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RESEARCH ON THE PHYSICAL PROPERTIES OF GEOTHERMAL RESERVOIR ROCKS

Progress Report 2

Research on the Physical Properties of Volcanic Rocks

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RESEARCH ON THE PHYSICAL PROPERTIES OF GEOTHERMAL RESERVOIR ROCKS

Report of Progress During the Period from
September 1, 1976 to January 10, 1977

INTRODUCTION

In the art of interpretation of geophysical well surveys, empirical correlations between pairs of physical properties of rocks are used. These correlations permit measurements made of one physical property in a well bore to be interpreted in terms of another physical property which is of more significance in evaluating the reservoir behavior of a rock. Often, these correlations are developed through a series of laboratory measurements because the properties which are needed in evaluating a reservoir cannot be measured directly with the rock in place. In the evaluation of oil and gas reservoirs, interpretations based on such an approach have reached a high degree of development.

With a growing geothermal industry, it is likely that geophysical well surveys can play an equally important role in estimating the performance of geothermal reservoirs. However, this will require the development of correlations between physical properties for the rock types that are commonly found in geothermal reservoirs. Existing correlations developed for the oil and gas industry apply only for those rocks in which oil and gas are commly found, such as clastics and carbonates.

Some geothermal reservoirs also may occur in such rock types, but probably a larger fraction will occur in volcanic rocks and in metasedimentary rocks. This report describes research being carried on at the Department of Geophysics, Colorado School of Mines under contract to the Energy Research & Development Administration to address the problem of interpretation of geophysical logs in volcanic rocks.

The intent of the study is to establish correlations between measurable properties such as electrical resistivity and acoustic wave speed, and properties which need to be known, such as porosity, water salinity, temperature, and well productivity. The first stage of the study was collection of suites of samples from extensive Cenozoic volcanic fields in the western United States, fields which might reasonably be expected to serve as reservoir rocks. Sampling was carried out during the summer of 1976 in the Snake River Plain volcanic field, the Columbia Plateaus volcanic field, the Cascade Range, the Modoc Volcanic Province, the central Nevada volcanic field and the Jemez volcanic field. The geologic setting of these fields and the strategy used in collecting samples has been described in the preceeding progress report.

During the period from September 1, 1976 to January 10, 1977, a major part of the effort has been in preparing samples for laboratory measurements of physical properties. The field samples consisted of rough blocks of rock with dimensions of several tens of centimeters. From each of these field samples, one to three core plugs were cut. These plugs are cylindrical in shape, with a diameter of 1.6 centimeters and a length ranging from three to six centimeters. The shape and size of the samples was dictated to a considerable extent by the requirements for sample holders used in making measurements of acoustic wave speed.

Following preparation of the core plugs, a variety of physical properties was measured at laboratory ambient conditions; that is, at approximately 20° centigrade 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 by a simple water saturation technique. In this, the samples were first dried at a temperature of approximately 105° C. Dry weight was determined by weighing the samples at this elevated temperature. 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 at atmospheric pressure for a prolonged period of time, ranging from several days to several weeks. This procedure can be expected to result in the saturation of 95 to 98% of the connected pore space. Vacuoles and other pore spaces separated from the pore structure by impermeable barriers is not saturated and for the purposes of this study cannot be considered as being part of the porosity of the rock.

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

The volume of each sample was determined in two ways. The volume is determined approximately by measuring the dimensions of the sample and calculating the volume. A more exact determination of volume was made by weighing each sample while suspended in a beaker of water. The loss of weight with respect to measurements made on the wet samples in 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.

Resistivity Measurements

Two sets of resistivity measurements were made. In the first set, the samples were saturated with distilled water. The resistivity was then measured using a two-terminal method, in which the resistance to current flow through the sample was observed. The two-terminal method of measuring resistance is very convenient, but is sometimes subject to errors caused by contact resistance at the ends of the samples. Experiments indicated that the amount of error caused by this contact resistance is a few ohms. The relatively high resistivity of the volcanic samples combined with the use of samples with a high length to diameter ratio minimized the error caused by contact resistance. It almost certainly did not exceed 1 or 2% of the measured resistance value.

The resistivity was computed from measured resistance and the dimensions of the samples.

After measurements were made with distilled water in the pores, the samples were dried and resaturated with a 1-normal solution of sodium chloride. Resistivities were determined a second time for this higher salinity. The need for the two measurements is as follows. When samples were taken from the field, no information was available about the salinity of the original water content. When the samples were dried, it is obvious that any original salt in the pore spaces would have remained. On resaturation, this salt will go back into solution and possibly contribute significantly to the salinity of the water in a pore space. By making measurements first with the sample saturated with distilled water and then with samples saturated with a known solution, the amount of original salinity can be calculated, and if necessary, a correction can be made to the second measurement of resistivity. The data have indicated that original salinities in the pore space amount to less than 1% of a 1-normal solution and so are negligible in terms of affecting the accuracy of the second measurement. It is likely that the original salinity actually represents cation exchange capacity of the rocks rather than salts present in the rocks. This is reasonable, inasmuch as all samples were surface samples which have probably been washed clean of salts by rainfall.

The conventional means of correlating resistivity measurements with porosity consists of forming a quantity known as formation factor. The formation factor is the ratio of the bulk resistivity of a rock to the resistivity of the solution saturating its pore spaces. If measurements are done correctly, the formation factor is independent of the salinity of the water in the pore spaces, and represents the geometric distribution of electrical conduction paths through the rock. It has been observed that in ordinary oil and gas reservoir rocks, such as limestones and sandstones, the formation factor is simply related to porosity through an empirical relationship known as Archie's Law:

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

Here, the symbol ϕ indicates the fractional pore space, F is the formation factor as defined above, and the parameters a and m are derived empirically to make the expression fit a given set of observed data. Normally, for clastic rocks, the coefficient a has a value between 0.6 and 1, and the parameter m has a value between 1.6 and 2.0.

If measurements of porosity and formation factor are plotted to logarithmic coordinates, Archie's Law will be represented by a straight line. To test whether or not Archie's Law reasonably represents the measurements on volcanic rocks, such plots have been prepared for 5 of the 6 rock suites studied and are included in this report as Figures 1 through 5. On each of these plots a solid line is drawn representing Archie's Law for maximum reasonable values of the parameters a and m, which are 1.0 and 2.0, respectively. It is important to note that in all cases the values of formation factor measured on these volcanic rocks are considerably higher than the highest values observed for clastic rocks over the same porosity range. This means that for a given porosity and for a given water salinity, the electrical resistivity of a volcanic rock will be 3 to 10 times higher than a similar clastic rock.

Measurements of Acoustic Wave Speed

Acoustic wave speeds for both compressional and shear modes of transmission were also determined on each of the samples. The measurements were made by mounting a 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 the second set of transducers. Two sets of transducers could be used, one of which excited compressional waves travelling along the sample, and the other which excited torsional waves travelling along the sample. The transmitted pulse and the vibrations received at the other end of the sample are displayed on a two-trace oscilloscope. The travel time for the acoustic waves through a sample is determined by moving the time base on 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, particularly a volcanic rock, it is necessary to compress the rock under a substantial pressure. In the system which we have used, the frame pressure and the confining pressure can be controlled separately. The 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 amounted to 1,000 pounds per square inch.

