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RESEARCH ON THE PHYSICAL PROPERTIES
OF GEOTHERMAL RESERVOIR ROCK

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RESEARCH ON THE PHYSICAL PROPERTIES
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ABSTRACT

It is necessary to know the correlation between various physical properties such as electrical resistivity, acoustic wavespeed, and density in order to interpret geophysical well surveys in terms of the amount of water present in a rock, its temperature, and its chemistry. Extensive studies have been carried on in the petroleum industry which have established such relationships for rock types in which oil and gas commonly occur, including clastic and carbonate rocks. Little attention has been paid to other rock types including volcanic and crystalline rocks. In the present research measurements have been made of the electrical resistivity, the acoustic wave speed, density, and water content of six groups of rock samples taken from Cenozoic volcanic units. It has been found from these measurements that the correlations between physical properties are significantly different in the case of volcanic rocks than in the case of sandstones and limestones. For a given porosity and water content, the resistivity of a volcanic rock is several fold greater than that of a sandstone or limestone. Also, there is a weaker correlation between acoustic wave speed and porosity in volcanic rocks than in sandstones and limestones. The effect

of temperature on the properties of these rocks appears to be predictable from fundamental considerations to temperatures as high as 100° C.

RESEARCH ON THE PHYSICAL PROPERTIES
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INTRODUCTION

Geothermal energy is one of several alternatives to the use of oil and gas for the generation of electricity being considered to alleviate the demand for diminishing oil and gas supplies. The geothermal exploration industry has grown rapidly in recent years, with increasing numbers of prospect and production wells being drilled each year. It has become apparent that effective means for interpreting geophysical well surveys in geothermal wells are needed. To some extent, the methods which have been developed in the petroleum industry for evaluating reservoir properties can probably be extended to geothermal wells. To a considerable extent, new methods and new interpretation techniques will be required for several reasons. First, the information sought in a geothermal test well differs from that sought in a well drilled to produce oil or gas. The temperature of the reservoir and the chemical properties of the fluids in the reservoir assume a far greater importance in geothermal drilling than in oil and gas drilling. Second, the rock types that comprise reservoirs for geothermal fluids may be quite different than those which serve as oil and gas reservoirs. In particular,

volcanic rocks are probably important as reservoirs in geothermal systems. Volcanic rocks have received very little attention in petrophysical studies for oil and gas application.

Quantitative interpretation of borehole geophysical surveys started with the work of Archie (1942; 1947). Archie developed the concept of formation factor, defined as the ratio of rock resistivity to the resistivity of the contained water:

$$F = \rho_t / \rho_w,$$

where F is a dimensionless factor characteristic of a rock, ρ_t is the actual resistivity of the rock and ρ_w is the resistivity of the water contained in the pore spaces in the rock. Archie's Law is an empirical correlation between formation factor and the water content of a rock:

$$F = a\phi^{-m},$$

where ϕ is usually defined as the water-filled fractional porosity of a rock, and a and m are empirical parameters required to make this expression fit data for a given set of rock samples.

Following the original work of Archie, many attempts have been made to improve the relationship between water content and resistivity and many efforts have been made to determine the petrophysical significance of the parameters a and m in the expression. Wyllie and Rose (1950) and Wyllie and Spangler (1952) attempted to develop a relationship between the parameters a and m and rock characteristics such as specific surface area of the grains, grain size and size distribution, and capillary pressure behavior in rocks.

Various efforts have been made to model the shape of pore space in the rock mathematically to provide a solid basis for Archie's Law (Greenberg and Brace, 1969; Kwon, 1975; Madden, 1976). It was established in an early stage of such studies that simplistic geometric models cannot predict a correlation between resistivity and porosity that will satisfy Archie's Law. The most satisfactory relationships as indicated by Kwon (1975) and Madden (1976) require the simulation of a pore structure with a statistical distribution of sizes and shapes.

It has been observed experimentally that the parameters a and m can differ significantly for different suites of rock samples. Work by Towle (1962), by Carothers (1968) and by Gomez-Rivero (1976) indicate that even within the limited class of sandstones and limestones which have been widely studied the value for the exponent m must be established for each age and type of lithology.

Early in the study of Archie's Law, it was recognized that other factors may also affect resistivity, which are not included in the formulation as written above. The most significant of these other factors is the clay content of a rock (Patnode and Wyllie, 1950; Keller, 1953). Rocks which contain significant amounts of clay tend to have lower resistivities than predicted by the use of Archie's Law. Some investigators treat the clay minerals as being electrically conductive and connected more or less in parallel with electrolyte filled pore structures. Other investigators treat clay as a substance which electrolyzes in the same

manner as salt, but which is nonconductive in the dry state. In either case in clay-rich rocks, some provision must be made for the added conductance representing clay minerals.

Temperature can be expected to affect the electrical resistivity of rocks significantly also. Limited laboratory studies such as those by Sanyal, Marsden, and Ramey. (1973) indicate that in addition to the primary effect of temperature, which is to change the conductivity of the electrolyte in the pore spaces of the rock, there are also secondary effects which change the formation factor. No laboratory measurements have yet been reported of the effect of conversion of water to steam in reservoir rocks. The effect of this partial conversion is difficult to predict. Keller (1953) has indicated that the effect of partial gas saturation in the pore spaces of a rock can cause greatly different effects on the bulk resistivity of that rock when there are differences in the interfacial tensions between the gas phase, the liquid phase, and the solid phase.

