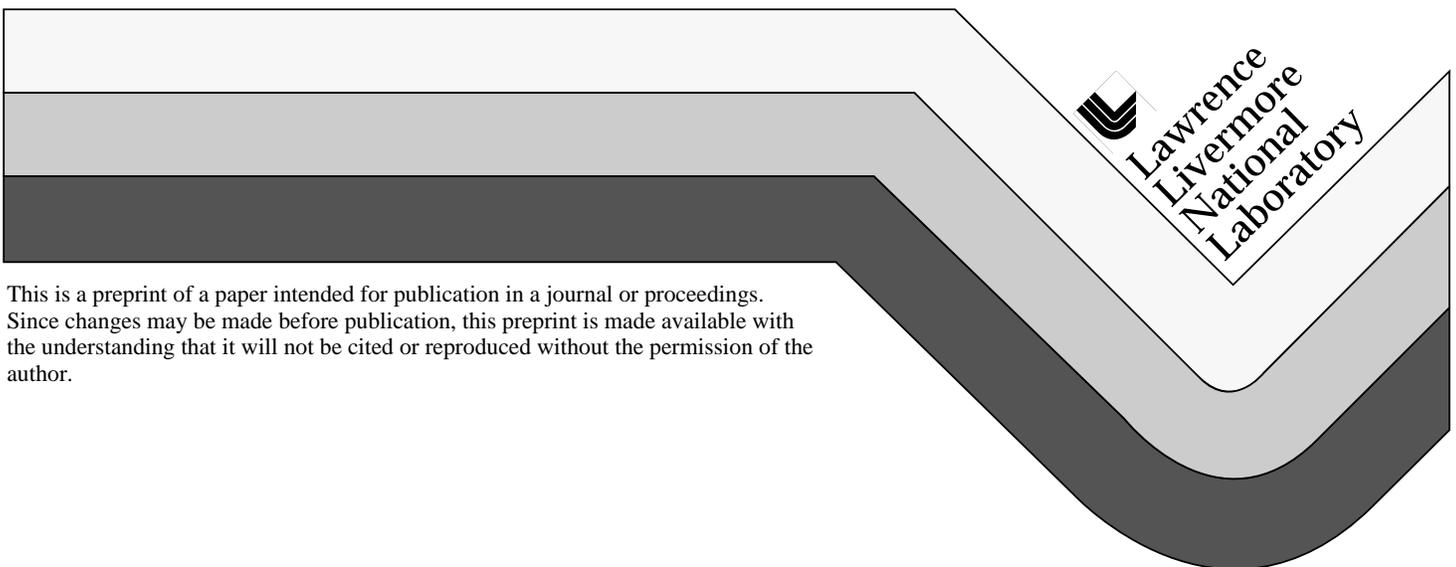


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A. Duba
J. Roberts
B. Bonner

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ELECTRICAL PROPERTIES OF GEOTHERMAL RESERVOIR ROCKS AS INDICATORS OF POROSITY DISTRIBUTION

Al Duba, Jeff Roberts, and Brian Bonner

Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94551

ABSTRACT

Measurements of the electrical resistivity of metashales from borehole SB-15-D in The Geysers geothermal area at a variety of conditions in the laboratory provide information regarding the distribution of porosity as interpreted from observations of boiling as downstream pore-pressure or confining pressure is decreased at constant temperature, or as temperature is increased at constant downstream pore-pressure. Electrical resistivity measurements on core, with and without pore-pressure control, to confining pressures up to 100 bars and temperatures between 20 and 150°C allow assessment of the separate and combined effects of confining pressure, pore pressure and temperature for rocks from this borehole.

INTRODUCTION

The electrical properties of rocks are sensitive to factors such as the nature and amount of pore saturant, temperature and pressure (Llera et al., 1990). Of these, the amount and nature of the pore saturant (liquid water, other fluids, steam, and other gases) are the most important since most dry rocks are excellent insulators *in vacuo*, whereas saturation with distilled water decreases resistivity 8 orders of magnitude and more (Duba et al., 1978). For most rocks, the effect of pressure is to close off cracks and diminish pore size, thereby increasing the electrical resistivity of saturated rocks by as much as an order of magnitude at 1 kbar (Brace et al., 1965). In water-saturated rocks, increasing temperature from 25°C to 250°C decreases the electrical resistivity by about an order of magnitude (Llera et al., 1990).

