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ELECTRICAL RESISTIVITY MEASUREMENTS OF ANDESITE AND HYDROTHERMAL BRECCIA FROM THE AWIBENGKOK GEOTHERMAL FIELD, INDONESIA

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ABSTRACT

Laboratory measurements of the electrical resistivity of rocks and synthetic rocks with confining pressures up to 100 bars and temperatures between 20 and 211°C were performed to further investigate how the pore-size distribution and associated capillarity affects boiling in porous media. In all cases, resistivity gradually increased when pore pressure was decreased below the phase-boundary pressure of free water, indicating that boiling is controlled not only by temperature and pressure, but also by pore size distribution. This effect was first reported by us for metashale from The Geysers. Total changes in resistivity with boiling are comparable to Geysers rock for andesite from Awi 1-2 and much larger for a hydrothermal breccia. Large resistivity changes associated with boiling for the highly permeable breccia suggest that a resistivity increase would correlate with high-permeability zones if steam is present. If confirmed in further experiments, these results may lead to a new geophysical diagnostic for locating boiling in high-permeability areas of geothermal reservoirs, detecting steam in situ, and determining the pressure–temperature conditions of steam-cap formation.

INTRODUCTION

The electrical properties of fluid-saturated rocks are important for numerous reasons. Improved resistivity data for rocks from the Awibengkok site will be valuable for understanding field wide properties, such as defining the field boundaries, following the effects of production including formation of a steam cap, and tracking injectate. These data are of fundamental value for interpreting logs of electrical properties measured in the field. As samples from the Awibengkok geothermal field have become available, carefully performed laboratory experiments provide data necessary for interpretation of field results as well as investigating important physical–chemical properties such as permeability and vapor-pressure lowering.

Rock electrical properties are sensitive to factors such as the nature and amount of pore saturant, temperature, and pressure (Llera et al., 1990), surface conduction, and microstructural properties such as porosity and tortuosity. Of these, the amount of the pore saturant and its nature (i.e., whether it is liquid water, other fluids, steam, and other gases) and microstructural properties are significant factors that are investigated in this study. Most dry rocks are excellent insulators in vacuo, but saturation with distilled water decreases resistivity by 8 orders of magnitude and more (Duba et al., 1978). In water-saturated rocks, increasing temperature from 25 to 250°C decreases the electrical resistivity by about an order of magnitude (Llera et al., 1990).

Background

The Awibengkok geothermal field is located in West Java 60 km south of Jakarta. It is situated on the western flank of Gunung (mount) Salak, one of three overlapping composite volcanoes. The Sunda–Banda volcanic arc marks the southernmost extent of the Eurasian plate and is one of the world's richest geothermal regions (Noor et al., 1992). Awibengkok is an ideal representative of a composite-hosted volcanic “andesitic” system, typical of those which supply an increasingly large portion of the world’s geothermal power. A comprehensive overview of Awibengkok and of the research project aimed at studying core recovered from Awi 1-2 to improve understanding of all composite hosted systems is described by Hulen and Anderson, 1998.

The geothermal reservoir at Awibengkok is Indonesia’s largest, producing power at over 300 MW installed capacity. It is liquid-dominated with temperatures ranging from 220 to 300^{o}C. Well-interference tests generally indicate high reservoir permeability and good communication between wells, with certain linear features acting as partial permeability barriers on the field scale (Murray et al., 1995).

A scientific corehole, Awi 1-2, was drilled in November 1995 near the shallowest expression of the reservoir. Approximately 1.1 km of continuous core was recovered (Hulen and Anderson, 1998). This area is often described as a "cupola" of the reservoir, where Murray et al. (1995) speculated that a preproduction steam cap might exist. At the first fluid entry in Awi 1-1, the pressure and temperature of the reservoir fluid is close to the phase boundary.

Electrical surveys were critical in the discovery of the Awibengkok field. The resistivity anomaly, now attributed to a highly argillitized layer containing significant smectite, was detected by a magnetotelluric survey. The electrical anomaly at one second period as defined by the 2.5-ohm meter contour was used to guide initial drilling. As a result, the first five wells, Awi 1-1 through 5-1, were completed in the reservoir. Electrical anomalies may also be indicative of outflow of brine (Ganefianto and Shemeta, 1996).