All of the studies described in the preceding paragraphs have been directed towards rocks which are normally encountered in oil and gas reservoirs; that is, clastic, detrital rocks in which the pore space has the character of space left over between relatively equant mineral grains. The other major groups of rocks, including crystalline and volcanic rocks, can be expected to have very much different pore shapes and structures than sedimentary clastic rocks. In view of the fact

that even within the sedimentary rocks the empirical parameters a and m vary significantly from formation to formation, it might be expected that markedly different correlations between resistivity and water content will be found in the igneous and volcanic rocks. Studies of crystalline rocks in which porosity consists mainly of microfractures rather than of intergranular pore spaces have been carried out by Brace and his colleagues (Brace, Orange, and Madden, 1965; Brace, 1977). These studies have shown that the relationship between resistivity and porosity is different than in sedimentary rocks but can be predicted by a modified form of Archie's Law.

Volcanic rocks also have been little studied. Keller (1960) has described the results of extensive petrophysical surveys studies done by the U. S. Geological Survey on the Oak Springs formation, a Miocene rhyolite, in southern Nevada. More recently, Keller, Murray, and Towle (1974) have described the results of petrophysical studies of modern basalt collected from a drillhole in Hawaii. The resistivity of a volcanic rock has been found to be several times larger than that of a crystalline or granular rock for the same water content and related conditions. It is simple to posulate that this phenomenon results from the presence of a great deal of blind porosity in bubbles in volcanic rocks. Also, it has been observed that the correlation between acoustic wave-speed and porosity in volcanic rocks is weaker than in other rocks (Keller, 1960; Keller, Murray and Towle, 1974; Overton and Smith, 1966).

Quantitative interpretation of borehole geophysical surveys may follow one of two strategies. The first strategy is one of absolute determination of a parameter such as water content by solution of Archie's Law and other empirical relationships relating log-derived parameters and sample properties. In the absolute approach all the parameters that are present in an equation, except one are determined from log responses. The additional parameter can be determined by algebraic solution of an equation such as Archie's Law. Often, such direct solution of the empirical equations requires knowledge of a parameter that cannot be determined directly from log responses, such as pore water, salinity, or resistivity. In such cases the missing parameter may be inferred by geologic intuition, or expensive additional core sampling may be required. In either case if the missing parameter cannot be determined with a high degree of reliability, the absolute determinations using empirical laws will be consistently in error.

The second approach to log interpretation which has come into use in the last few years is that of pattern recognition or as it is sometimes called, cross plotting (Pickett, 1973). In this approach the responses of several logging tools are plotted against one another on a work sheet. The data representing rocks with a particular suite of geological properties will often fall within a restricted area on such a

cross plot. Thus, rocks with different geological properties can often be recognized by the fact that they form different patterns on a cross plot, even though no empirical relationships had been used to differentiate between these rock types. Basically, cross plotting consists of the use of several empirical relationships simultaneously in such a way that the unknown parameters are no longer needed.

With either the direct approach to interpretation or pattern recognition, knowledge of the empirical relationships is essential. As has been pointed out by Lang (1973) and Ransom (1974), knowledge of the parameters which control the log responses is absolutely essential to the interpretation of well logs in areas where no previous information has been obtained. This is true for sandstones and other oil and gas reservoir rocks; it is even more true for the types of rocks which are drilled in geothermal exploration. These wells will penetrate rocks which are further from the experience of well log analysts than are new formations in oil and gas provinces. Therefore, the purpose of the research described in this report was to establish empirical relationships between petrophysical properties for volcanic rocks.

SELECTION OF SAMPLES

Suites of samples were taken from major Cenozoic volcanic units in the western United States including volcanic fields in the Snake River Plain, the Colorado Plateau, the Cascade Range, the Modoc Field, the south-central Nevada volcanic field, and the Jemez volcanic area in northern New Mexico. In each sampling locality 64 individual rock samples were taken from outcrop, with each sample being several kilograms in size. Samples were taken insofar as possible to represent the entire vertical accumulation as well as an appreciable lateral coverage from the volcanic complex being sampled. Because a volcanic field is extremely complex stratigraphically, and since volcanic rocks are highly variable in composition and in physical properties, it must be appreciated that the sampling process for such a modest number of samples unavoidably was biased towards the competent rocks. The pyroclastic and volcanoclastic components are probably fairly representative.

No claim can be made that the physical properties measured in this study are representative values for the rock units being sampled. The object of the study is to determine relationships between, and not the most likely value for, any of the physical properties in the field.

A brief description of each occurrence of volcanic rock that was sampled is as follows.

Snake River Plain

The Snake River Plain volcanic plain of Idaho extends in an arc for a distance of 400 miles from Yellowstone National Park on the northeast to the Boise-Vale area of Oregon and Idaho in the southwest. The many thousands of feet of volcanic and interbedded clastic and lacustrine beds that comprise this section were oldest in the western part of the area (Miocene) and become progressively younger toward the eastern end where quaternary volcanism occurred in Yellowstone National Park. All the rocks are siliceous and younger rocks are dominated by flood basalts with local silicic eruptive centers and flows.