Because of the large effect of pore saturant on electrical resistivity discussed above, it may be possible to distinguish steam-rich from water-filled zones by field electromagnetic techniques and to assess, and monitor changes in, the geothermal potential of portions of a steam-dominated geothermal system such as that at The Geysers. Reported below are the results of a laboratory study of changes in electrical resistivity in geothermal-reservoir rocks from borehole SB-15-D of The Geysers as the pore saturant boils.

Systematic study of the electrical response of geothermal-reservoir rocks to changes in pore-fluid content in the laboratory can aid in interpreting data from field electromagnetic studies, from the surface or within and between boreholes.

EXPERIMENTAL

Samples were prepared by machining right-circular cylinders approximately 1.5 cm high and 2.5 cm diameter from cores that had been stored in sealed aluminum cylinders immediately upon removal from the core-barrel from the 919-foot-depth interval (919 feet ~ 280 m—note: we prefer to use the standard nomenclature of the industry rather than SI units, SI units will follow in parentheses, the first time that the industry unit is used) of Run 12 in hole SB-15-D at The Geysers Geothermal Area. Effective porosity, obtained from 15 samples and determined by subtracting dry and wet densities (determinations of these quantities are discussed in the paragraph below), varied between 1.0 and 6.5% with a mean of 3.5 and a standard deviation of 1.9. Table I lists the samples, sizes, densities, and porosities to three significant figures.

Nr.	Height cm	Dia. cm	Dry density, g/cc	Wet density, g/cc	Porosity %
1	1.52	2.54	2.62	2.68	5.67
2	1.52	2.54	2.60	2.66	6.40
3	1.52	2.54	2.60	2.67	6.54
4	1.50	2.54	2.61	2.64	2.18
5	1.52	2.54	2.61	2.63	2.15
6	1.52	2.54	2.61	2.63	2.59
7	1.49	2.54	2.59	2.61	1.56
8	0.917	2.54	2.62	2.63	0.973
9	1.48	2.41	2.84	2.91	6.50
10	1.50	2.52	2.62	2.65	2.93
11	1.50	2.52	2.61	2.64	3.82
12	1.50	2.52	2.62	2.65	3.19
13	1.42	2.54	2.62	2.65	3.40
14	1.32	2.54	2.61	2.63	2.11
15	1.42	2.54	2.62	2.64	2.14
Avg	—	—	2.63±0.06	2.66±0.07	3.48±1.89

Table I. Dimensions and porosity of cores used in this study.

After removal from the aluminum cylinders and coring with diamond core tools the rocks were dried under vacuum, the saturant was allowed to flow into the evacuated system, and an air pressure of 10 bars was imposed on the fluid-rock system. After this saturation process, the rock was kept in the fluid for at least a week. The pore fluid was prepared from high-purity salts and distilled water. Samples 1-3 were saturated with a mixture of 1.65 g NaCl plus 0.73 g NaHCO₃ per litre water (fluid conductivity ~0.45 S/m), the others were saturated with 1.87 g NaCl per litre water (fluid conductivity ~0.35 S/m) and further saturation was monitored by measurement of weight increase. After no additional significant increase in weight was observed, the sample was assumed fully saturated. One sample (#15) was saturated in the above fashion, but with a saturant which had previously been boiled in order to remove any gases dissolved in the fluid as suggested by Satik (1996) and with nitrogen instead of air as the pressurizing medium following pore-fluid saturation.

Samples were jacketed in Viton with Hastalloy end-caps backed by a perforated platinum-foil electrode. Figure 1 is a schematic of the two sample assemblies that were used in the externally-heated pressure vessel.