For clastic rocks, a simple relationship between acoustic wavespeed and porosity has often been used in evaluating well logs. This is a time averaging formula developed originally by M. R. J. Wyllie at Gulf Research Laboratories. If a rock consists of two phases, one a mineral, and the other a liquid, the speed of propagation for acoustic waves can reasonably well be approximated by considering that the energy has to flow through the two phases in sequence. The travel time is then the sum of the travel times through each of the two phases. The wavespeed observed for a sample lies someplace between a maximum wavespeed which would be observed in a rock with no porosity and a minimum wavespeed which would be observed in a rock with 100% porosity. Wyllie's relationship would plot as a straight line if porosity and velocity are plotted to linear co-ordinates.

We soon realized that the measurements we have made did not fit well with the Wyllie relationship and so have not presented such plots. Instead, compressional and shear wavespeeds are shown plotted as scatter plots against porosity on Figures 6 through 15, accompanying this report.

It is important to note that there is at best only a weak dependence between acoustic wavespeed and porosity in the samples which we have measured. The compressional wavespeeds are relatively high, with inverse wavespeeds being in the range 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. Because of the very small change in wave with porosity, these apparent changes may be in part a consequence of experimental error. The incompressibility of a sample can be expected to decrease with increasing porosity. Under a frame pressure of 1,000 pounds per square inch, there may be a shortening of the samples, and this has not been taken into account in the determinations of velocities made so far.

The results obtained so far indicate that acoustic velocity measurements cannot be used as a guide to porosity in volcanic rocks.

Effect of Temperature on Physical Properties.

At the time this report is being prepared, only an experimental effort has been done in making measurements of the properties of these samples as a function of temperature. The immediate objective is to devise equipment and a measurement scheme which will permit reliable determinations of physical properties at temperatures between laboratory ambient and laboratory boiling point. Temperature control appears to be a relatively minor problem. In the acoustic wavespeed measurements, temperature can be controlled precisely by heating the oil reservoir around the sample holder. In measuring formation factor, a somewhat more complicated procedure will probably need to be devised. At present, we have developed a nonmetallic Hassler sleeve core holder for the resistivity measurements. In the Hassler sleeve, a core is mounted inside a rubber tube which in turn is contained within a rigid tube. The rubber tube is lightly pressured with a nitrogen supply so that it forms a close contact with the rock sample and prevents escape of water. Measurements of resistance are made using wire mesh electrodes installed near the end of the sample but not in immediate contact with it. Contact between the electrodes and the sample is made through a water saturated paste.

The reason for this fairly complicated resistivity cell is that we plan to use a microwave induction heating device to increase the temperature of the sample in a series of steps from laboratory ambient to laboratory boiling. The microwave heating device operates by inducing current flow in any conductive material within the microwave field. Thus, the sample holder must be nonmetallic or any metal parts such as the electrodes must not lie in direct contact with the sample. Any metal in contact with the sample will lead to local heating. An advantage of microwave heating is that it introduces the desired amount of energy uniformly through the sample as it is irradiated. Other heating processes require conduction of heat from the outside of the sample to the center and this can be very slow.

To date, measurements have been carried out on only a single sample as a function of temperature. For the resistivity measurements, the resistivity decreased by a factor of approximately 3 over the temperature range from 20° C. to 97° C. With further heating, the resistivity increased as water was converted to steam in the pore space. At this stage, no effort was made to make careful determinations of the steamwater ratio. It should be pointed out that the variation in resistivity is that which one would expect on the basis of the change in properties of the electrolyte alone. No significant second order effects caused by interaction between the electrolyte and the rock framework were expected, and none was apparent.

A similar set of measurements of acoustic wavespeed was made on a single sample as the temperature was raised from 20° C. to the boiling point. Somewhat to our surprise, the compressional wavespeed did not change by more than 1% until the boiling point was reached. On dehydration, a relatively small change in compressional wavespeed was observed.

PLANS

As indicated in our original proposal for this project, a major objective is determining the effect of temperature and of the conversion of water to steam on the physical properties of volcanic rocks. Measurements will be made of both acoustic wavespeeds and formation factor as a function of temperature and steam saturation. However, considering the results obtained so far, we expect to place less emphasis on the acoustic velocity measurements than on the formation factor measurements. At this stage, we believe that a relatively limited number of measurements will show that over the temperature ranges that we are operating, that acoustic velocity is relatively unaffected by temperature, and that the information obtained from borehole measurements of acoustic velocity may not be useful in estimating temperature or water content in volcanic rocks.

With measurements of formation factor, up to the boiling point, it is likely that the effect of temperature can be taken into account merely by applying a temperature correction based on the properties of the electrolyte. However, when pore space is partially saturated with water vapor, it must yet be established whether the behavior of the rock is the same as in the cases where water is displaced by gas or oil, or if there is a significant difference. One may expect some difference, based on the differences in wetabilities of the nonwater phase in the various cases. The shape of the remaining water saturation when a sample is saturated with two phases will depend on the surface tension between the two phases, and the angle of absorption when the two phases are in contact with the solid mineral. All of these factors may be quite different in volcanic rock than in the normal oil and gas reservoir rock. Thus, we plan to make careful measurements of the change in resistivity as steam displaces water in the pore spaces of these samples.