Columbia Plateau

The Columbia Plateau volcanic basin is roughly equal with the diameter of 200 miles, located in southeastern Washington, northeastern Oregon, and western Idaho. Flood basalt flows dominate and reach thicknesses of over 5,000 feet, with the total volume of the basalt in the province possibly exceeding 100,000 cubic miles. Marginal facies of the basalt are silicic extrusives and interbedded clastics.

Modoc Volcanic Province

The Modoc volcanic province of northwestern California is transitional between the Pliocene-Quaternary Cascades on the west, the Oligocene-Miocene volcanic fields of the Basin and Range Province to the east and the Miocene to Quaternary high lava plains of Oregon to the north. Over 15,000 feet

of section underlies the Modoc Plateau. The lower part is composed of acidic and intermediate flows, ash breccia, and lahars of the Cedarville Series. The upper part is mainly bimodal basalt-rhyolite flows derived from local vents forming shield volcanoes, glassy domes, and stratovolcanoes. The Modoc is transected by Quaternary faults which locally coincide with eruptive centers.

Southcentral Nevada Volcanic Fields

The volcanic fields of southcentral Nevada are characterized by a wide variety of acidic, intermediate, and to a lesser extent, basic extrusives that erupted from at least seven volcanic centers in the region. Tuffs and ashflow tuffs predominate. The volcanics range in age from late Oligocene to middle Miocene and in thickness from 3,000 to 5,000 feet.

Jemez Volcanic Field

The Jemez volcanic field of northcentral New Mexico covers about 2500 square miles and consists mainly of rhyolite and basalt that erupted from a single large center of complex caldera and resurgent dome activity. Many of the eruptions are Pliocene to quaternary in age. Thicknesses range up to 10,000 feet within the caldera.

MEASUREMENTS AT ROOM TEMPERATURE

From each of the field samples, one to three core plugs were cut for physical properties tests in the laboratory. These plugs are cylindrical in shape, with a diameter of 1.6 centimeters and a length ranging from 3 to 6 centimeters. The shape and size of the samples was dictated by the requirements for sample holders used in making acoustic wave speed measurements and resistivity measurements. Following preparation of the core plugs, a variety of physical properties was measured at laboratory ambient conditions; that is, at approximately 20° C and under 1 atmosphere pressure.

Textural properties

The first of the physical properties to be measured in the laboratory were the textural properties, including porosity, bulk density, and grain density. Porosity was determined using a simple water saturation technique. The samples were first dried at a temperature of approximately 105° C. Dry weight was determined by weighing the samples at this elevated temperatures. The samples were then placed in a container and a vacuum drawn for a period of 24 to 72 hours. The samples were then submerged in water and permitted to saturate under atmospheric pressure for a period ranging from

several days to several weeks. This procedure can be expected to result in a saturation of 95 to 98 per cent of the connected pore spaces. Vesicles and other pore spaces separated from the pore structure by impermeable barriers are not saturated and for the purpose of this study cannot be considered as being a part of the porosity of a rock. Ransom (1974) has pointed out that it is the bulk water content of a rock which is important in determining its reservoir properties rather than the total porosity or similar measures.

The samples were weighed a second time with the pore spaces saturated with water. For some of the samples in which large vesicles are present, it was necessary to wrap the core plugs in thin plastic film to prevent water from draining during measurements.

The volume of each sample was determined in two ways. Volume can be determined approximately by measuring the dimensions of a sample and calculating the volume. A more exact determination was made by weighing each sample while suspending in a beaker of water. The loss of weight with respect to measurements made on the wet samples in the air represents an exact determination of sample volume. From these various determinations of weight and volume, effective porosity for the water saturation method was calculated, as well as bulk and grain density. These data are listed in Tables 1 through 6 in the appendix for the 6 groups of samples studied.

Resistivity Measurements

A four-terminal resistivity cell was used in making resistivity determinations. Each sample was placed in a plastic sleeve which was pressured to a few pounds per square inch to prevent water from leaking from the samples. Current was driven through the samples with contact being made through felt pads pressed against the open ends of the cylindrical samples. The total voltage drop from end to end of the sample was measured as well as the voltage drop between a pair of probes contacting the sample near its mid-point. This provided information for computing both a two-terminal and a four-terminal resistivity value for the samples. Presumably, the four-terminal measurements are more precise than the two-terminal measurements because errors caused by contact resistance are not present. On the other hand, the four-terminal measurements represent a much smaller volume of rock than do the two-terminal measurements. Cross plots between four-terminal and two-terminal values of resistivity are shown in Figures 1 through 6. Close inspection of these plots shows that the two-terminal resistivities are consistently higher than the four-terminal resistivities by a small but significant percentage. Therefore, in the correlations between resistivity and textural properties, only the four-terminal measurements were used.

Scatter plots for formation factor and water filled porosity are shown in Figures 7 through 12 for the six suites of samples. In all cases a wide scatter of plotted points is apparent. This scatter is greater than is commonly

seen for similar measurements made on a suite of sandstones or detrital rocks. This scatter does not reflect experimental error, but rather the greater variability in properties of volcanic rocks from small sample to small sample. This sample to sample variation has been considered for sandstones by Keller (1959). Even in uniform sandstones, the porosity and the resistivity vary by factors of 2 or 3 over distances of a few centimeters. In volcanic rocks where pore structures are physically much larger, large samples would be required to obtain a sufficiently representative sample that the scatter shown on the plots in Figures 6 through 12 could be reduced.