EXPERIMENTAL PROCEDURE

Experimental Apparatus

A complete description of the experimental apparatus and measuring procedures is reported by Roberts et al. (1999b). The apparatus consists of an externally heated pressure vessel with separate pumps and controls for confining pressure and pore pressure on either side of the sample (Figure. 1). Pore pressure was controlled independently between 0 and 50 bars, and for convenience the two systems are referred to as up- and down-stream pressure systems. An impedance bridge was used to measure the resistance of the electrically isolated samples at 1 kHz. Electrical resistivity was calculated from the resistance and geometry of the core. Temperature was measured with type J thermocouples with an accuracy of ±2°C. Data collection was automated by use of a scanning unit and microcomputer.

Samples and Preparation

A brief description of the samples studied and microstructural details is listed in Table 1. Based on previous results on samples from The Geysers (Roberts et al., 1999b) wherein we observed boiling phenomena attributed to vapor-pressure lowering, we decided to investigate samples with a higher porosity and permeability to help understand how microstructure controls boiling. The samples selected for electrical properties measurements were cored from segments of the Awi 1-2 core. The porphyritic andesite from 1384 m (4500 ft) is a "typical" flow rock from the reservoir. It is dense, medium dark gray-green, with "intense propylitic alteration" as described by Hulen and Nielson (1995) in drill logs from the site. The permeability of nearby core plugs was measured to be 19 µDarcy (unpublished data, Unocal Geothermal Operations, Santa Rosa, CA). The porosity of the sample used in the electrical resistivity apparatus is ~11.5%. The hydrothermal breccia was selected to be representative of a high-permeability zone and is

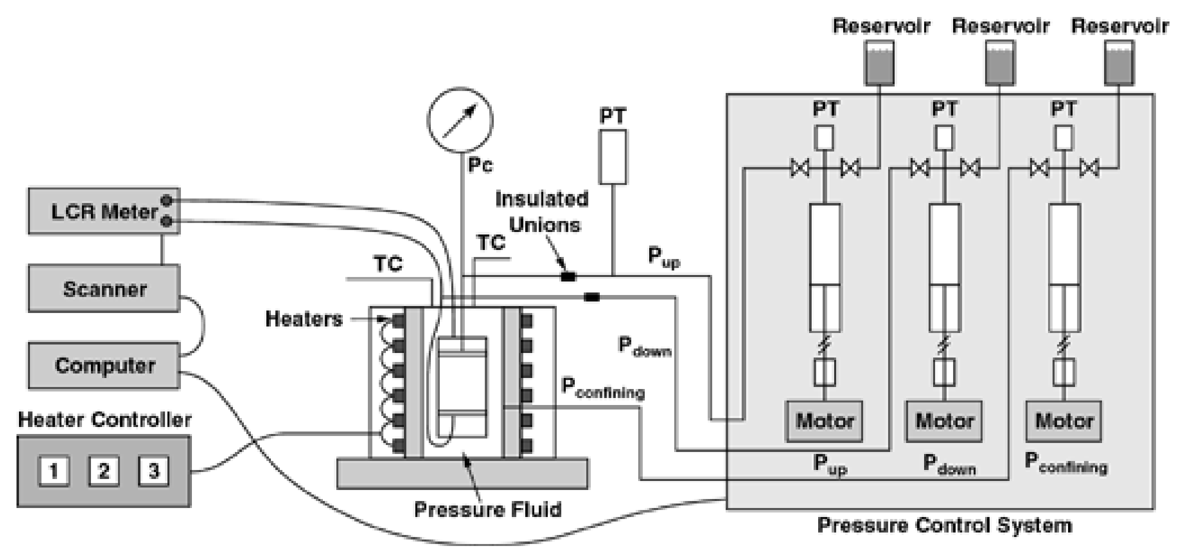

Figure 1. Schematic of apparatus. Sample is electrically isolated and held in an externally heated pressure vessel with separate reservoirs, pumps, and controls for confining and pore pressure. Type J thermocouples measure temperature of the three-zone heater and at two locations within the vessel, adjacent to the sample. A standard impedance bridge (LCR meter, HP4284a) is used to measure the electrical properties of the sample using a four-terminal pair, two-electrode technique. All data are collected and stored automatically with a microcomputer.

