Preprint
UCRL-JC-134711

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This article was submitted to
1999 Annual Meeting of the Geothermal Resources Council
Reno, NV
October 17-20, 1999

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

June 28, 1999

ELECTRICAL RESISTIVITY MEASUREMENTS OF BRINE SATURATED POROUS MEDIA NEAR RESERVOIR CONDITIONS: AWIBENGKOK PRELIMINARY RESULTS

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Keywords: Awibengkok, resistivity, electrical properties, permeability

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 capillarity affects boiling in porous media. Similar to previous measurements on samples from The Geysers, CA, we observed a gradual increase in resistivity when pore pressure was decreased below the phase-boundary pressure of free water, an indication that boiling is controlled not only by temperature and pressure, but also by pore size distribution. Other important phenomena observed were strong resistance fluctuations during boiling that may be chaotic, and salt deposition that caused sample cracking. If confirmed in further experiments, these results may lead to a new geophysical diagnostic for locating boiling in high permeability areas of geothermal reservoirs and for methods of permeability alteration.

INTRODUCTION

The electrical properties of fluid saturated rocks are important for numerous reasons including interpretation of well logs and surface and cross borehole electromagnetic geophysical surveys. Carefully performed laboratory experiments provide data necessary for interpretation of field results as well as important physical-chemical properties such as permeability, vapor pressure lowering, and microstructural properties. Experiments were performed on synthetic rocks composed of fused glass beads, welded tuff from Yucca Mountain, Nevada, and andesite from Awibengkok, Indonesia. Electrical resistance (and resistivity) were measured as functions of temperature (up to 250°C), confining pressure (0 to 100 bars) and pore pressure (0 to 50 bars).

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).

EXPERIMENTAL PROCEDURE

Experimental Apparatus. A complete description of the experimental apparatus and measuring procedures is reported by Roberts et al. (1999). 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 (Fig. 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 Studied. A brief description of the samples studied and microstructural details are listed in Table 1. Based on previous results on samples from The Geysers (Roberts et al., 1999) 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 Geysers samples were of very low porosity (~3.5%) and permeabilities less than 1 μDarcy (Persoff and Hulen, 1996; Finsterle and Persoff, 1997). The extremely low permeability of these samples made it difficult to know precisely the pressure distribution within the sample and, hence, made our efforts to determine the effects of vapor pressure lowering on boiling more difficult. To avoid complications resulting from polymineralic systems and weathering, we chose to study synthetic rocks made by fusing glass beads of size 230 μm diameter into dense solids (Berge et al., 1993; 1995). By carefully controlling temperature, ramp rate, and cooling times, samples can be made with a specific porosity. An advantage of studying the fused glass bead samples is the research performed on these and similarly created samples including electrical properties (Roberts et al., 1999) , elastic properties (Berge et al., 1995; Blair et al., 1996), and detailed microstructural characterization (Roberts et al., 1998).

The second type of sample studied here is a densely-welded tuff from Fran Ridge, Nevada (Topopah Spring Tuff). This sample was chosen because of its similarity to other geothermal host rocks, i.e., Awibengkok, and because of the large amount of research performed on this rock as host of the potential nuclear waste repository at Yucca Mountain, Nevada (i.e., Roberts and Lin, 1997).

Awibengkok samples from borehole Awi 1-2 have been prepared (Table 1). Electrical properties measurements on these samples are currently in progress and preliminary results are presented for a sample from run 76, 4500 ft depth. The sample is described in the drilling log (Hulen) as a porphyritic andesite; dense, medium dark gray-green, with intense propylitic alteration. The permeability of nearby core plugs was measured to be 19 μDarcy (unpublished data, Unocal Geothermal Operations, Santa Rosa, CA). The porosity of the first sample to be used in the electrical resistivity apparatus is ~11.5%. The permeability and porosity are quite similar to those of the Topopah Spring Tuff and thus we might expect that the two samples will behave similarly with respect to petrophysical properties.

Sample Preparation. 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/m). 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.