Archie's Law is represented by a straight line when porosity and formation factor are cross plotted on logarithmic scales. The data in Figures 6 through 12 have been plotted on such a scale. The parameters a and m were determined by fitting a straight line to the scatter plots. The results are shown by the family of six straight lines in Figure 13. Along with the experimentally derived lines, a single dashed reference line is shown representing Archie's Law for values of $a = 1$ and $m = 2$. Normally, data collected on sandstone, limestone, and crystalline rock will lie below this line. In our case, many data for volcanic rocks lie significantly above this line.

The specific values for a and m which define the straight lines in Figure 13 are listed in Table 7.

Measurements of Acoustic Wave Speed

Acoustic wavespeeds for both compressional and shear modes of transmission were determined for each sample. Measurements were made by mounting the sample in a core holder in which piezoelectric transducers were pressed against each end of the sample. The transducers at one end were excited with an electric pulse to generate an acoustic wave and the arrival of this acoustic wave at the other end of the sample was detected with a second set of transducers. Either one of two sets of transducers could be used, one of which excited compressional waves traveling along a sample and the other which excited torsional waves traveling along the sample. The transmitted pulse and the vibrations received at the far end of the sample are displayed on a two-trace oscilloscope. The travel time for the acoustic wave through a sample is determined by moving the time base for the received signal until the initial onset of the acoustic vibration coincides with the instant of transmission. The time shift is calibrated and can be read to a tenth of a microsecond. The system is calibrated for delays in transmission which may take place at either end of the sample by making measurements on materials with precisely known acoustic wave speeds, such as halite and other crystalline materials. In order to obtain efficient transmission of acoustic energy through the rock sample, it is necessary to compress the rock under a substantial pressure. In the system which was used here, the frame pressure and confining pressure can be controlled separately. Frame pressure is controlled by a hydraulic ram which compresses the transducer pads against the two ends of the sample. The

entire sample is jacketed in a plastic tube and immersed in an oil-filled reservoir. The confining pressure on the sample is then controlled by a hydraulic pump. For the measurements described in this report, relatively low compressional and confining pressures were used; the two pressures were 1,000 psi.

Compressional and shear wavespeeds are shown plotted as scatter plots against porosity in Figures 14 through 18. It is important to note that there is at best only a weak dependence of acoustic wavespeed on porosity in the samples we have measured. The compressional wavespeeds are relatively high, with inverse wavespeeds being in the range from 5 to 10 microseconds per foot. Shear wavespeeds are correspondingly lower in the range from 10 to 30 microseconds per foot. For the compressional wavespeeds there is a slight decrease in wavespeed with increasing porosity. For the shear wavespeeds, if any relationship exists, wavespeeds increase slightly with increasing porosity. The results obtained so far indicate that acoustic velocity measurements cannot be used readily as a measure of porosity in volcanic rocks.

EFFECT OF TEMPERATURE ON PHYSICAL PROPERTIES

The second phase of the study is to determine the effect of temperature on the relationships between petrophysical properties at temperatures up to and including the boiling point. Initially, it is intended not to apply any substantial confining pressure, so that boiling will occur at approximately 100° C. The phenomenon of partial gas saturation at boiling will occur even without confining pressure. At a later stage, if it seems desirable, the effect of elevating the boiling point can be studied with an appropriate modification of experimental technique.

The initial studies of the effect of temperature on resistivity were accomplished by heating samples selected from the six suites listed above in an induction oven. The samples were mounted in the same cell that was used previously for resistivity determinations at laboratory ambient temperature. This cell is completely nonmetallic. Each core was mounted in a plastic tube pressured with a slight excess pressure of helium or nitrogen. Contacts were held against the open faces of the cylindrical cores with a spring-loaded tierod system which applied a pressure of a few tens of pounds per square inch. The temperature of the sample was monitored continuously with a thermister installed inside the rubber sleeve in contact with the rock.

The entire sample holding system was placed in an induction oven which operated at 2.7 gigaHertz. The oven was energized for time periods of five to twenty seconds. The radiant energy in the oven heated the sample uniformly throughout by ohmic loss. The oven was calibrated by making measurements of the temperature rise in samples with known resistivity of the same dimensions as the rock samples. This calibration permits conversion of time heating to number of calories dissipated within the sample.

Two samples of the results are shown in Figures 19 and 20. In each case the temperature change is plotted against time of heating. Time of heating is closely related to quantity of energy dissipated in each sample.

The behavior of all samples is generally the same. As energy is dissipated in the sample, at first the resistivity decreases gradually. The resistivity reaches a minimum and then begins to increase slowly. At some point, the resistivity increases abruptly with the addition of further energy. This last point almost certainly represents the energy level at which complete vaporization in the pore space takes place. Similar results have been obtained on all 30 samples on which measurements have been made. The data indicate that microwave induction heating is a simple and effective means for raising the temperature of the samples. Provisions are now being made to determine the steam content of the samples during heating, but no results are available at the time of preparation of this report.