Table 1. Samples Studied.

Sample	Description	Depth (ft)	Porosity	Permeability (mD)	Area/Length Ratio (m)
Awi-1	Awibengkok andesite	Run 76, 4500	11.5	0.019	0.025
Awi-2	Awibengkok hydrothermal breccia	Run 75, 4447	26.8	—	0.024

described by Hulen and Nielson in the field notes as “a multi-stage hydrothermal breccia complex.” This sample had a much higher porosity (26.8%) and a higher permeability than the andesitic sample.

Samples were prepared by machining right-circular cylinders approximately 1.5 to 2.5 cm high and 2.5 cm in diameter. Porosity was determined by subtracting dry density from wet density. Samples were saturated with a pore fluid prepared from high-purity salts and distilled water by taking samples dried under vacuum at 35°C and back-filling with the NaCl solution. Samples were then left immersed in the solution for several days until the weights were constant, indicating that saturation was complete. All samples were saturated with a mixture of 1.65 g NaCl per liter of water (fluid conductivity ~1.57 mS/cm). The fluid was boiled for one hour before being used for saturating the samples to remove dissolved gases. The fluid used to saturate the Awi-1 sample was also pumped under rough vacuum for about 2 hours for more complete gas removal. The sample assembly used in this study is shown in Figure 2. For some of the experiments at higher temperatures, KalRez (trademark DuPont) jacketing was used instead of Viton.

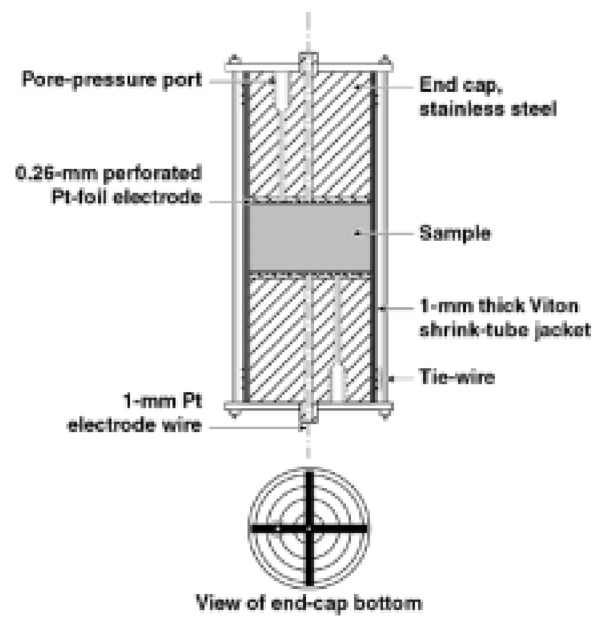

Figure 2. Schematic of sample assembly showing perforated endcaps, electrodes, jacket material, pore pressure inlets, and frame.

ELECTRICAL RESISTIVITY RESULTS AND DISCUSSION

Awibengkok 1-2

Preliminary results for the Awibengkok samples are reported. Additional data are being collected, and electrical properties of other samples will be studied. Resistivity as a function of temperature between 22 and 211°C is plotted in Figure 3. For this experiment, confining and pore pressures were generally held at a constant ratio of 2:1 with confining pressure typically ~35 bars. However, in order to prevent boiling, it was necessary to increase the pressures at the highest experimental temperatures. At 211°C the confining pressure was ~70 bars and the pore pressure ~35 bars. The boiling pressure for water at 211°C is about 20 bars. We anticipate that additional experiments will be performed at temperatures up to 250°C. For sample Awi-1 the resistivity decreased from 50 to less than 10 •-m. The trend is quite similar to that of a welded tuff sample with similar porosity studied by