ELECTRICAL RESISTIVITY RESULTS and DISCUSSION

Glass Bead Samples–Resistance Fluctuations During Boiling. Resistivity measurements were made for a synthetic rock fabricated from fused glass beads to investigate samples with high permeability, of the order of 1 Darcy, and porosity, 28%. For this sample, pore pressure equilibration occurs rapidly during experiments. Boiling is influenced by porosity effects, as in previous experience with metashale from The Geysers. Continuous recording of resistance for a sample at fixed pressure and temperature in the two phase region is presented as Figure 2. A particularly interesting and unanticipated behavior of the resistance was observed during boiling events at elevated pressure and temperature.

Resistance data show large fluctuations and are presented as collected. Instabilities in the data for stable thermodynamic conditions do not appear to be instrumental noise, but originate in the sample. The fluctuations appear to be caused by making and breaking electrical conduction paths as the two-phase fluid, consisting of conducting brine and insulating water vapor, moves and rearranges within the sample. It is well known that dripping of liquids can be described by nonlinear dynamics, e.g., chaos (Gleick, 1987). It appears that the time dependence of resistance observed during boiling in these high permeability samples may be controlled by nonlinear dynamics of fluid movement. The resistance appears to fall preferentially within three ranges of values, possibly corresponding to three attractors (or states) of a chaotic system. These ranges may result from preferred geometries of conducting pore fluid that form and break during refluxing of the two-phase pore fluid. The time series was not long enough to analyze data for nonlinear parameters. If confirmed in further experiments, this result may lead to a new geophysical diagnostic for boiling in high permeability areas of geothermal reservoirs based on measurement of 'electrical noise'.

The glass-bead experiment was eventually terminated when salt deposits formed within the sample after repeated boiling events and permeability was lost. An obvious increase in porosity was noted after removal from the pressure vessel. Closer examination showed that salt crystals had formed in the pore space between the sintered glass beads and caused fracturing, analogous to the process of freeze-thaw damage. The damage occurred against the action of the confining pressure over a range of scales, causing fractures that spanned the sample length. This preliminary result suggests that permeability might be modified by precipitation of dissolved solids, but further investigations are needed to characterize and generalize the process (Jackson and Chalmers, 1958).

Topopah Spring Tuff. Resistivity as a function of temperature for the Topopah Spring Tuff is shown in Figure 3. Confining pressure and pore pressure were held constant during these measurements, ~35 bars and 8 bars, respectively. Between approximately 80 and 146°C the resistivity decreases smoothly from 500 Ω-m to about 230 Ω-m. This decrease with temperature is similar to that observed for other samples including rocks from The Geysers (Roberts et al., 1999) and granites (Llera et al., 1990).

Resistance as a function of pore pressure at constant temperature (146.8°C) and constant confining pressure (34.6 bars) is shown in Figure 4. Because of the low permeability of the sample (less than 1 μDarcy) a pore pressure gradient could be supported. The pressure on one end of the sample was held constant ('downstream side') to 8.1 bars while that of the other side was varied. Starting at about 8.1 bars pressure the resistance was ~8800 Ω. As pore pressure was lowered to near 4 bars the resistance increased slightly. This is attributed to the increased effective pressure on the sample and the subsequent loss of relatively conducting fluid from the pore space. Bulk water at these experimental conditions will boil at pressure below ~4.08 bars

(Haas, 1971). A significant jump in resistance, indicating boiling and the presence of relatively non-conducting steam-filled pores does not occur until ~3.6 bars. This behavior is similar to that observed for sample from The Geysers (Roberts et al., 1999). At these pore pressures, resistance increases with time (as indicated by the upward arrow), as well as with further decreases in pore pressure. When the pore pressure was increased to the starting value of 8.1 bars, resistance dropped quickly to about 9800 Ω and gradually returned to close to the original value for that pressure and temperature.

Awibengkok 1-2. Preliminary results for the Awibengkok sample 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 5. For this experiment, confining and pore pressures were held at a constant ratio of 2:1. 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 Ω-m. The trend is quite similar to that of the tuff sample Tpt-1g, 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 6 shows the effect of reducing pore pressure at constant temperature (151°C) and constant confining pressure (34.6 bars). Again, the sample is relatively impermeable and can support a pore pressure gradient. Therefore pore pressure on only one side of the sample is varied. Similar to the tuff sample and the rocks from The Geysers, 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 he pressure excursion, an indication that any crystal deposition that took place during the boiling event was reversible.

