Sanematsu et al., 2005; Tohma et al., 2010). Favourably oriented fractures had a number of chances to form veins, but unfavourably oriented ones had such chances less often (Fig. 2b and c). As a result, the poles to veins make an elliptical cluster centered on the σ_3-axis upon an equal-area projection, and the cluster is elongated along the great circle defined by the σ_3-and σ_2-axes (Fig. 2). Poles to the veins formed under axial compression (Φ= 0) are scattered along this great circle to make a girdle pattern, because σ_2- and σ_3-axes are indistinguishable for this stress condition. In contrast, poles to veins formed under axial tension (Φ= 1) make a circular cluster, σ_2- and σ_1-axes being indistinguishable. The cluster shape indicates Φ (Jolly and Sanderson, 1997).

Such clusters and girdles can be represented by the Bingham distribution (e.g., Borradaile, 2003), which has the probability density function,

$$\mathrm{P_B}(\boldsymbol{x}) = \frac{1}{A}\exp[\boldsymbol{x}^{\mathrm{T}}\boldsymbol{Q}^{\mathrm{T}}\mathrm{diag}(\kappa_1,\ \kappa_2,\ 0)\boldsymbol{Q}\boldsymbol{x}], \tag{3}$$

where $\boldsymbol{x}$ is the unit vector indicating an orientation, A is the normalizing factor, κ_1 and κ_2 are concentration parameters ($\kappa_1 \leq \kappa_2 \leq 0$), and $\boldsymbol{Q}$ is the orthogonal matrix that indicates the minimum, intermediate and maximum concentration axes. Uniform distribution has the parameters, $\kappa_1 = \kappa_2 = 0$; and smaller clusters have larger $|\kappa_1|$ and $|\kappa_2|$ values. θ represents κ_1, κ_2 and $\boldsymbol{Q}$, collectively. Bingham distributions with various concentration parameters are shown in Fig. 3. The aspect ratio of a cluster is denoted by κ_2/κ_1.

It follows from Eq. (2) that normal stress upon the plane normal to $\boldsymbol{x}$ is written as

$$\sigma = \boldsymbol{x}^{\mathrm{T}}\boldsymbol{Q}^{\mathrm{T}}\mathrm{diag}(1,\ \Phi,\ 0)\boldsymbol{Q}\boldsymbol{x}, \tag{4}$$

where $\boldsymbol{Q}$ is the orthogonal matrix standing for the stress axes. The exponential function in Eq. (3) is a monotonously increasing function. Hence, Yamaji et al. (2010) pointed out that the contour lines of $\mathrm{P_B}(\boldsymbol{x})$ are identical with those of σ (Fig. 2) when the minimum, intermediate and maximum concentration axes are parallel to the σ_1-, σ_2- and σ_3-axes, respectively, and

$$\Phi = \kappa_1/\kappa_2. \tag{5}$$

Therefore, the stress axes and stress ratio are determined from vein orientations if a Bingham distribution is fitted to the orientations.

2.2. Mixed Bingham distribution

If veins formed under a few different stress conditions, the poles to veins make distinctive clusters. Therefore, the separation of stresses from such veins is achieved by the fuzzy clustering of the poles that are represented by the unit normal vectors, $\boldsymbol{x}^1, \ldots, \boldsymbol{x}^N$, where N is the number of data. For this purpose, we use the method of Yamaji and Sato