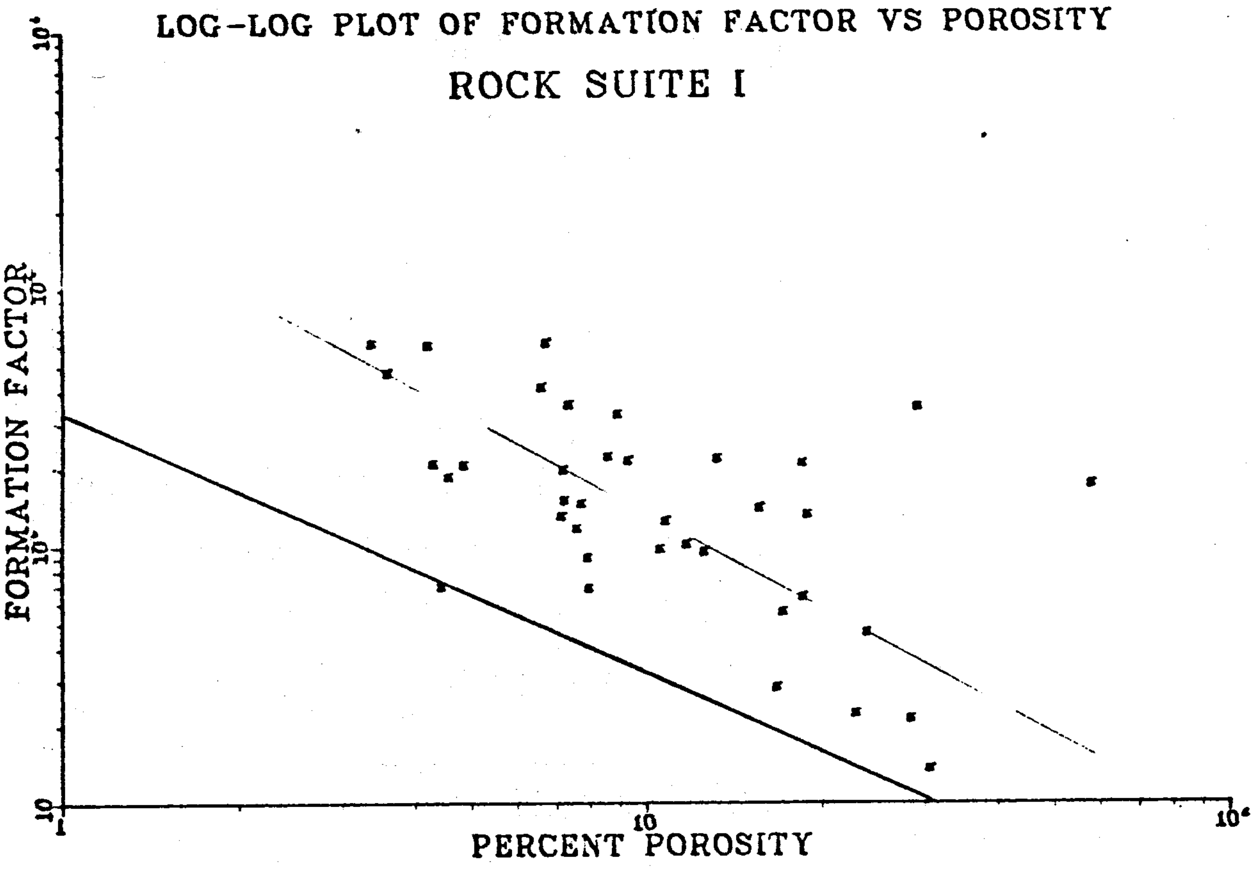

Figure 1. Scatter plot of formation factors and porosities for samples gather in the Snake River Plain volcanic field. The solid line is Archie's law for m= 2 and a= 1.

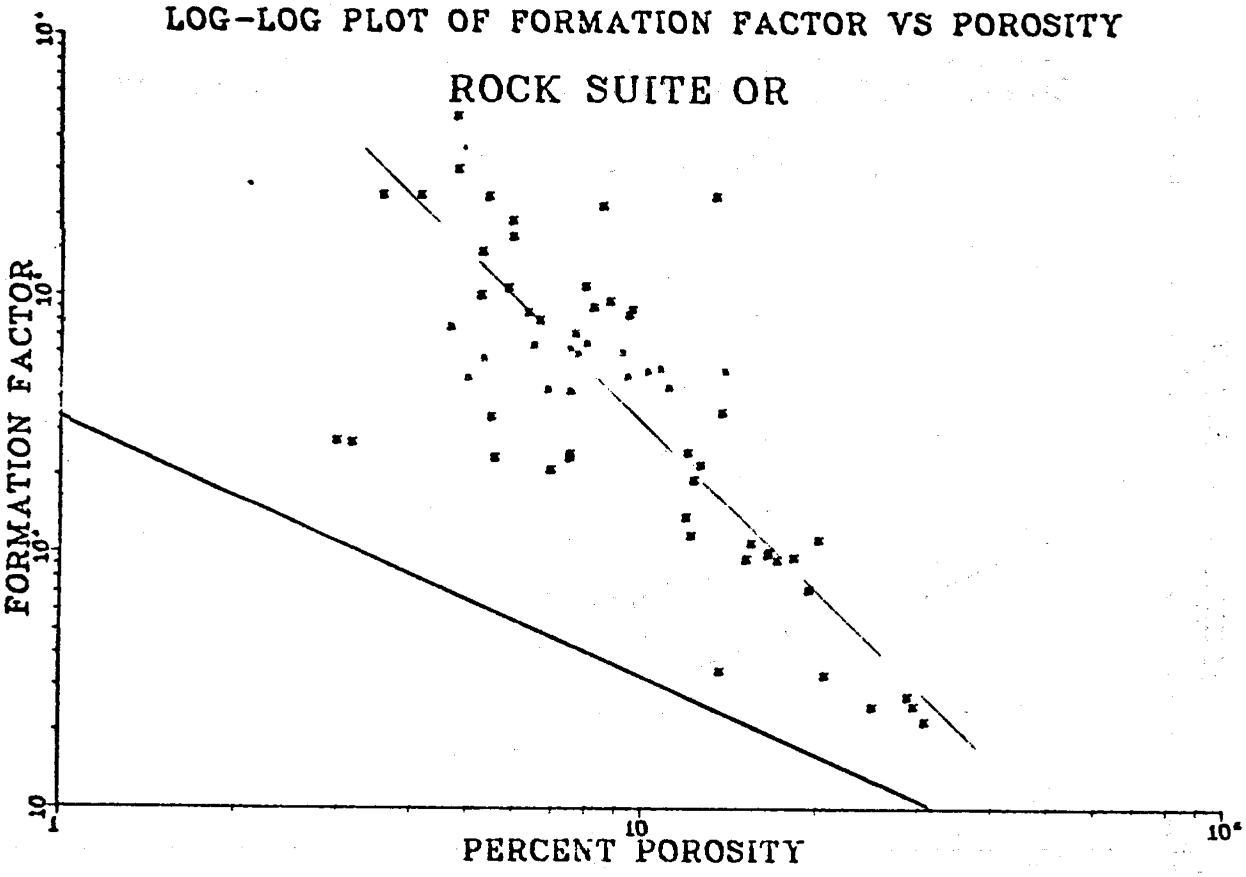

Figure 2. Scatter plot of formation factors and porosities for samples gathered on the Modoc Plateau volcanic field in Oregon. The solid line is Archie's law for m= 2 and a= 1..