CONCLUSIONS

The correlations between resistivity, acoustic wavespeeds, and porosity at room temperature indicate that such studies are essential before geophysical borehole surveys run in geothermal test wells can be interpreted accurately in terms of formation fluid contents. The resistivity versus porosity relationship in volcanic rocks is markedly different than that in most other rock types. If experience in sedimentary and igneous rocks is used, the volume of water present in a rock will be underestimated by a factor of approximately two. This can have serious consequences in the prediction of reservoir performance and life. Generally, geothermal reservoirs in volcanic rocks will have a higher fluid content and therefore a longer life than would be expected if interpretations of resistivity measurements are based on experience in other rock types.

The correlation between acoustic wavespeed and porosity is much weaker than in other rock types. Further work is necessary to determine whether this is an advantage or disadvantage in the interpretation of geophysical borehole surveys. Acoustic wavespeeds do vary from sample to sample, and if porosity is not the controlling factor, possibly the degree of microfracturing is. Further work will be needed to establish this.

It appears to be a straightforward matter to measure the petrophysical relationships of rocks at the boiling point of water. Microwave induction provides uniform heating, and the production of heat can be controlled very carefully. Further work is under way to determine the effect of partial steam saturation on both the resistivity and the acoustic wave speeds of volcanic rocks.

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APPENDIX

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<u>Sample</u>	<u>Porosity</u>	<u>Bulk Density</u>	<u>Grain Density</u>	<u>4 Term Resistivity</u>
N001	19.31	2.35	2.49	29.21
N010	15.25	2.53	2.58	24.70
N019	19.07	2.52	2.61	15.96
N024	22.46	2.59	2.52	4.35
N025	22.79	2.55	2.59	5.36
N032	14.46	2.72	2.93	22.84
N039	19.41	2.56	2.53	9.65
N-40	12.91	2.57	2.68	38.45
N-42	7.81	2.55	2.34	26.49
N-43	13.32	2.0	2.01	22.62
N-44	8.20	2.29	2.32	86.79
N-45	7.65	2.42	2.44	59.66
N-46	9.29	2.70	2.55	15.79
N-47	10.09	2.57	2.36	14.79
N-48	16.61	2.53	2.60	12.60
N-49	22.90	2.58	2.64	6.97
N-50	16.84	2.56	2.58	16.32
N-52	4.83	2.43	2.54	63.57
N-53	6.92	2.53	2.64	88.41
N-54	9.09	2.55	2.67	34.14
N-55	5.68	2.34	2.39	46.66
N-56	14.68	2.45	2.54	20.60
N-58	7.82	2.59	2.66	42.94
N-59	24.30	2.55	2.59	14.28
N-60	6.85	2.63	2.65	37.53
N-61	30.46	2.57	2.38	2.30
N--A	17.63	2.59	2.55	10.22
N--B	4.14	2.52	2.49	47.28
N--C	14.40	2.54	2.51	17.96
N--D	17.40	2.57	2.58	9.64
N--E	11.26	2.56	2.58	47.24
N--F	17.11	2.65	2.67	19.77
N--H	7.86	2.54	2.66	45.86
N--J	8.61	2.56	2.62	48.43
N--K	15.69	2.34	2.36	15.43
N--L	11.29	2.61	2.62	11.74
N--M	12.03	2.71	2.73	9.37
N--N	13.54	2.53	2.65	13.72
N--O	18.43	2.48	2.53	19.95
N--Q	13.56	2.80	2.75	32.06
N--R	16.32	3.47	2.49	17.24
N-41	5.35	2.57	2.40	50.87

TABLE 1
 PHYSICAL PROPERTIES OF ROCKS FROM SUITE N
 From South Central Nevada

<u>Sample</u>	<u>Porosity</u>	<u>Bulk Density</u>	<u>Grain Density</u>	<u>4 Term Resistivity</u>
C-01	26.92	2.93	4.01	15.01
C-02	25.26	2.90	3.87	8.78
C-04	16.41	2.94	3.52	15.77
C-06	10.42	2.89	3.23	30.21
C-07	24.39	2.92	3.86	13.41
C-08	15.06	2.93	3.45	23.35
C-11	37.34	2.63	4.20	1.90
C-13	8.98	2.72	2.98	43.56
C-14	10.29	2.69	3.00	36.61
C-16	12.63	2.80	3.21	16.65
C-17	7.64	2.71	2.93	58.28
C-20	11.66	2.68	3.03	18.48
C-21	17.37	2.73	3.30	18.64
C-22	8.45	2.85	3.11	28.21
C-23	19.03	2.57	3.18	12.23
C-24	11.72	2.69	3.05	16.21
C-25	7.30	2.73	2.95	46.69
C-26	25.31	2.69	3.61	4.18
C-27	25.36	2.71	3.63	4.18
C-28	16.58	2.65	3.18	10.26
C-30	7.90	2.61	2.83	41.03
C-31	14.01	2.61	3.03	14.49
C-32	13.33	2.72	3.14	24.96
C-33	9.41	2.72	3.00	32.10
C-34	7.56	2.70	2.92	53.73
C-35	9.33	2.67	2.95	37.81
C-37	20.54	2.80	3.53	16.62
C401	23.49	2.92	3.82	24.19
C402	9.65	2.58	2.85	18.48
C-41	15.03	2.76	3.25	20.81
C-42	9.04	2.78	3.05	58.72
C-45	8.34	2.82	3.07	31.68
C-47	11.73	2.96	3.35	56.53
C-52	27.91	2.80	3.88	9.66
C-53	16.88	2.80	3.37	16.58
C-54	27.00	2.95	4.04	7.39
C-57	21.05	2.90	3.68	16.06
C-58	11.73	2.55	2.89	19.65
C-59	4.08	2.55	2.66	58.54
C602	34.98	2.73	4.20	5.88
C611	28.99	2.70	3.80	8.94
C612	28.56	2.68	3.76	13.01
C-62	13.52	2.91	3.36	21.63
C-63	13.71	2.89	3.35	22.70
C-64	20.43	2.80	3.52	16.99
C601	29.52	2.72	3.86	7.86

