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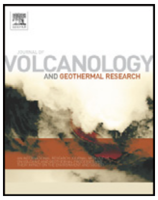

Short communication

Effect of the hydrothermal alteration on the surface conductivity of rock matrix: Comparative study between relatively-high and low temperature hydrothermal systems

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ABSTRACT

In volcanic areas, hydrothermal systems are characterized by high bulk electrical conductivity, which is a combination of high-salinity/temperature pore water and hydrothermally-altered rock matrix. The present study focuses on better understanding the influence of the hydrothermal alteration on the surface conductivity associated with generation and stability of smectite. As a case study, the GSB borehole site at Beppu geothermal area in southwest Japan was selected; at this site, hydrothermal fluids with a relatively high temperature (150 °C) flow at a shallow depth.

The physical properties related to electrical conductivity (formation factor, surface conductivity, and porosity) were estimated on the basis of Revil model using conductivity measurements of the drillcores. Strong hydrothermal alteration at the site GSB was shown by high surface conductivity (10^{-2}–10^{-1} S/m) and high cementation exponent (2.5–4.5). From the comparison between the vertical profiles of the bulk conductivity, pore water conductivity, and surface conductivity, it was shown that the rock matrix makes a non-negligible contribution to the bulk conductivity at the site. This contribution to bulk conductivity is quite different from that of low-temperature hydrothermal systems, where the contribution from the pore water dominates because there is little or no hydrothermal alteration. Furthermore, comparison between the findings of this study and low-temperature hydrothermal systems showed that the surface conductivity could simply reflect temperature to which the rock has been exposed. The surface conductivity maintains the small value at the low temperatures such as <40 °C, and significantly increases at the relatively high temperatures (100–150 °C). At the higher exposed temperatures >150 °C, its value decreases relative to that at the temperatures of 100–150 °C. This relationship is consistent with the generation and stability of smectite at active hydrothermal systems, and places strong constraints on the quantitative interpretation of the electrical conductivity structure of a volcano.

1. Introduction

In volcanic areas, volcanic fluids released from magma are dissipated within the volcanic edifice by the groundwater flow, driven by the rainfall recharge. Volcanic fluids usually have high salinity and high temperature, resulting in hydrothermal activity and a region of high electrical conductivity in the shallow part of the edifice (Keller and Rapolla, 1974; Wannamaker et al., 2004; Kanda et al., 2008; Komori et al., 2013). The spatial distribution of temperature and salinity in the aquifer may be controlled by the influx of mass and heat from degassing magma (Hurwitz et al., 2003; Matsushima, 2011); in return, the spatial extent of the high electrical conductivity region may also reflect the flux of the volcanic fluids (Komori et al., 2012). It is therefore crucial to understand the relation between temperature, salinity and bulk electrical conductivity.

Generally, bulk electrical conductivity, obtained from electromagnetic surveys at volcanic areas, contains two conductivity components: the pore water conductivity and the surface conductivity of the rock matrix. Pore water conductivity can be relatively easily represented as a function of the salinity and temperature, using known equations (Arps, 1953; Revil et al., 1998; Atkins et al., 2009). On the other hand, surface conductivity depends predominantly on the smectite content of the rock matrix, because smectite has a large surface area and develops an electrical double layer on its surface (Revil et al., 1998,

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2002). A certain level of high temperature is usually necessary to generate smectite by hydrothermal alteration; however, smectite is unstable under higher temperature conditions, changing into other, less conductive clay minerals such as illite (Pytte and Reynolds, 1989; Anderson et al., 2000). To date, the effect of temperature on the surface conductivity associated with generation and stability of smectite has been poorly investigated quantitatively, although a pioneering study was done by Mogi (1992) with respect to the effect of hydrothermal alteration on the electrical properties of the rock matrix.

One way to investigate this problem is to examine the surface conductivity of drillcores taken from volcanic and geothermal areas, because these drillcores are exposed to a variety of temperatures, depending on the strength of subsurface hydrothermal activity. Ideally, this would provide quantitative relationships between surface conductivity and the temperatures of alteration, with the eventual goal of evaluating the mass flux of volcanic fluids using the spatial distributions of pore water and surface conductivities in the volcanic aquifer. This is possible because these conductivity components can be related with the temperature and salinity distributed by the influx of the volcanic fluids released from magma. Additionally, drillcores may be useful for inferring the contributions to the observed bulk conductivity from pore water and the rock matrix beneath the drilling site; which could inform an understanding of the flow of hydrothermal fluids and the structural features controlling them, from the viewpoint of electrical conductivity (Komori et al., 2010).

To date, Komori et al. (2010) have estimated the surface conductivity using drillcores from borehole USDP-1, a borehole at Unzen volcano (SW Japan) that penetrated the shallow low-temperature hydrothermal system. Those investigators found that the rock matrix demonstrates low surface conductivity, due to little/no alteration by the low-temperature fluid. The present study focuses on drillcore samples from a geothermal well at Beppu, in SW Japan, where relatively high-temperature fluids flow in the shallow part of the well. There is also a large number of geophysical and geochemical data from well testing and the analysis of rock and water samples. The drillcore samples were used to make measurements of bulk conductivity by changing the pore water conductivity, after which surface conductivities were estimated using the Revil model. The vertical profile of estimated surface conductivity was used for comparison with the profiles of bulk and pore water conductivities, to investigate their relationship under relatively high-temperature conditions. Furthermore, this study examined the effect of exposure temperature on surface conductivity by comparing the present results with the case of low temperature fluids at the Unzen USDP-1 site.