CONCLUSIONS

The temperature dependence of resistivity of liquid saturated Nevada tuff and Awi 1-2 andesite is controlled by the temperature dependence of ionic conductivity of the brine. This is in agreement with previous results as reported by Llera et al. (1990) and Roberts et al. (1999). 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. This effect was first reported by Roberts et al. (1999) for samples from The Geysers and is a consequence of 'heterogeneous boiling'. It occurs because vapor pressure lowering in fine pores maintains fluid in the liquid state across the phase boundary for bulk brine. This conducting brine keeps measured resistance relatively low. Resistivity of the Awi 1-2 sample and tuff depends only weakly on pressure when brine saturated, in agreement with previous observations for metashale from The Geysers, as reported by Roberts et al. (1999).

Measurements on a synthetic high porosity, high permeability material, fused glass beads, revealed a surprising instability in resistance when the sample contained a two phase pore fluid. The fluctuations in the resistance may to be caused by making and breaking electrical conduction paths as the two phase fluid, consisting of conducting brine and insulating water vapor, refluxes within the sample. If this process can be detected by electrical measurements made in the field, boiling in high permeability areas of geothermal reservoirs might be located. Salt deposits formed within the fused glass bead sample after repeated boiling events. Salt deposition caused fracturing producing a net increase in porosity (some salt filled) after the experiments. This preliminary result suggests that permeability might be modified by precipitation and subsequent removal of dissolved solids, but further investigations are needed to characterize and generalize the process.

ACKNOWLEDGMENTS

C. Boro, E. Carlberg, and W. Ralph provided essential technical support and expertise. We thank P. Kasameyer, P. Persoff, J. Hulen and G. Boitnott for fruitful discussion and comments. This work was supported by the Geothermal Technology Division, under the Assistant Secretary for Energy Efficiency and Renewable Energy of the U.S. Department of Energy and was performed by Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

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Table 1. Samples Studied.

Sample	Description	Porosity *	Permeability (mD)	Area/Length Ratio (m)
GB-1.1	fused glass bead	17.3	1300	0.02
GB-1.2	fused glass bead	28.5	17000	0.02
Tpt-1g	Topopah Spring Tuff	13.0	~0.001§	0.02
AWI-1	Awibengkok andesite	11.5	0.019	0.025

*data summarized in Roberts et al., 1998
§ estimate

Figure Captions

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.

Figure 2. Resistance measured at 1 kHz versus time for fused glass bead sample 1-2. The sample, at 125°C and pore pressure of only 2.3 bars is within the boiling field (Haas, 1971). The resistance fluctuates about a factor of 6 between ~5000 and 30,000 Ω. This behavior was observed for several samples, including the Awibengkok sample, but to a lesser extent. The magnitude of the fluctuations seems to depend on porosity and permeability, with larger fluctuations occurring the greater the porosity.