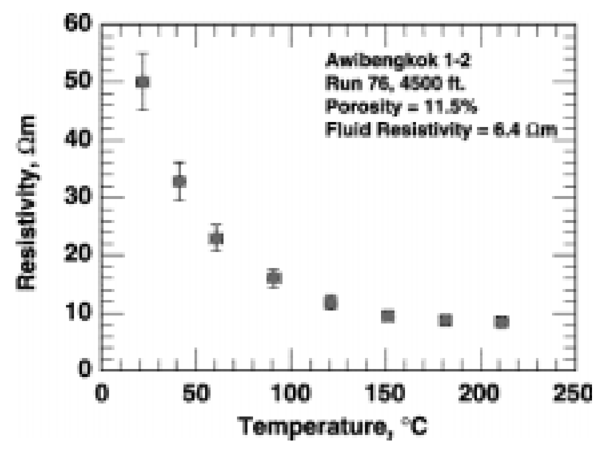

Figure 3. Resistivity vs temperature for the Awibengkok run 76 andesitic sample between 22 and 211°C. Confining and pore pressures were varied at a constant ratio of 2:1 as the temperature was increased. Fluid resistivity at room temperature was ~6.4 •-m (conductivity = 1.57 mS/cm).

Roberts et al. (1999a). However, the magnitudes of the resistivity values differ by about a factor of 25 in spite of the similar porosities and permeabilities and the use of the same saturating fluid. One possible explanation is that the formation waters of the Awibengkok samples are much more saline, and much more conductive. Thus, when the sample is recovered and subsequently dried out, salt deposits are left behind that go back into solution during saturation of the sample in the laboratory. Another possibility is a high-surface-conduction component caused by the propylitic alteration. These possibilities are currently being investigated.

Figure 4 shows the effect of reducing pore pressure at constant temperature (151°C) and constant confining pressure (34.6 bars). The sample is relatively impermeable and can support a pore-pressure gradient over the time scale of the experiment. Therefore pore pressure on only one side of the sample is varied. Similar to the tuff sample discussed above and the rocks from The Geysers (Roberts et al., 1999b), the resistivity of this sample indicates gradual boiling as pore pressure is reduced. Although the data are sparse and the boundary cannot be precisely defined, the first pressure at which the resistivity increases significantly is 4 bars. Each subsequent lowering of pressure results in an additional increase in resistivity. The sample resistance returned to pre-boiling values after the pressure excursion, an indication that any crystal deposition that took place during the boiling event was reversible.

Figure 5 shows the behavior of a second sample, which is a hydrothermal breccia with high porosity, between 22 and 135°C and ~9.3 bars confining pressure. At a given temperature, the resistivity of this sample is about half that of the previous sample at any pressure. This decrease in resistivity is the result of a combination of increased porosity in this sample and a lower confining pressure. The observed behavior is consistent with results from a study of the effect of pressure on resistivity of core from The Geysers geothermal field (Duba et al., 1997).

Figure 6 shows the behavior of the hydrothermal breccia as pore pressure is lowered at confining pressure of 7.9 bars and 135ºC. The vertical dashed line marks the pore pressure (Haas, 1971; see Figure 7, for example) where boiling is expected to occur for brine of this composition. No large increase in resistance due to boiling is observed at 3.08 bars. Rather, as pore pressure is lowered further, the resistivity increases gradually with time but does not precipitously increase until almost a bar lower than the nominal boiling point.

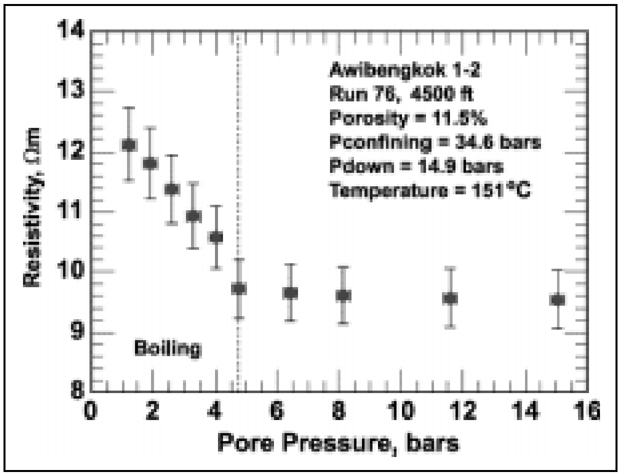

Figure 4. Resistance as a function of pore pressure for the Awibengkok andesitic sample from run 76. Confining pressure was held constant while pore pressure was dropped. Boiling is expected at about 4.7 bars as indicated by the dashed vertical line. Below this pressure resistivity increases gradually as more of the pore space boils, effectively cutting off electrically conductive pathways.