TABLE 2

PHYSICAL PROPERTIES OF ROCKS FROM SUITE C
From the Modoc Plateau, California

<u>Sample</u>	From the Columbia Plateau, Oregon			4 Term
	<u>Porosity</u>	<u>Bulk Density</u>	<u>Grain Density</u>	<u>Resistivity</u>
OR01	8.82	2.72	2.76	59.59
OR02	9.35	2.90	2.86	34.46
OR03	4.46	2.63	2.64	66.26
OR04	3.69	2.60	2.64	149.98
OR06	7.99	2.77	2.86	71.17
OR08	3.78	2.66	2.79	123.72
OR09	8.85	2.77	2.85	33.12
OR10	6.87	2.82	2.86	28.04
OR11	9.90	2.87	3.02	25.69
OR12	8.98	2.85	2.89	43.74
OR13	13.57	2.93	2.99	33.86
OR14	12.01	2.86	2.85	52.44
OR16	11.30	2.94	3.05	62.15
OR17	9.83	2.91	2.96	55.29
OR18	9.42	2.92	2.96	57.53
OR19	5.92	2.34	2.39	33.90
OR20	4.75	2.34	2.38	25.43
OR23	29.75	2.91	2.64	4.77
OR25	6.65	1.46	2.94	68.61
OR26	6.08	2.70	2.86	71.14
OR29	16.96	2.92	2.86	7.76
OR30	21.56	2.93	2.88	17.39
OR31	2.97	2.94	3.05	112.76
OR32	13.72	2.94	2.96	38.88
OR33	3.35	2.95	2.99	128.86
OR34	12.79	2.92	2.95	22.65
OR35	8.16	2.92	3.00	98.88
OR36	15.90	2.97	3.18	16.05
OR37	27.50	2.80	2.80	3.71
OR39	13.89	2.94	3.09	27.50
OR41	4.33	2.92	2.95	93.25
OR43	3.79	2.92	2.97	142.41
OR44	19.70	2.96	2.98	10.02
O244	22.88	2.95	3.12	35.58
OR45	6.44	2.90	2.90	58.01
OR46	7.58	2.85	2.82	26.31
OR47	3.81	2.82	2.86	131.58
OR48	3.76	2.82	2.87	144.16
OR50	16.78	2.85	2.97	40.42
OR57	5.82	2.81	2.86	47.81
OR51	18.88	2.83	2.86	35.62
OR52	7.34	2.82	2.86	57.43
OR58	9.68	2.94	3.00	75.60
OR60	12.22	2.86	2.89	19.64
OR62	7.06	2.91	3.04	75.70
OR-A	25.38	2.78	2.51	7.28
OR-B	18.90	2.89	2.70	22.01
OR-C	23.86	2.98	2.99	9.22
OR-D	26.49	2.90	2.68	5.03
OR-E	7.79	2.93	2.93	44.91
OR-F	39.79	2.77	8.21	17.67
OR-G	5.24	2.95	2.90	73.51
OR-H	8.26	2.70	2.66	42.21
OR-I	4.76	2.88	2.86	180.67
OR-J	4.22	2.68	2.73	191.92
OR-K	4.07	2.67	2.71	90.67
OR-L	7.13	2.63	2.59	23.29
OR-M	33.89	2.93	2.89	2.25
OR-N	9.14	2.86	2.90	43.10
OR-O	4.75	2.89	2.97	62.76

<u>Sample</u>	<u>Porosity</u>	<u>Bulk Density</u>	<u>Grain Density</u>	<u>4 Term Resistivity</u>
I--1	10.23	2.97	2.87	18.62
I--2	13.06	3.04	2.93	20.57
I--3	15.96	3.00	3.09	31.14
I--5	22.00	2.97	3.00	19.90
I--7	40.30	2.92	2.96	1.92
I-18	17.83	3.02	3.11	22.14
I-21	5.94	2.96	2.95	66.83
I-22	7.16	2.97	3.04	30.13
I-24	19.28	2.95	2.92	7.50
I-26	22.33	2.97	2.48	17.36
I-29	30.58	2.98	2.93	2.42
I-30	6.13	2.91	3.03	87.20
I-31	17.63	3.00	3.14	32.44
I-32	11.00	3.01	3.17	56.37
I-34	16.80	3.01	3.04	15.33
I-35	8.98	3.00	3.14	41.82
I-36	9.70	2.98	3.07	49.08
I-37	5.22	3.00	3.06	79.71
I-38	8.48	2.53	2.63	47.10
I-39	8.73	2.50	2.61	32.67
I-43	5.30	2.42	2.44	29.41
I-44	10.16	2.46	2.42	8.67
I-46	11.82	2.47	2.55	21.57
I-47	5.02	2.39	2.51	29.83
I-48	5.52	2.46	2.47	17.45
I-49	9.25	2.46	2.55	17.76
I-50	9.55	2.47	2.57	11.22
I-51	9.59	2.46	2.50	22.25
I-52	20.07	2.48	2.54	2.92
I-53	13.79	2.44	2.56	10.25
I-55	20.71	2.50	2.47	7.84
I-56	26.70	2.60	2.73	2.32
I-57	22.38	2.57	2.61	1.93
I-58	8.48	2.57	2.69	32.49
I-59	5.28	2.57	2.70	60.49
I-61	16.52	2.60	2.77	13.64
I-62	9.72	2.46	2.53	14.44
I-63	10.77	2.45	2.56	7.57
I-64	10.15	2.48	2.56	11.99