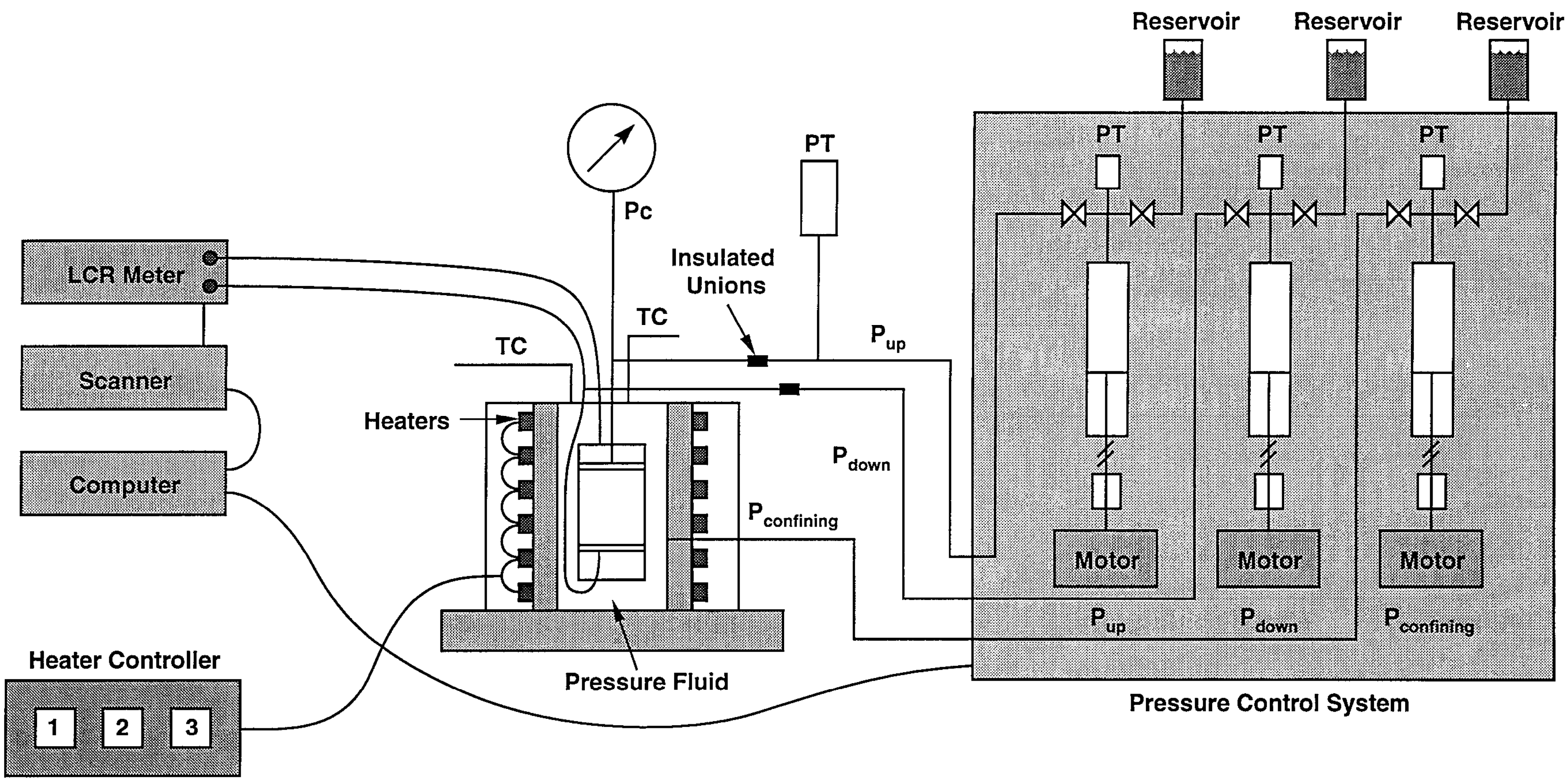
Figure 3. Resistivity versus temperature for sample Tpt-1g, Topopah Spring Tuff. Confining pressure was controlled to ~35 bars and the pore pressure to ~8 bars. Fluid resistivity at room temperature was ~6.4 Ω-m (conductivity = 1.57 mS/cm).

Figure 4. Resistance as a function of pore pressure for the Topopah Spring Tuff sample. Confining pressure was held constant at 34.6 bars, while pore pressure was varied (one side only). At these experimental conditions water boils at pressures below approximately 4.08 bars as indicated by the dashed vertical line. A significant increase in resistance, indicating boiling in

the largest pores at the low pressure end of the sample, did not occur until pore pressure was lowered to approximately 3.6 bars.

Figure 5. Resistivity versus temperature for the Awibengkok sample between 22 and 211°C. Confining and pore pressure were varied at a constant ratio of 2:1 as the temperature was increased.

Figure 6. Resistivity as a function of pore pressure for the Awibengkok sample, preliminary data. Confining pressure was held constant at 34.6 bars, while pore pressure was varied. At these experimental conditions water boils at pressures below approximately 4.08 bars as indicated by the dashed vertical line. The gradual increase in resistivity with decreasing pore pressure below 4.08 bars indicates heterogeneous boiling, similar to samples from The Geysers.