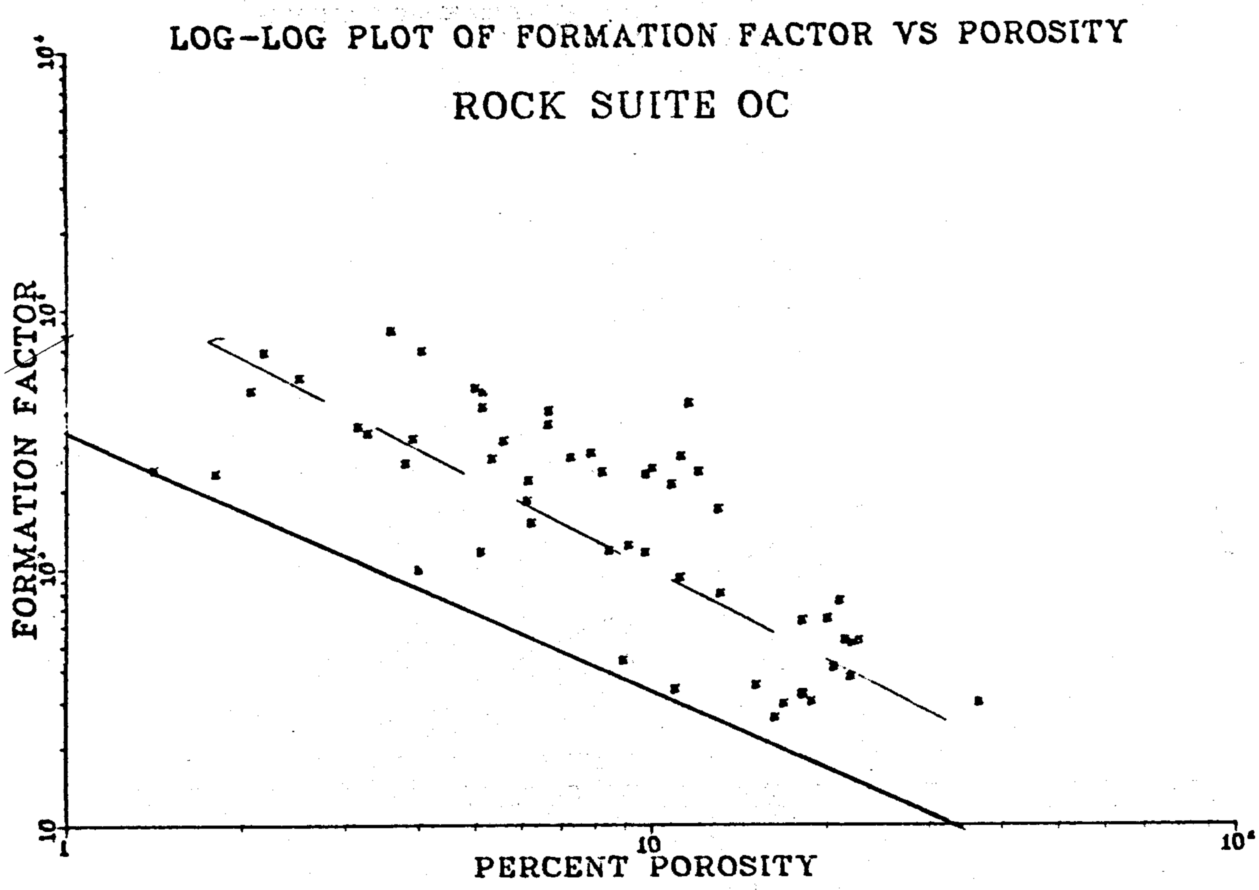

Figure 3. Scatter plot of formation factors and porosities for samples gathered in the Cascade Range of Oregon. The solid line is Archie's law for m= 2 and a= 1.

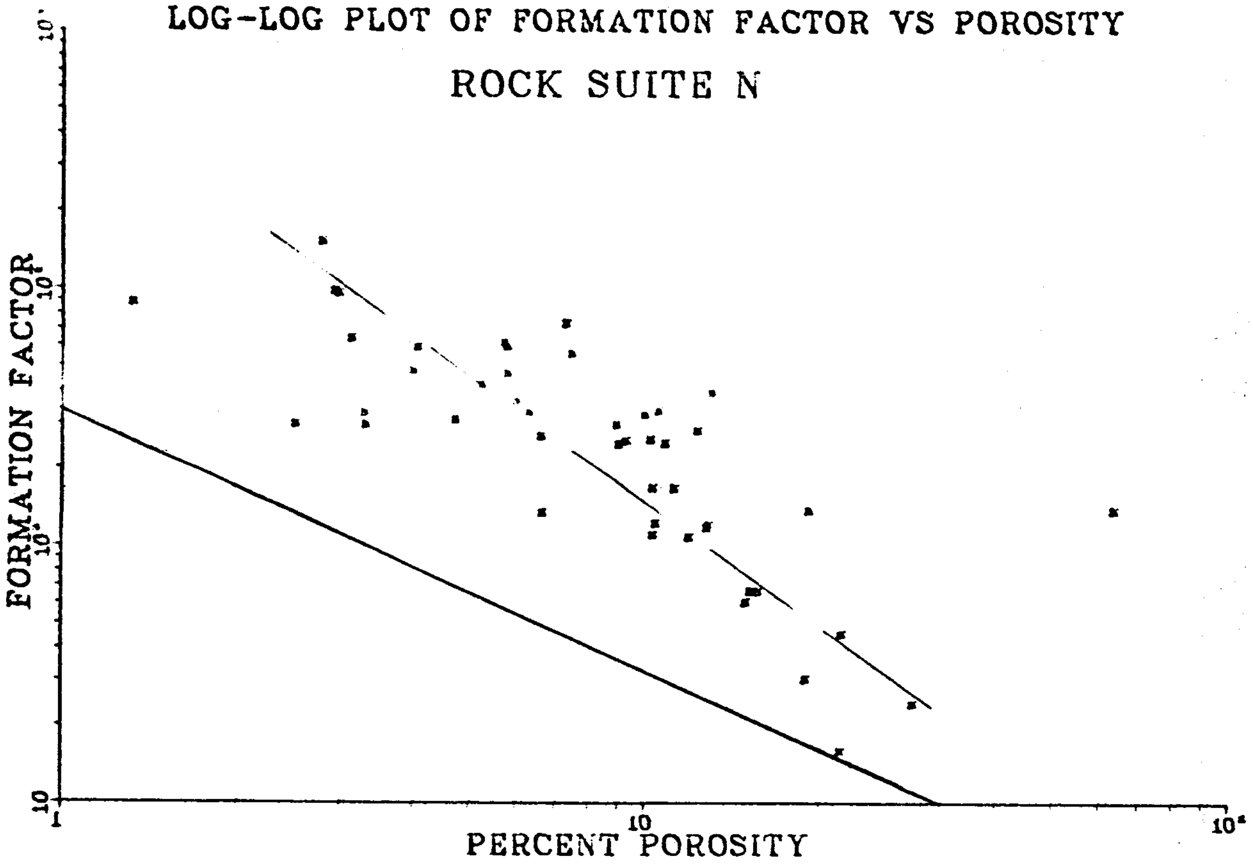

Figure 4. Scatter plot of formation factors and porosities for samples of volcanic rock obtained in central Nevada. The solid line is Archie's law for m= 2 and n= 1.

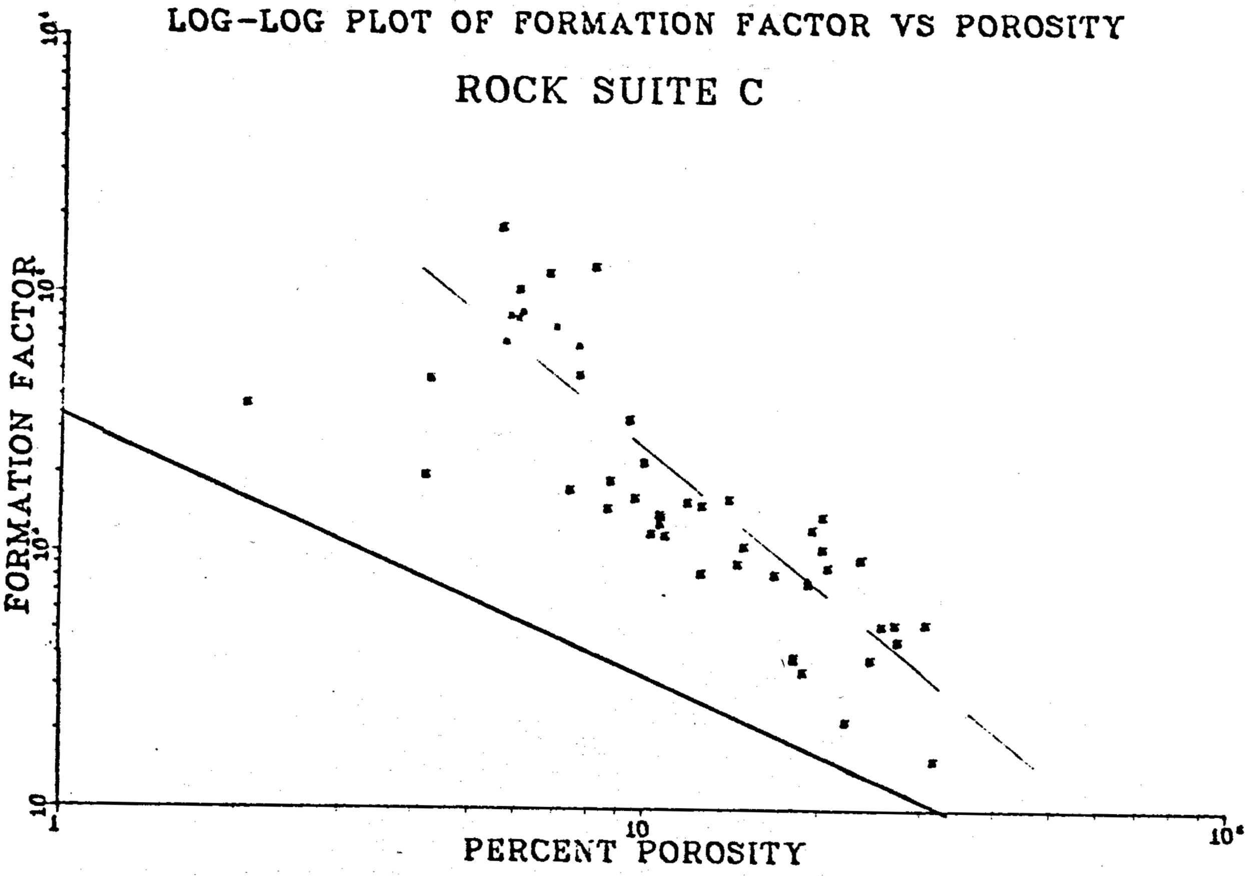

Figure 5. Scatter plot of formation factors and porosities for samples from the Columbia Plateaus volcanic field. The solid line is Archie's law for m= 2 and a= 1.