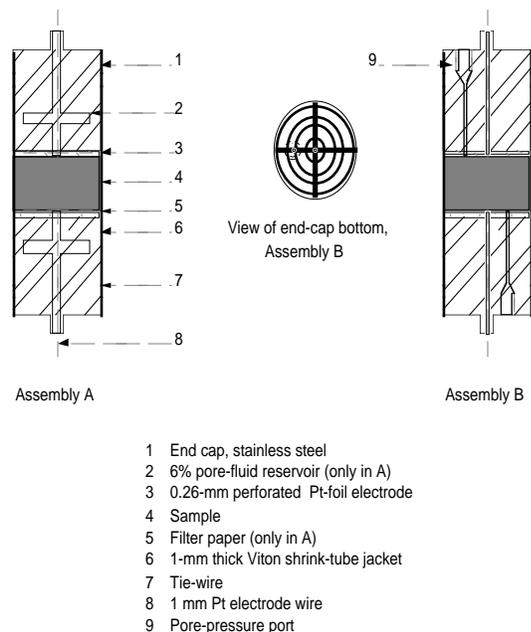


Figure 1. Assemblies used in this study. The addition of a pore-pressure port to the end caps used in Assembly A.

For measurements without separate pore-pressure control, the end caps contained a chamber, shown as item 2 in Assembly A of Figure 1, that acted as a reservoir for water exiting the sample upon pressurization. This configuration permitted up to four samples to be present simultaneously in the externally-heated pressure vessel. The pressure medium was refined kerosene. Reactions between this medium and the sample jacketing at high temperatures limited the duration of experiments to a few days only, otherwise leaks of the pressure fluid into the sample terminated the experiment. Assembly B was used for those measurements made with pore-pressure control. Only one sample was examined at a time and a Si-based oil was used as the confining pressure medium to minimize reactions with the jacket. A system of valves, screw presses, and gauges was used so that pore-pressure could be controlled and monitored on either end of the sample.

For both assemblies, electrical leads exited the vessel through conical seals in the high pressure plug. The resistance to ground through these seals was always more than 20 M ohm (the highest resistance that our bridge could measure). Sample resistances were typically less than 10 k ohm, except during boiling in samples without pore-pressure control, when the apparent sample resistance sometimes exceeded the measurement capability of the bridge. This was likely because the expansion of water turning to steam was sufficient to expand the jacket and push the electrode/end-cap assembly away from contact with the rock. The impedance bridge that was used to measure the resistance and capacitance of the samples between 100 and 2000 Hz was an HP 4274A LCR meter with a stated accuracy of 1%. The accuracy of this bridge is periodically checked with standard resistors. Electrical resistivity was calculated from the resistance and geometry of the core.

Temperature was measured with type J thermocouples with an accuracy of $\pm 2^\circ\text{C}$. One thermocouple touched the Viton-jacketed sample, the other was just below the bottom stainless-steel cap. Temperatures reported here are the average of the readings of the two thermocouples, which differed less than a degree from each other. Confining pressure was measured with an external manganin coil with an accuracy of ± 2.5 bars (1 bar = 0.1 MPa) and checked against a Bourdon-tube gauge with an accuracy of ± 0.25 bars. Pore pressure was measured with transducers with an accuracy of ± 0.5 bars. Pressures were maintained manually, thus adjustments in pressure were made to correct for pressure-fluid volume changes during heating and cooling cycles. Collection of resistance, temperature, confining-pressure, and pore-pressure data was accomplished with an HP 3497a using Labview on a Macintosh computer.

RESULTS AND DISCUSSION

Experiments with pore pressure not explicitly controlled.

Measurements began on three samples at room temperature ($\sim 21^\circ\text{C}$) and ~ 3 bars pressure. As shown in Figure 2, resistivity values for the samples ranged between 70 and 100 ohm-m.

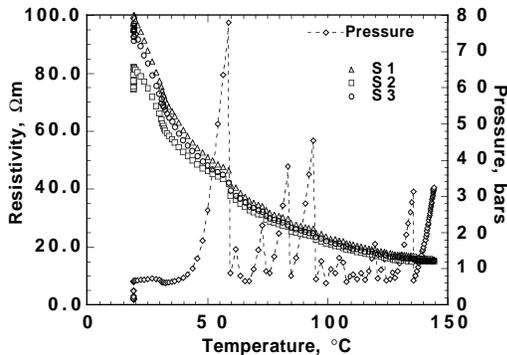


Figure 2. Electrical resistivity of three samples as a function of temperature to $\sim 150^\circ\text{C}$.