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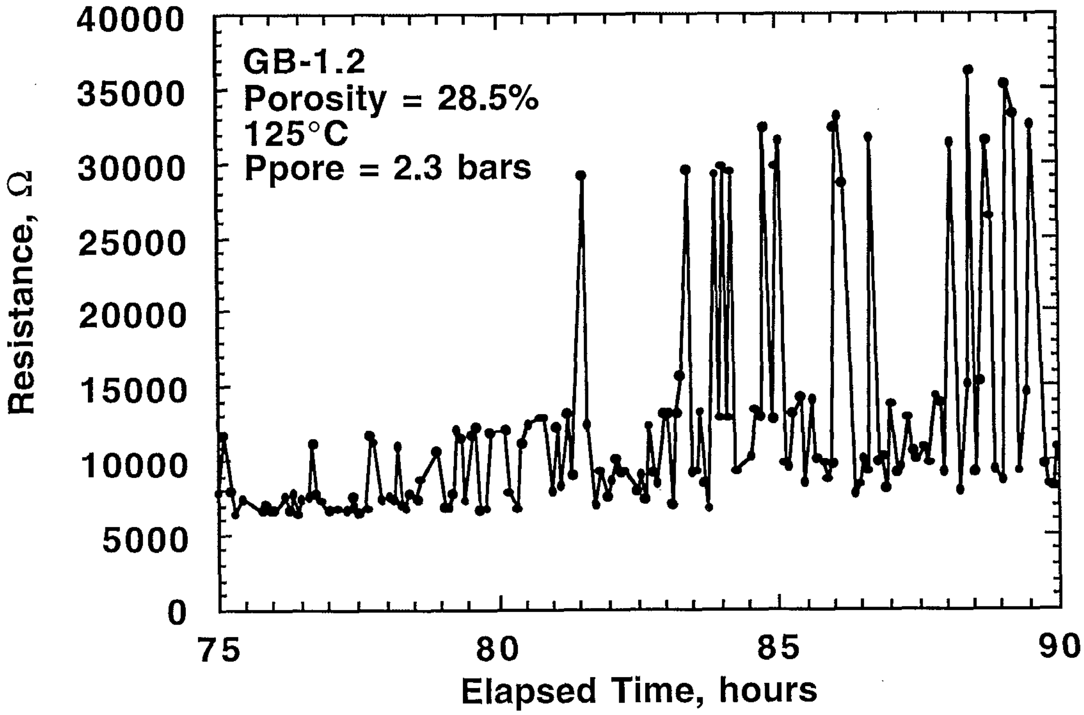

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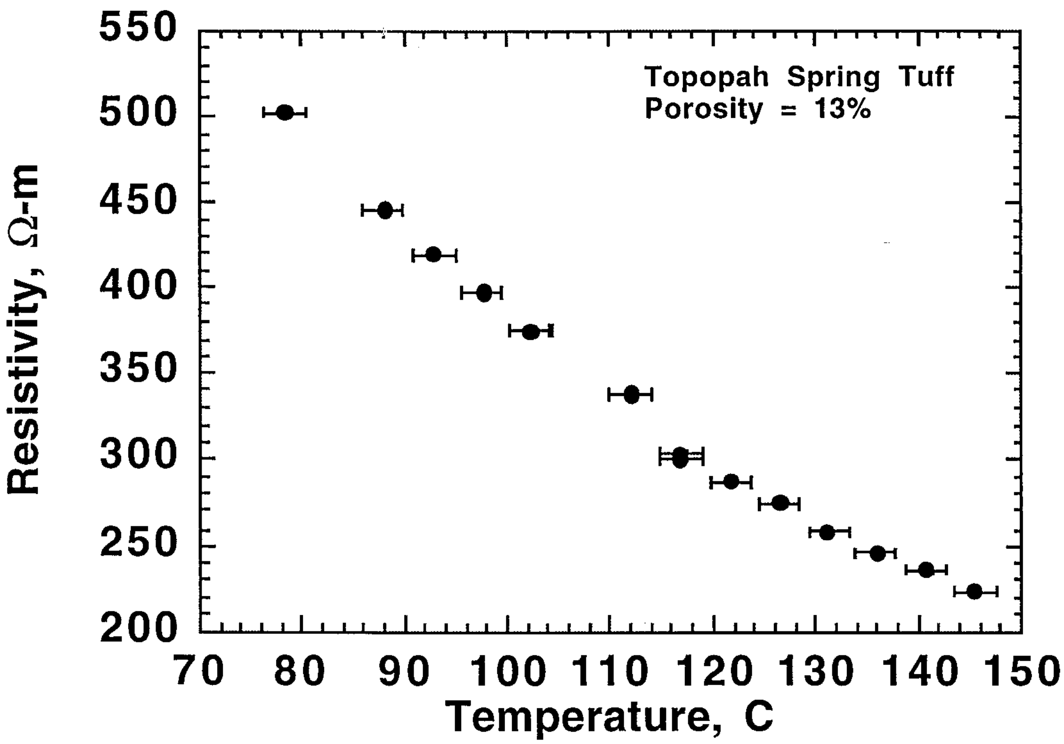