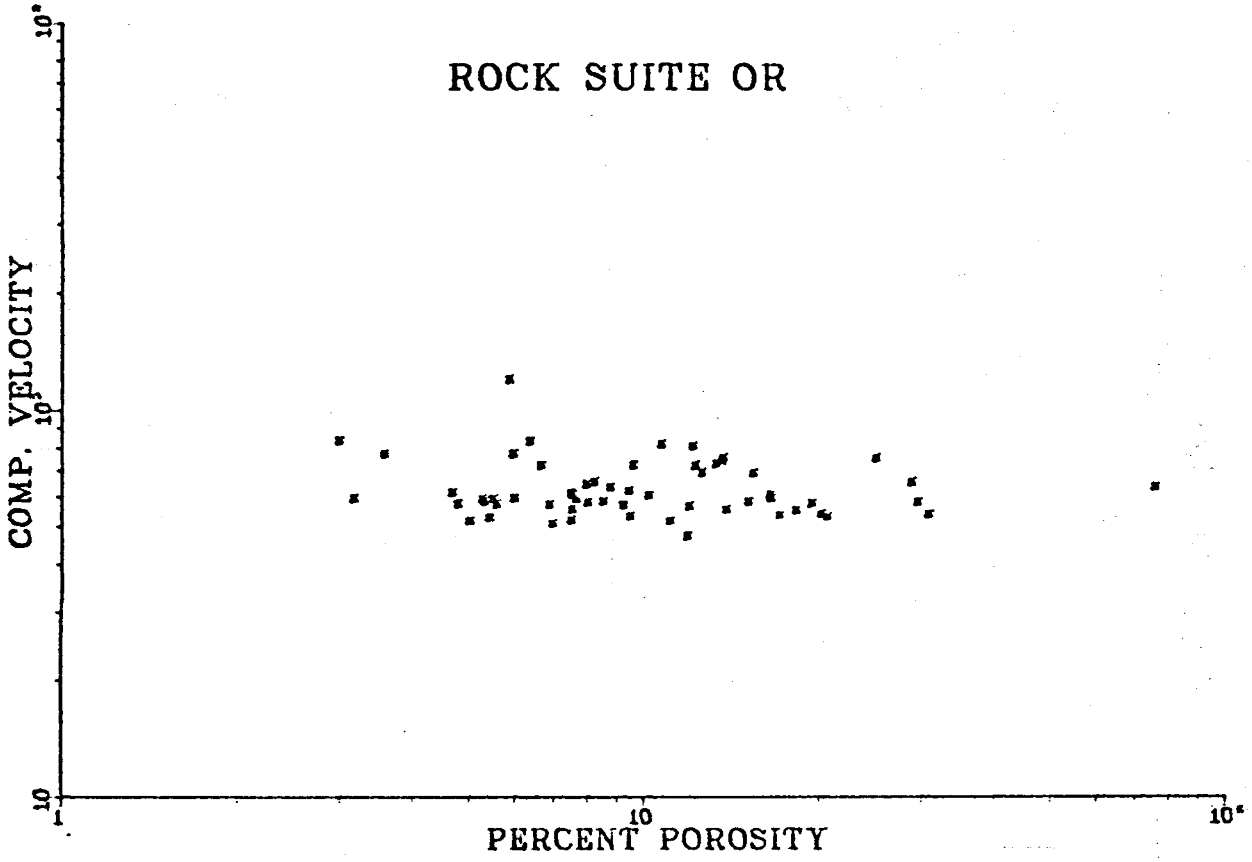

Figure 6. Scatter plot of compressional wavespeeds and porosities for samples from the Modoc Plateau volcanic field. The vertical scale is in microseconds per foot.

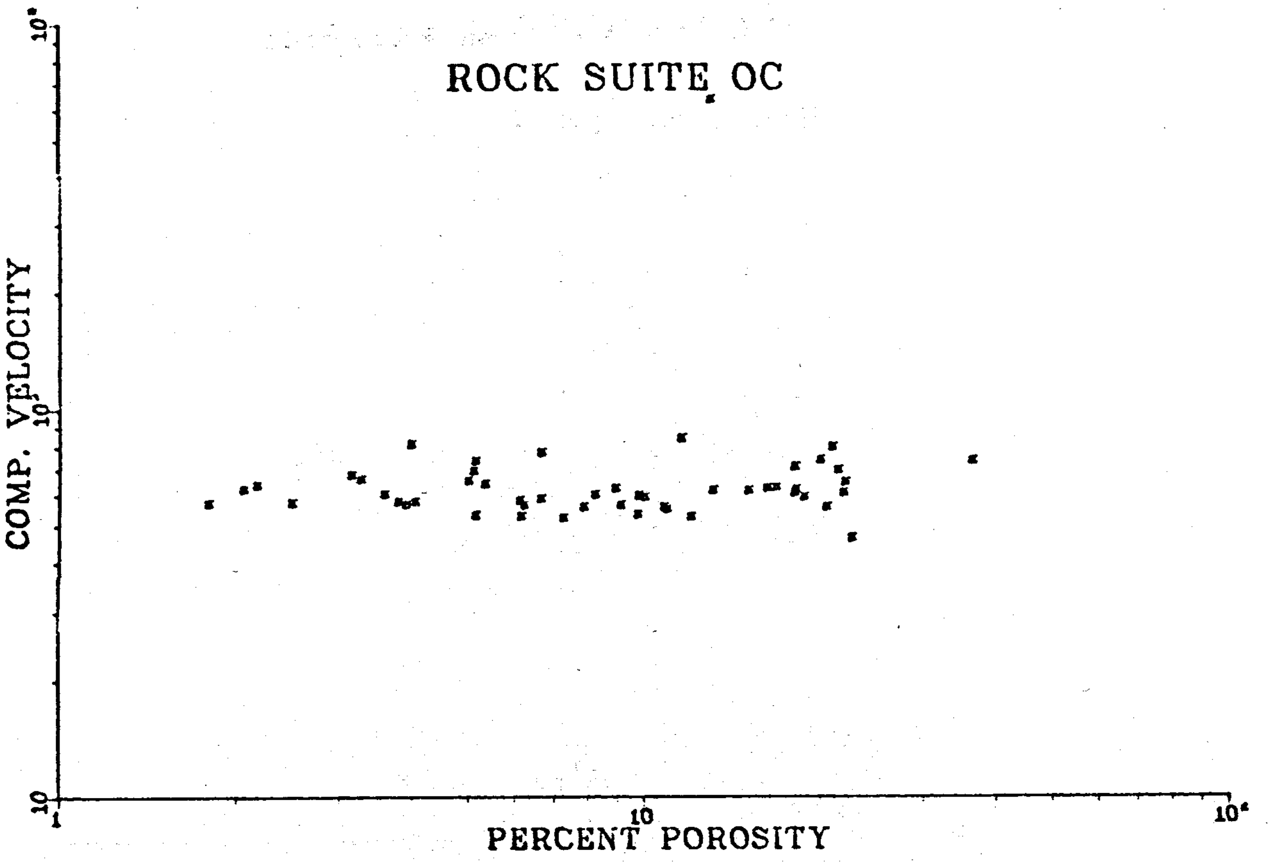

Figure 7. Scatter plot of compressional wavespeeds and porosities for samples from the Cascade Range in Oregon. The vertical scale is in microseconds per foot.