Increasing pressure had only a small effect on the electrical resistivity for measurements made at any temperature as the rock was heated up to about 150°C at a confining pressure of at least 6 bars (0.6 kPa). Because of external heating and sporadic manual control of pressure as heating progressed, confining pressure occasionally increased due to expansion of the oil upon heating. These pressure excursions are shown in Figure 2, with pressure plotted along the right margin of the figure. A decrease in pressure from ~ 80 bars to ~ 10 bars decreased the resistivity of all three samples by about 10% as illustrated by the decrease in resistivity shown at about 60°C in Figure 2. However, increasing temperature to 150°C decreased resistivity of the samples by factors between 5 and 7; thus, temperature has a much larger effect than pressure on the electrical resistivity of all samples measured in this study.

Figure 3 shows the effect of pressure up to 100 bars on the electrical resistivity of two of the samples of Figure 2 at room temperature.

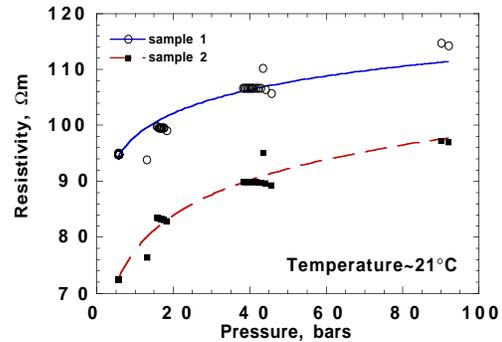


Figure 3. Resistivity as a function of pressure.

As in most saturated rocks, increasing pressure causes the resistivity to increase as water is squeezed from cracks and pores. The effect of increasing pressure from ~ 3 bars to 100 bars is to increase the resistivity at ambient temperature by 20 to 35%. These data emphasize that the resistivity decrease caused by a few degrees increase in temperature can offset the increase in resistivity caused by a hundred bars increase in pressure in saturated rocks below the boiling point.

Lowering the pressure when all three samples were at temperatures of $\sim 145^\circ\text{C}$ produced some interesting effects. Although the pore pressure was not controlled explicitly, lowering the confining pressure lowered the pore pressure enough so that the steam field was entered. At 145°C , the electrical resistivity increases by up to 2 orders of magnitude between 4 and 5 bars confining pressure (Figure 4).

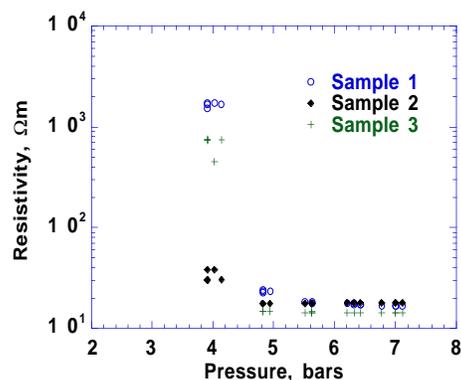


Figure 4. Resistivity of three SB-15-D samples at $\sim 145^\circ\text{C}$ as a function of confining pressure.

Samples 1 and 3, in which open fractures had been observed during jacketing, showed slight increases in resistivity between 5 and 6 bars. The resistivity of sample 2, in which no open fractures had been observed, remained unchanged between 5 and 6

bars. Although the resistivity of all samples increased dramatically between 4 and 5 bars, the increase was substantially larger for the two fractured samples than for the unfractured one. We interpret this difference to be due to the larger amount of water that is available to boil in the two fractured samples because of their higher permeability.

As discussed above, part of this increase in resistivity is an artifact of the lack of control of pore pressure since the volume in each of the end caps (Assembly A in Figure 1) is only ~0.5 ml and even the lowest-porosity rock in Table I has enough water to produce steam to exceed this volume by several factors of ten. Hence, we designed Assembly B in Figure 1 to permit control of pore pressure in subsequent experiments.

Experiments with pore pressure explicitly controlled.