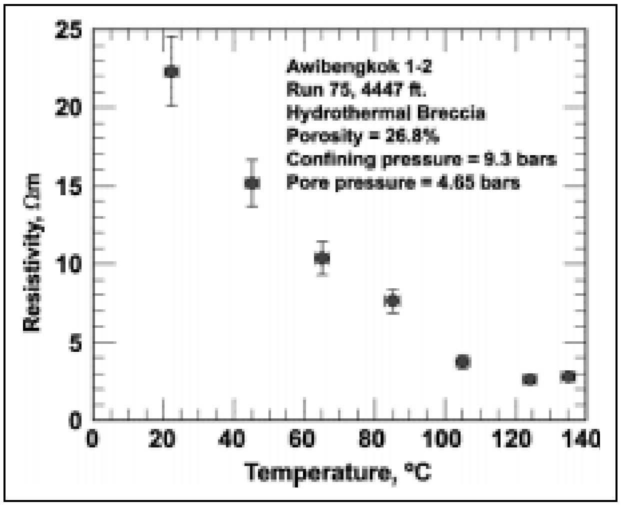

Figure 5. Resistivity versus temperature for the Awibengkok Run 75 hydrothermal breccia sample between 22 and 135°C. Confining and pore pressures were varied at a constant ratio of 2:1 as the temperature was increased. Fluid resistivity at room temperature was ~6.4 •-m (conductivity = 1.57 mS/cm).

Similar behavior was first reported by us for rocks from The Geysers geothermal field (Roberts et al., 1999b). Figure 7 is from that report and shows the effect of pore-size distribution on the suppression of boiling (heterogeneous boiling) in core from The Geysers. We suggest that a similar effect is occurring in the core from the Awibengkok, Indonesia, geothermal field. This has major implications for geothermal reservoirs.

Detection of occult steam, either by electrical or other means, is important because of the consequences for interpretation of well-interference tests. These tests are a primary tool for evaluating the mass in place in a fluid-dominated geothermal field (Murray et al., 1995). Unknown or occult steam would greatly increase the actual compressibility of the field, introducing errors on mass estimates made under the assumption of a single incompressible (liquid) phase.

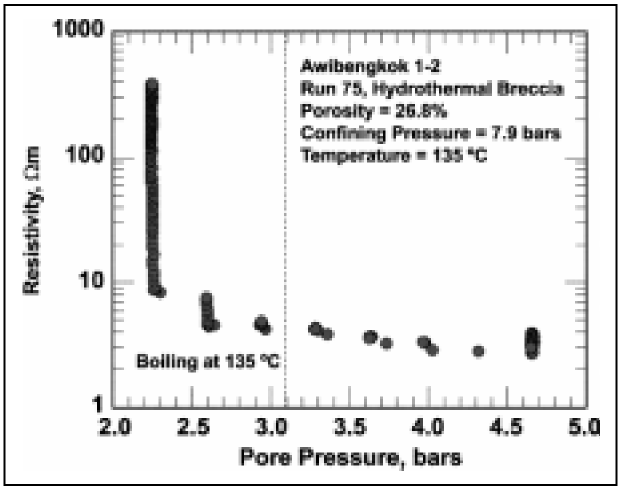

Figure 6. Resistivity as a function of pore pressure for the Awibengkok Run 75 hydrothermal breccia sample. Confining pressure was held constant at 34.6 bars, while pore pressure was varied. At these experimental conditions water boils at pressures below approximately 3.08 bars as indicated by the dashed vertical line. At a specific pore pressure (below 3.08 bars) the resistivity steadily increases as shown by the upward trending points. The gradual increase in resistivity with decreasing pore pressure below 3.08 bars indicates heterogeneous boiling, similar to samples from The Geysers. Note the log resistivity scale.