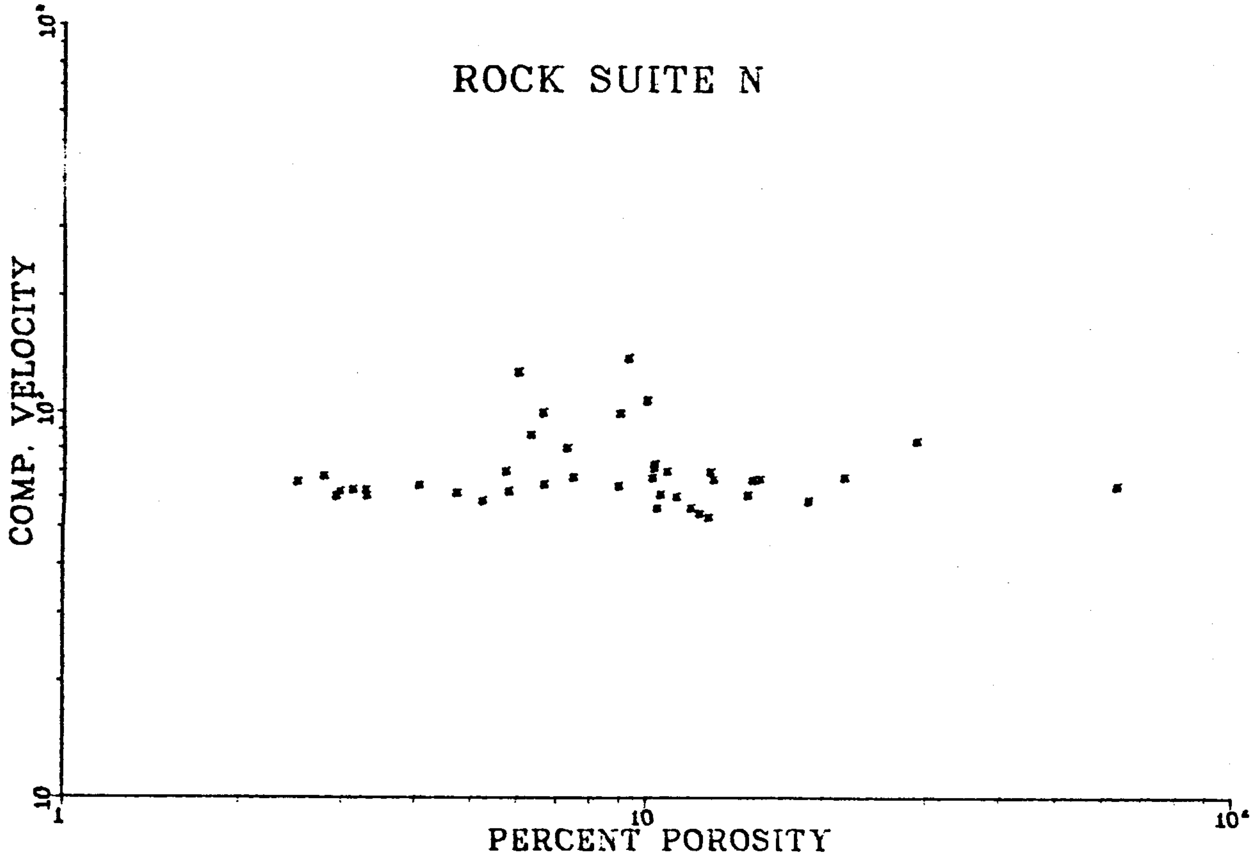

Figure 8. Scatter plot of compressional wavespeeds and porosities for volcanic samples from central Nevada. The vertical scale is in microseconds per foot.

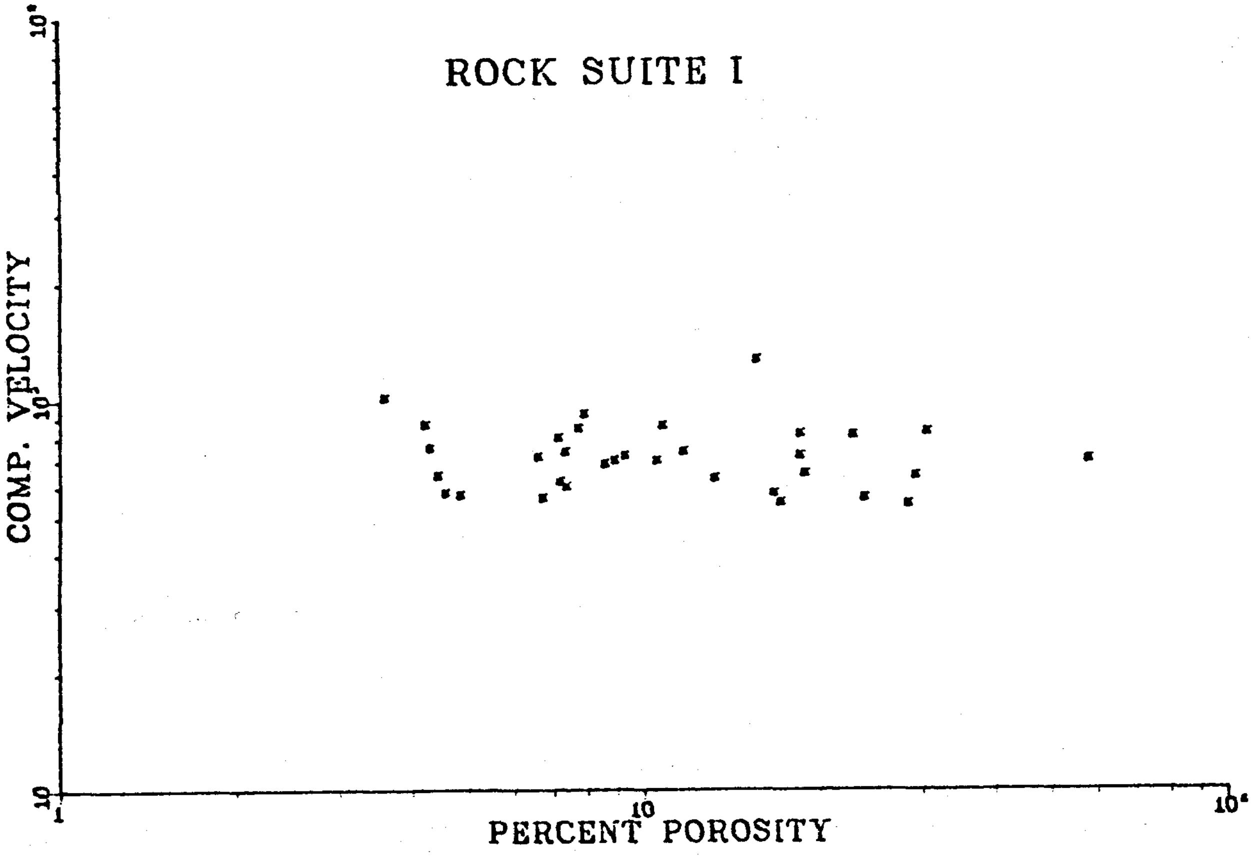

Figure 9. Scatter plot of compressional wavespeeds and porosities for volcanic samples from the Snake River Plain. The vertical scale is in microseconds per foot.