Two experiments were successfully run controlling the pore pressure separate from that of confining pressure, samples 13 and 15. Sample 15 was saturated with fluid which had been boiled to remove dissolved gases (Satik, 1996). For sample 13 the total length of the experiment was almost three months; during most of this time, temperatures were in excess of 100°C. For sample 15, the duration was less than 2 weeks before a jacket leak developed, terminating the experiment. Up until the jacket leak, the response of sample 15 to experimental parameters was quite similar to that of sample 13, indicating that boiling the water prior to saturation had no observable effect on our measurements. Despite creating differential pressures in excess of 15 bars, there was never observable flow—indicated by a decrease in upstream pore-pressure with a concomitant increase in downstream pore-pressure—through either of the samples, even in the steam stability field, for periods up to several days. This is consistent with the low matrix-permeability of 10^{-21} m^2 (1 nanoDarcy) reported for core from this hole (Persoff and Hulen, 1996).

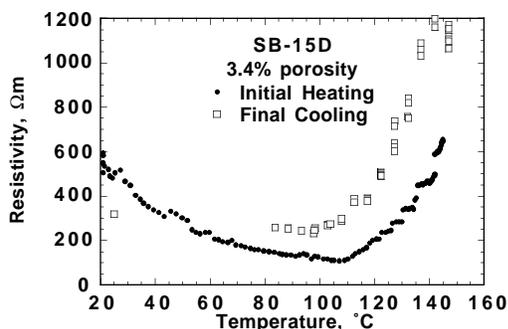


Figure 5. Resistivity of sample 13 from SB-15-D

as a function of temperature at a confining pressure of ~50 bars during initial heating and final cooling. Pore pressure was explicitly controlled to ~15 bars on one end and 1 bar on the other end of the sample. The datum at the lowest temperature on cooling is for confining pressure of 2 bars and pore pressures at 1 bar.

The closed symbols in Figure 5 show the resistivity of sample 13 as a function of temperature as the sample was heated at a rate of 1.5°C per minute. During heating, one end of the sample was held to a pore pressure of 1 bar, pore pressure at the other end of the sample varied between 8 and 15 bars, and confining pressure was maintained at about 50 bars. Thus, boiling was allowed to occur only at the low-pore-pressure end of the sample. All other pressures were sufficient to prevent steam production for the temperatures achieved in this experiment.

As seen in Figure 5, the initial resistivity at ~20°C is near 600 ohm-m, and reaches a minimum of 100 ohm-m between 100 and 110°C. Close examination of Figure 5 indicates that boiling—defined here as the point at which the resistivity begins to increase with temperature as a result of the production of relatively non-conducting steam from the pore fluid—probably occurs at about $108 \pm 2^\circ\text{C}$ in this rock. At higher temperatures the resistivity continues to increase, due to the formation of steam at the downstream end of sample 13. At 145°C the resistivity of the steam-saturated rock is slightly higher than the resistivity of the water-saturated rock at 20°C. Thus, there is an inherent ambiguity in electrical resistivity data alone. In a geothermal reservoir, high electrical resistivity can mean either low temperature or a high-resistivity pore-saturant such as steam. Therefore, care should be used in interpretation of field results. If it is known that the temperature is above boiling in a borehole, then a local zone of high resistivity would likely indicate the presence of a steam-filled fracture. However, steam-filled fractures may be zones of mineralization and the presence of interconnected sulfides in such fractures can certainly decrease electrical resistivity (Duba et al., 1988). It should be noted that pyrite occurs throughout the caprock and in the steam-production zone of SB-15-D (Hulen and Nielson, 1995).

In order to check that the boiling phenomena in Figure 5 was not an artifact of the relatively fast heating rate used for Sample 13, we cooled sample 15 from 147°C in 5-10°C intervals at a rate of about 10°C/hour and collected resistance data for several hours at each interval to allow the sample to come

to complete thermal equilibrium before recording the resistance measurements. The boiling point is at about 108°C for sample 15 as well.