TABLE 4
PHYSICAL PROPERTIES OF ROCKS FROM SUITE I
From The Snake River Plain, Idaho

<u>Sample</u>	<u>Porosity</u>	<u>Bulk Density</u>	<u>Grain Density</u>	<u>4 Term Resistivity</u>
NM02	5.09	2.79	2.94	46.96
NM03	7.08	2.85	3.06	68.93
NM04	10.42	2.87	3.21	43.40
NM09	32.14	2.49	3.68	2.02
NM10	21.05	2.48	3.14	4.26
NM11	10.81	2.50	2.80	15.20
NM12	15.40	2.48	2.93	12.29
NM13	14.59	2.48	2.90	7.15
NM14	24.10	2.51	3.31	4.26
NM15	11.12	2.50	2.81	12.74
NM16	9.61	2.47	2.73	13.40
NM17	10.75	2.47	2.77	18.07
NM18	22.04	2.58	3.31	10.61
NM19	19.49	2.54	3.16	8.53
NM20	15.09	2.47	2.91	7.73
NM21	16.63	2.47	2.96	10.19
NM22	16.82	2.57	3.09	9.18
NM24	14.80	2.56	3.01	11.69
NM25	16.42	2.36	2.82	8.29
NM26	8.33	2.38	2.60	25.75
NM27	9.42	2.44	2.69	21.57
NM28	20.88	2.43	3.07	4.84
NM29	22.72	2.73	3.53	5.15
NM30	18.79	2.71	3.34	11.42
NM32	7.69	2.83	3.06	50.56
NM33	10.43	2.45	2.73	7.63
NM41	17.71	2.38	2.89	13.15
NM43	20.98	2.38	3.01	11.68
NM44	12.01	2.40	2.73	10.76
NM45	3.46	2.36	2.44	40.49
NM46	4.85	2.37	2.49	27.67
NM47	3.92	2.37	2.47	64.21
NM48	3.86	2.37	2.46	55.29
NM49	19.22	2.35	2.90	7.70
NM53	15.90	2.28	2.71	13.23
NM54	21.97	2.35	3.01	4.77
NM58	17.22	2.49	3.00	5.98
NM59	16.77	2.47	2.97	6.08
NM60	37.41	2.51	4.01	1.06
NM61	17.27	2.49	3.01	4.77
NM62	24.21	2.37	3.13	3.59
NM63	26.48	2.49	3.39	2.51

TABLE 6

PHYSICAL PROPERTIES OF ROCKS FROM SUITE NM

From The Jemez Mountains, New Mexico

<u>Sample</u>	<u>Porosity</u>	<u>Bulk Density</u>	<u>Grain Density</u>	<u>Resistivity</u>
0322	9.54	2.77	3.06	21.90
0C33	12.16	2.74	3.12	21.13
0C37	21.69	2.68	3.43	11.15
0C40	4.33	2.71	2.83	105.45
0411	8.31	2.65	2.89	18.90
0412	9.33	2.65	2.92	14.54
0C42	6.55	2.73	2.92	37.46
0C43	5.35	2.62	2.77	38.18
0C44	8.92	2.70	2.97	32.84
0C46	9.51	2.78	3.08	15.20
0C47	6.11	2.77	2.95	48.27
0C50	26.64	2.69	3.67	9.75
0C51	26.71	2.77	3.78	5.46
0C52	9.88	2.79	3.09	21.16
0C53	5.93	2.81	2.99	30.95
0C55	11.93	2.71	3.08	23.42
0C56	21.97	2.71	3.48	7.56
0C57	8.05	2.74	2.98	60.78
0C59	4.93	2.88	3.03	22.38
0621	12.38	2.94	3.36	26.43
0622	4.50	2.76	2.89	57.34
0C63	14.71	2.82	3.30	10.79
0C64	13.47	2.84	3.28	15.94
0C28	3.67	2.72	2.83	82.75
0C29	1.64	2.75	2.80	30.69
0C30	9.90	2.73	3.03	32.13
0C31	11.34	2.72	3.07	20.52
0321	7.47	2.72	2.94	49.24
0C01	4.85	2.81	2.96	48.85
0C02	18.64	2.81	3.46	10.09
0C03	14.67	2.81	3.30	10.48
0C04	15.55	2.84	3.36	9.93
0C05	20.67	2.72	3.43	3.49
0C06	6.29	2.73	2.92	12.50
0C07	17.10	2.69	3.24	6.46
0C08	15.91	2.69	3.20	7.68
0C91	11.15	2.68	3.01	9.15
0C92	13.44	2.69	3.11	9.18
0C10	20.33	2.70	3.39	4.97
0C11	9.29	2.86	3.15	15.45
0C12	16.42	2.83	3.39	9.93
0C13	21.10	2.76	3.50	9.00
0C14	13.39	2.78	3.21	16.96
0C15	14.57	2.65	3.10	14.71
0C17	23.86	2.59	3.40	7.65
0C18	22.69	2.50	3.23	7.86
0C22	1.61	2.68	2.72	66.24
0C24	7.47	2.66	2.87	28.22
0C25	16.36	2.57	3.07	8.93
0C26	4.96	2.59	2.72	45.40
0C27	6.06	2.55	2.72	34.18