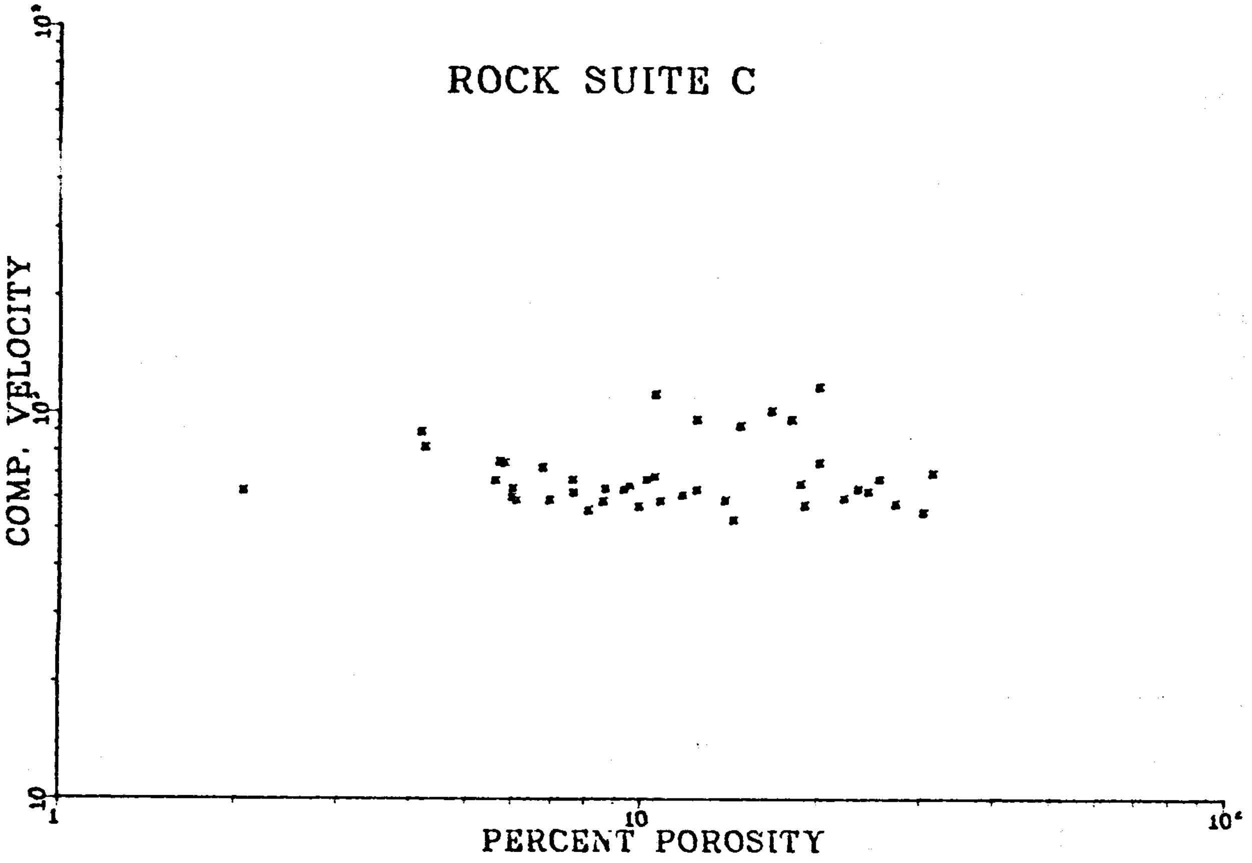

Figure 10. Scatter plot of compressional wavespeeds and porosities for volcanic samples from the Columbia Plateaus. The vertical scale is in microseconds per foot.

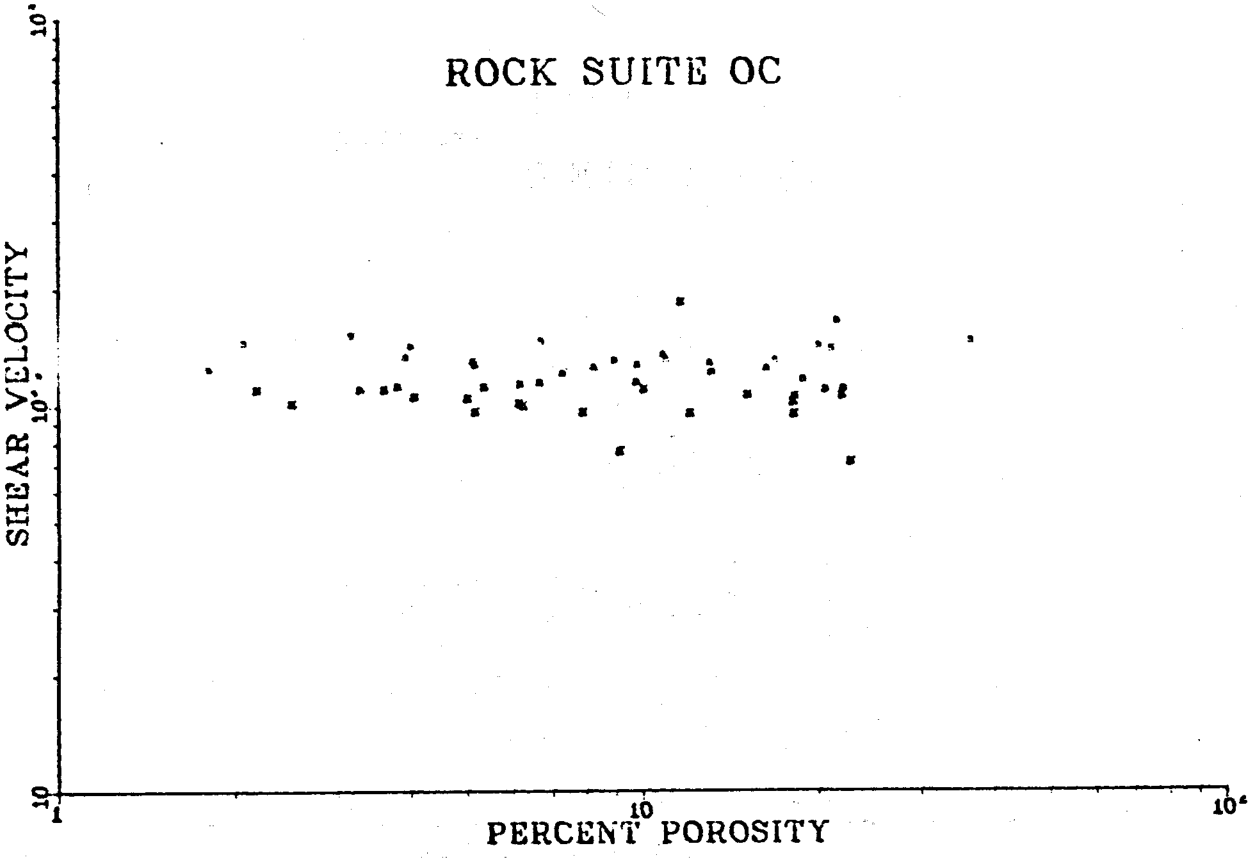

Figure 11. Scatter plot of shear wavespeeds and porosities for samples from the Cascade Range in Oregon. The vertical scale is in microseconds per foot.