Above 80°C, the open symbols in Figure 5 refer to data collected upon final cooling over a period of several weeks. As during initial heating of the sample, confining pressure was kept at about 50 bars. However, pore pressure on both ends of the sample was at one bar, so that boiling could occur at both ends of the sample. During cooling, temperature was decreased 5°C in about one hour, then temperature was maintained constant for at least 24 hours before it was decreased again. Temperature was decreased in this manner until 80°C, when the furnace was turned off and further manual control of pressure was discontinued. The open symbol at about 25°C is the electrical resistivity of the sample at the end of the experiment when pore pressure was at 1 bar and the confining pressure was about 2 bars. The higher resistivity at high temperature on cooling could be the result of boiling in both ends of the sample.

However, at 2 bars and about 25°C, the resistivity is much lower than it was in the rock before heating. This lower resistivity at near ambient conditions could be the result of crack growth in the sample at elevated temperatures, as suggested by Llera et al (1990) to explain decreased resistivity in their geothermal rocks after temperature cycling. Increased porosity due to cracking could account for some of the increased resistivity of the sample upon cooling through the boiling zone as well. Other factors which could affect the resistivity are ion exchange between pore fluid and clays as well as solution and deposition of minerals in the pore space.

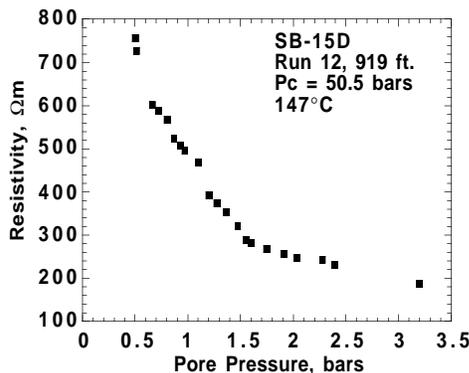


Figure 6. Resistivity as a function of pore pressure for sample 13 from SB-15-D, Run 12, 919 ft. Confining pressure was held to ~50.5 bars and temperature was 147°C. The pore pressure on one end of the sample was held to 15 bars while that of the low-pressure end was varied.

Figure 6 is a plot of the resistivity as a function of pore pressure at 147°C and a confining pressure of ~50 bars for sample 13. The 'downstream' or low-side pore pressure was varied while the pore pressure on the other side of the sample was held to ~15.3 bars. Only the downstream pressure was varied as discussed above. This plot shows a trend of gradually increasing resistivity with decreasing pore pressure. Because of the higher resistivity of steam, we expected to see an abrupt increase in resistivity when the pressure was lowered to permit steam to form. Based on the data of Haas (1971), both water and water with NaCl content of that used in our study boil at ~4.4 bars at 147°C (see Figure 8). Our data show a gradually increasing resistivity as the pore pressure is lowered rather than the abrupt increase expected at the water-steam phase-boundary pressure. We propose that this gradual increase in resistivity as pore pressure decreases at 147°C is the result of boiling in successively smaller pores. Small pores retain the fluid as a liquid because of strong capillary suction. The effect of increasing capillary suction is to decrease the pore pressure required to maintain water in the liquid state for a given temperature. Boiling over a range of temperature could indicate a range of pore sizes in the sample and would account for the increase in slope at lower pressure.

Analysis of the microstructure by mercury injection porosimetry indicates that fine porosity dominates in samples from SB-15-D (Figure 7). In this figure, pore-size distribution is plotted as cumulative intruded volume of mercury as a function of decreasing pore diameter for two samples.

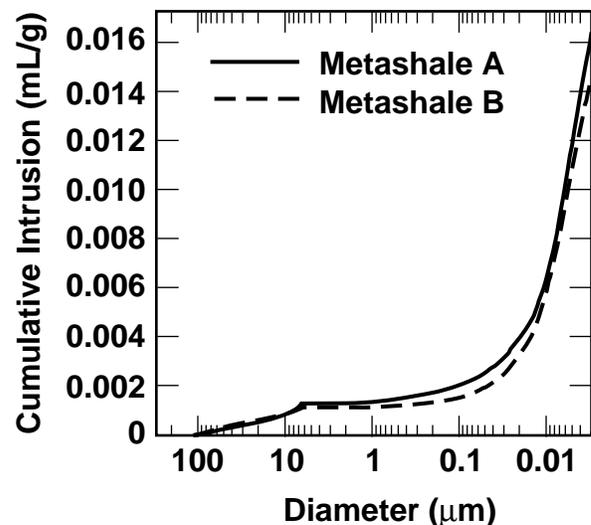


Figure 7. Mercury porosimetry data for two pieces of core SB-15-D from The Geysers.