2. Site description — Beppu geothermal area

The Beppu geothermal area is one of the most active geothermal fields in Japan. It is located in the pull-apart-like depression developed in the northern part of Kyushu Island, SW Japan (Takemura et al., 1994; Takemura, 2004). The andesitic volcaniclastic rocks that outcrop in Beppu area have been supplied by the Tsurumi and Garan volcanoes located to the west; these are the source rocks of the alluvial fan that extends towards the coast of Beppu Bay (New Energy Development Organization, 1990). Hot springs and fumaroles, which originate from the NaCl-type deep hydrothermal fluid with a temperature of 250–300 °C, have been developed extensively at the surface, and heat discharge in the area is estimated to be a few hundreds of MW (Allis and Yusa, 1989). In this study area, drilling was conducted to investigate the flow paths of the hot spring waters with different origins (Ohsawa et al., 1994; Yusa et al., 1994).

Fig. 1(b)–(e) shows the vertical profiles of temperature, permeability by in-situ aquifer testing, and authigenic minerals (Gianelli et al., 1992; Yusa et al., 1994), together with the profile of bulk electrical conductivity obtained from CSMT (Controlled Source Magnetotellurics) surveys (Mogi et al., 1995). Note that the in-situ permeability is normalized by its uppermost value (~10^{-12} m^2) for comparison with the core permeability at the Unzen USDP-1 site, as discussed later. In CSMT, NS-oriented 11 receivers were used for acquisition of the electromagnetic waves with frequencies of 4.2–8700 Hz, which were generated by the transmitter located at about 4 km west of the receivers [Fig. 1(a) (Mogi et al., 1995)]. The bulk conductivity increases with depth, and has maximum values of 3×10^{-1}–10^{0} S/m at depths between 150 and 250 m. The low permeability layer composed of a large amount of smectite has developed at depths between 150 and 200 m, below which hydrothermal fluids at a temperature of 150 °C are flowing. The high bulk electrical conductivity region corresponds to both the low permeability layer and the fluid-bearing layer.

This study used the drillcores sampled from the low permeability layer (174 m and 201 m depths), the fluid-bearing layer (228 m depth), and the temperature-decreasing section (298 m depth). These samples, which have been retained in the Institute for Geothermal Sciences, Kyoto University, were used for porosity and bulk electrical conductivity measurements under controlled conditions of pore water conductivity.

3. Electrical conductivity measurements

3.1. Principle of the estimation of the surface conductivity

In general, the bulk electrical conductivity is represented as the function of the pore water and the surface conductivities (Revil et al., 1998, 2002):

$$\sigma = \begin{cases} \frac{\sigma_f}{F}\left[\left(1-t_{(+)}\right)+F\frac{\sigma_S}{\sigma_f}+\frac{1}{2}\left(t_{(+)}-\frac{\sigma_S}{\sigma_f}\right)\left(1-\frac{1}{t_{(+)}}\frac{\sigma_S}{\sigma_f}+\sqrt{\left(1-\frac{1}{t_{(+)}}\frac{\sigma_S}{\sigma_f}\right)^2+\frac{4F}{t_{(+)}}\frac{\sigma_S}{\sigma_f}}\right)\right] & \text{for} \quad \sigma_f \geqq \frac{\sigma_S}{t_{(+)}} \\ \sigma_s+\frac{1-t_{(+)}}{F}\sigma_f & \text{for} \quad \sigma_f \leqq \frac{\sigma_S}{t_{(+)}} \end{cases} \tag{1}$$

where: σ is the bulk electrical conductivity (S/m), σ_f is the pore water conductivity (S/m), σ_s is the surface conductivity of rock matrix (S/m), and $t_{(+)}$ is the Hittorf transport number of a cation in the free electrolyte (Revil et al., 1998). F is the formation factor, defined as:

$$F = \phi^{-m} \tag{2}$$

where: ϕ is the porosity, and m is the cementation exponent ($m > 0$). In this study, there are two unknown parameters: the formation factor F and the surface conductivity σ_s. These unknowns can be determined if there are at least two measured pairs of bulk and pore water conductivities (Komori et al., 2010).

3.2. Core measurements

The drillcores are column-shaped bodies, composed mainly of andesitic volcaniclastic deposits (Gianelli et al., 1992). Table 1 shows their cross-sectional areas, and lengths. They were initially saturated with pure water in a vacuum using the desiccator and the vacuum pump, to remove the soluble materials on the grains. After drying at 100 °C for 48–96 hours, they were saturated with NaCl solutions at various controlled salinities, in a vacuum as mentioned previously. After the saturation for 48 hours, the electrical conductivity of the water inside the desiccator was measured, and its value was defined as the pore water electrical conductivity for each. Bulk electrical conductivity of the samples was measured by the four electrodes method, as shown in Komori et al. (2010). During the measurements, the room temperature was maintained at 25 °C.

Almost all the measurements were conducted by the Oyo Corporation's “miniOHM”; which applies the square wave current with a frequency of 8 Hz to the samples, and measures the current and the electric potential between the electrodes with a precision of two significant digits. Some measurements were done by the Agilent's