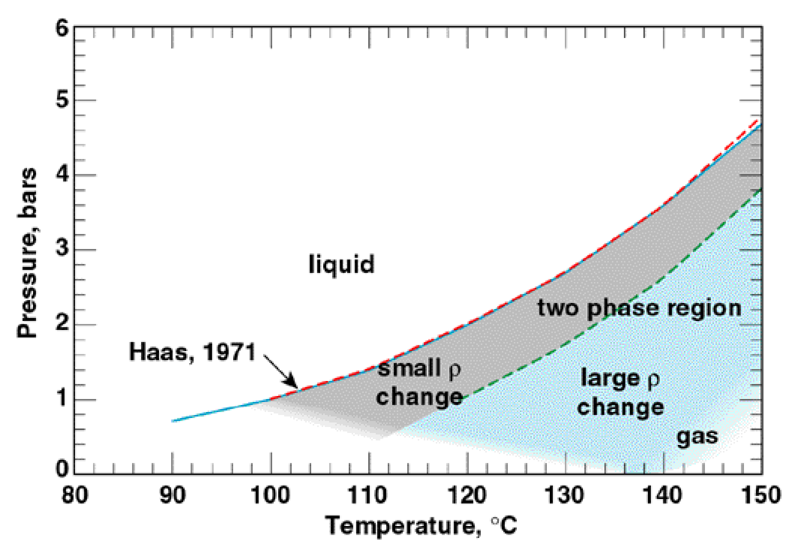

Figure 7. Phase diagram for water and dilute NaCl solutions (Haas, 1971). This figure schematically shows the consequences of heterogeneous boiling, which is the development of a two-phase region. Resistivity changes are large when significant numbers of pores are steam-filled, cutting off electrically conductive pathways

CONCLUSIONS

Resistivity is sensitive to temperature, composition, and state of the pore fluid and lithology. The temperature dependence of resistivity of the andesite and hydrothermal breccia is controlled by the temperature dependence of ionic conductivity of the brine when the samples are fully saturated, in agreement with previous results as reported by Llera et al. (1990) and Roberts et al. (1999b). Resistivity of both rocks depends only weakly on pressure when brine-saturated, in agreement with previous observations for metashale from The Geysers. This observation suggests that hydrothermal alteration stiffens the matrix by eliminating compliant features of the microstructure, such as microcracks, which ordinarily cause the physical properties of crustal rocks to be strongly pressure-dependent. After steam is produced in the sample by lowering the pore pressure, the increase in resistance caused by replacing (in part) conducting brine with insulating water vapor is gradual and therefore inconsistent with an abrupt steam transition, as predicted by bulk thermodynamics. Resistivity data indicate that pore fluid entrained within the matrix transforms to steam below the bulk fluid phase boundary. These effects were first reported by Roberts et al. (1999) for samples from The Geysers and are reported here for much different lithologies. The observations are consistent with the "heterogeneous boiling" model, which occurs because vapor-pressure lowering and adsorption in fine pores maintains fluid in the liquid state across the phase boundary for bulk brine. This conducting brine keeps measured resistance relatively low. The magnitude of the change of resistivity with boiling depends on porosity and surface conduction, and was much larger for the high-permeability hydrothermal breccia.

Localized high resistivities may be useful for locating and following "super permeability zones" in the field when steam is present. If confirmed in further experiments, these results may lead to a new geophysical diagnostic for locating boiling in high-permeability areas of geothermal reservoirs. These measurements show that resistivity data can also be valuable for understanding field-wide properties, such as defining the field boundaries, following the effects of production including formation of a steam cap, and tracking injectate. In particular, remote detection of occult steam, either by electrical or other means, is important because of the consequences for interpretation of well-interference tests. Interference tests are a primary tool for evaluating the mass in place in a fluid-dominated geothermal field. The presence of steam greatly increases the actual compressibility of the field, introducing errors in mass estimates made under the assumption of a single incompressible (liquid) phase in the reservoir. Detailed interpretation of interference testing and consequences of a steam cap at Awibenkok are discussed by Murray et al. (1995).

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