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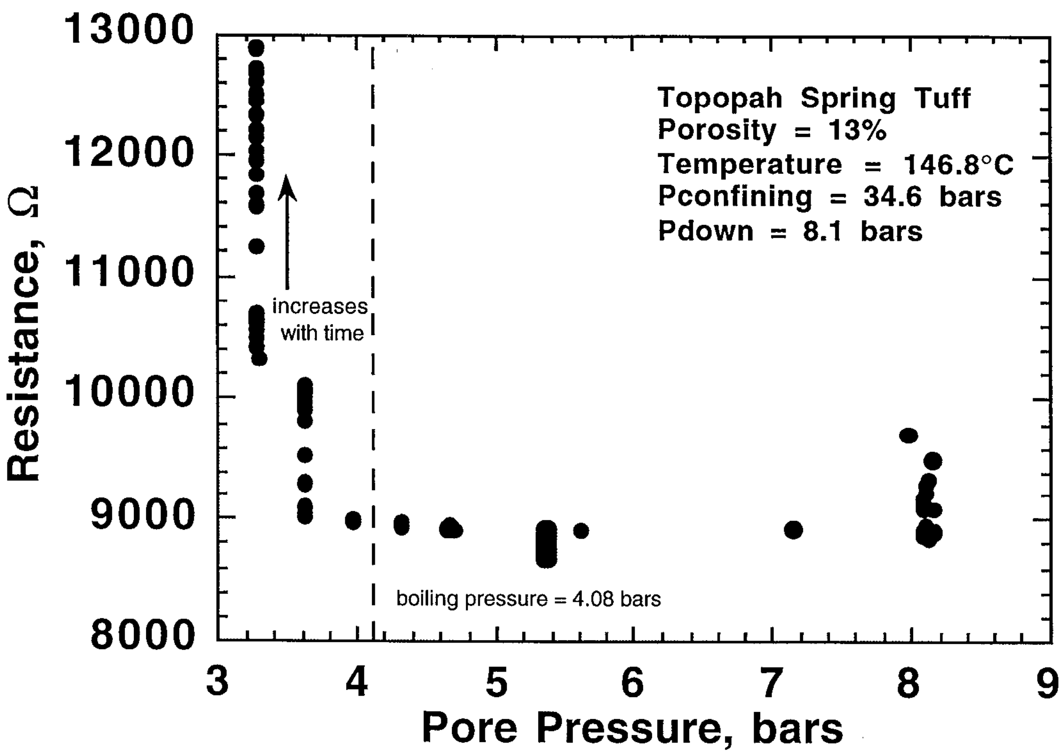