Detected pore sizes range from 3 nm to 100 μm . Using a linear extrapolation of surface tension data (Marshall and Holmes, 1992) from 40°C to 150°C, we estimate capillary pressures for 100 μm pores of 0.02 bars (little effect on boiling pressure) and greater than 300 bars for the smallest pores. These capillary pressures are consistent with those measured in SB-15-D rocks (Persoff and Hulen, 1996).

Referring again to Figure 6, there is a change in slope of resistivity vs pressure when the pore pressure is reduced to about 1.5 bars. Since approximately 12 % of the porosity is in pores that are larger than 100 nm, the fluid in these pores boils first. This boiling has little effect on the resistivity because of the small volume fraction of fluid-filled porosity involved. Fluid in the smaller pores (<100 nm), which make up almost 90% of the fluid-filled porosity, boils as pressure is decreased further.

The results in Figure 6 are in basic agreement with the experiment performed without explicit pore-pressure control (Figure 4), in that decreasing the pressure (pore pressure) causes a large increase in resistivity at high temperature. With pore-pressure control, however, there are two important differences: (1). There is a smaller increase in resistivity, presumably since steam pressure does not build up in the end caps, forcing the electrode away from the rock, as it did in experiments without pore-pressure control, and (2). Boiling occurs at lower pressure in rocks with pore-pressure control and with confining pressure well above boiling.

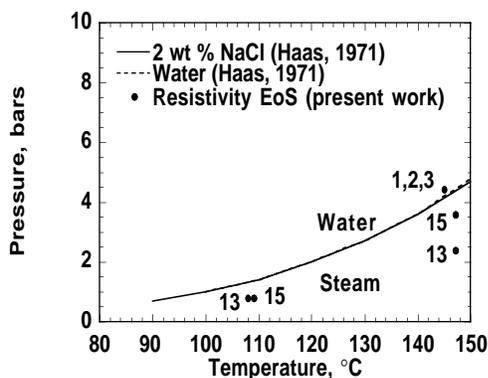


Figure 8. The water to steam transition for pure water and water with 2% salt as reported by Haas, 1971 compared with boiling points (filled circles) determined in this study. Number beside the data refers to sample number.

As can be seen from Figure 8, boiling points interpreted from Figures 5 and 6, and from similar

data for sample 15, are at consistently higher temperature than those given by the pressure-temperature equation-of-state for a fluid of this composition (Haas, 1971). This could have a large impact on assessments of reservoir potential. However, further investigation is needed, with more accurate temperature and pressure measurement, before a definitive statement may be made. If subsequent experiments bear out these preliminary observations, then boiling within a geothermal reservoir is controlled not just by pressure and temperature but also by pore size distribution. Increased capillary pressure as pore size decreases prevents the fluid boiling at temperatures derived from steam tables which do not take capillary pressure into account.

Future work will be directed toward refining our experimental procedure to allow more precise long-term control of pressure and more accurate measurement of pressure and temperature in order to more accurately determine boiling points in the pores

of these rocks. In addition, we plan to perform post-experiment porosimetry and microscopic examination of our samples to determine the pore size distribution and to attempt to quantify the changes that occur in the porosity structure and clay composition as a result of laboratory metamorphism of the rock during the experiment in future investigations.

The implication of these laboratory measurements is that it is possible to observe reservoir behavior by monitoring changes in electrical resistivity as reservoir conditions change. This work has demonstrated that it is possible to track boiling fronts and high temperature zones by monitoring the resistivity of the formation. This implies that some form of electromagnetic monitoring would be useful to track changes in geothermal reservoirs during production. For shallow reservoirs, this may involve surface measurements but, for deeper reservoirs, it would likely involve logging or cross-hole measurements.

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