TABLE 5

PHYSICAL PROPERTIES OF ROCKS FROM SUITE OC
FROM THE CASCADE RANGE

TABLE 7

ARCHIE'S LAW PARAMETERS

<u>ROCK GROUP</u>	<u>A</u>	<u>M</u>
N	0.81	2.23
OC	2.34	1.57
OR	2.09	1.86
NM	2.34	1.59
C	2.00	1.94
I	1.62	2.06

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- Figure 2: Cross plot for two-terminal and four-terminal resistivity measurements made on samples from the Columbia Plateau.
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- Figure 13: Linear regressions on a double Logarithmic scale for the scatter plots shown in Figures 7 - 12. Archie's Law with $a = 1$ and $m = 2$ is shown as a dashed line. Data previously reported for Hawaiian basalts and rhyolites from the Oak Springs formation (Miocene (?)) from southern Nevada are shown as the two dotted lines.

- Figure 14: Scatter plot of inverse wavespeeds (msec/km) and core porosities for samples from the Snake River Plain, Idaho. Inverse compressional wavespeeds are plotted on the upper graph, and inverse shear wavespeeds on the lower.
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FIGURE 1: Cross plot for two-terminal and four-terminal resistivity measurements made on samples from the Snake River Plain, Idaho.

FIGURE 2: Cross plot for two-terminal and four-terminal resistivity measurements made on samples from the Modoc Plateau, California.

FIGURE 3: Cross plot for two-terminal and four-terminal resistivity measurements made on samples from the Cascade Range.

FIGURE 4: Cross plot for two-terminal and four-terminal resistivity measurements made on samples from the Columbia Plateau in Oregon.

FIGURE 5: Cross plot for two-terminal and four-terminal resistivity measurements made on samples from south central Nevada.

FIGURE 6: Cross plot for two-terminal and four-terminal resistivity measurements made on samples from the Jemez Mountains in New Mexico.

FIGURE 7: Scatter plot of core porosities and formation factors for measurements made on samples from the Columbia Plateau.

FIGURE 8: Scatter plot of core porosities and formation factors for measurements made on samples from the Modoc Plateau.

FIGURE 9: Scatter plot of core porosities and formation factors for measurements made on samples from the Cascade Range.

FIGURE 10: Scatter plot of core porosities and formation factors for measurements made on samples from the Columbia Plateau in Oregon.

FIGURE 12: Scatter plot of core porosities and formation factors for measurements made on samples from the Jemez Mountains in New Mexico.

FIGURE 13: Linear regressions on a double Logarithmic scale for the scatter plots shown in Figure 7-12. Archie's Law with a $a = 1$ and $m = 2$ is shown as a dashed line. Data previously reported for Hawaiian basalts and rhyolites from the Oak Springs formation (Miocene (?)) from southern Nevada are shown as the two dotted lines.

FIGURE 14: Scatter plot of acoustic wavespeeds and core porosities for samples from the Snake River Plain, Idaho. Inverse compressional wavespeeds are plotted on the upper graph, and inverse shear wavespeeds on the lower.

FIGURE 15: Scatter plot of inverse wavespeeds (msec/km) and core porosities for samples from the Modoc Plateau in California. Inverse compressional wavespeeds are plotted on the upper graph, and inverse shear wavespeeds are plotted on the lower.

FIGURE 16: Scatter plot of inverse wavespeeds (msec/km) and core porosities for samples from the Columbia Plateau in Oregon. Inverse compressional wavespeeds are plotted in the upper graph, and inverse shear wavespeeds are plotted on the lower.

FIGURE 17: Scatter plot of inverse wavespeeds (msec/km) and core porosities for samples from south central Nevada. Inverse compressional wavespeeds are plotted on the upper graph, and inverse shear wavespeeds are plotted on the lower.

FIGURE 18: Scatter plot of inverse wavespeeds (msec/km) and core porosities for samples from the Cascade Range. Inverse compressional wavespeeds are plotted on the upper graph, and inverse shear wavespeeds are plotted on the lower.

FIGURE 19: Example of variation in resistivity with temperature. Sample 1~~4~~ from the Cascades.

FIGURE 20: Example of variation in resistivity with temperature. Sample is from the Modoc Volcanic Province.

FIGURE 19: Example of variation in resistivity with temperature. Sample is from the Cascades.

FIGURE 20: Example of variation in resistivity with temperature. Sample is from the Modoc Volcanic Province.