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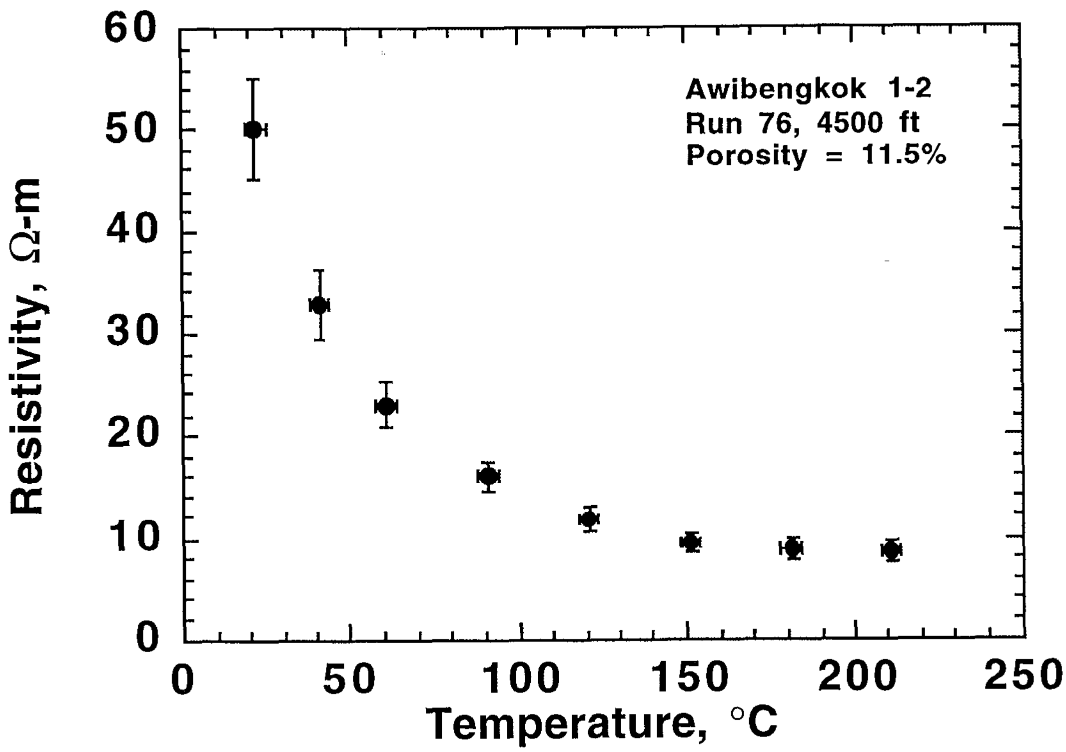

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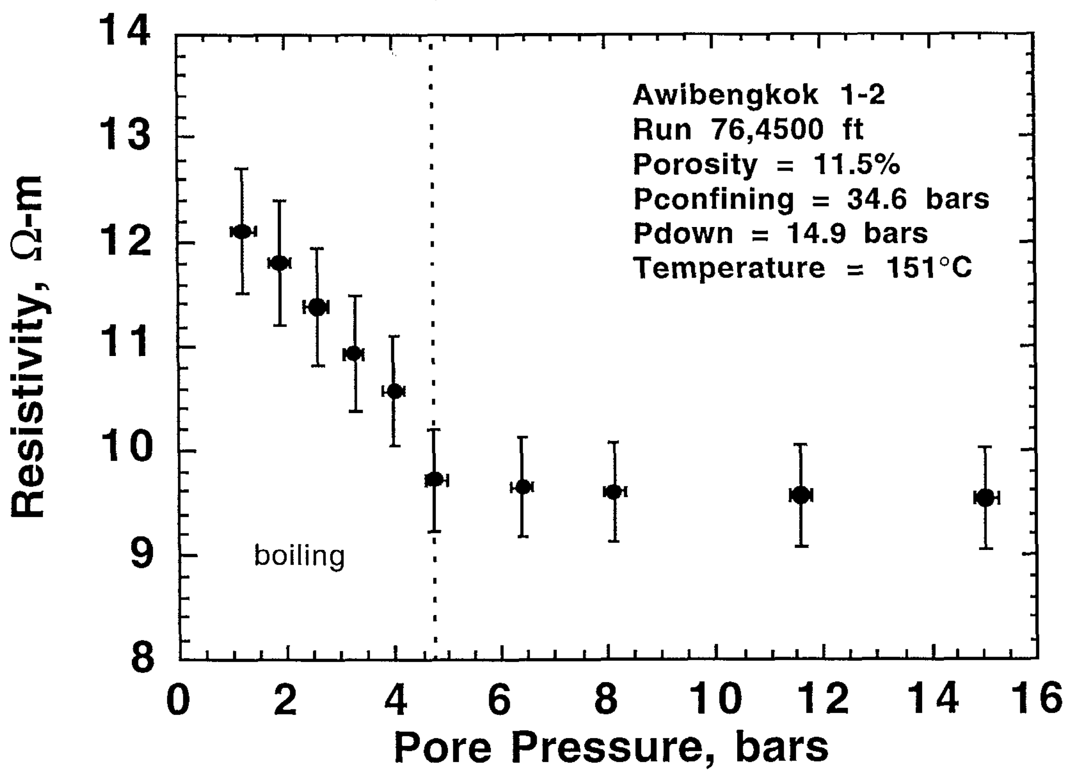

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