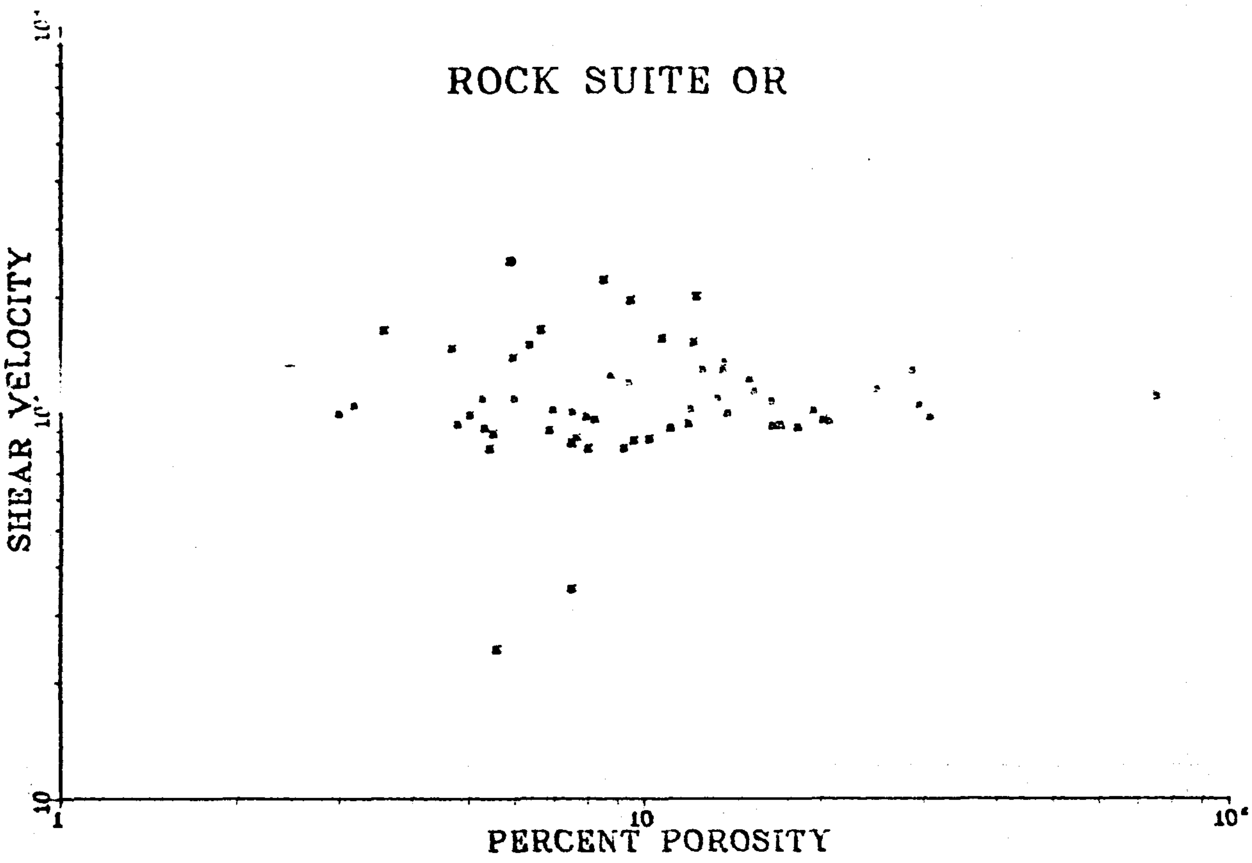

Figure 12. Scatter plot of shear wavespeeds and porosities for samples from the Modoc Plateau Volcanic Field. The vertical scale is in microseconds per foot.

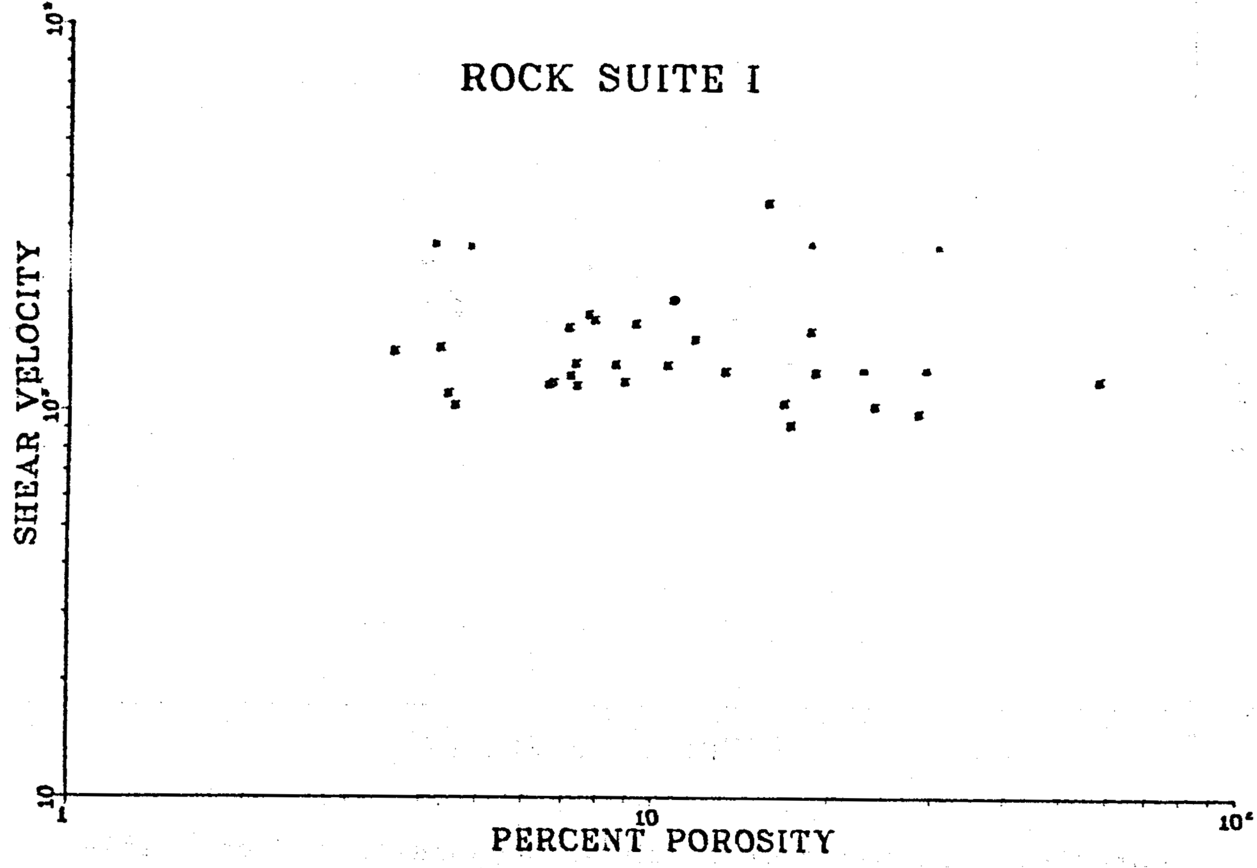

Figure 13. Scatter plot of shear wavespeeds and porosities for samples from the Snake River Plain. The vertical scale is in microseconds per foot.

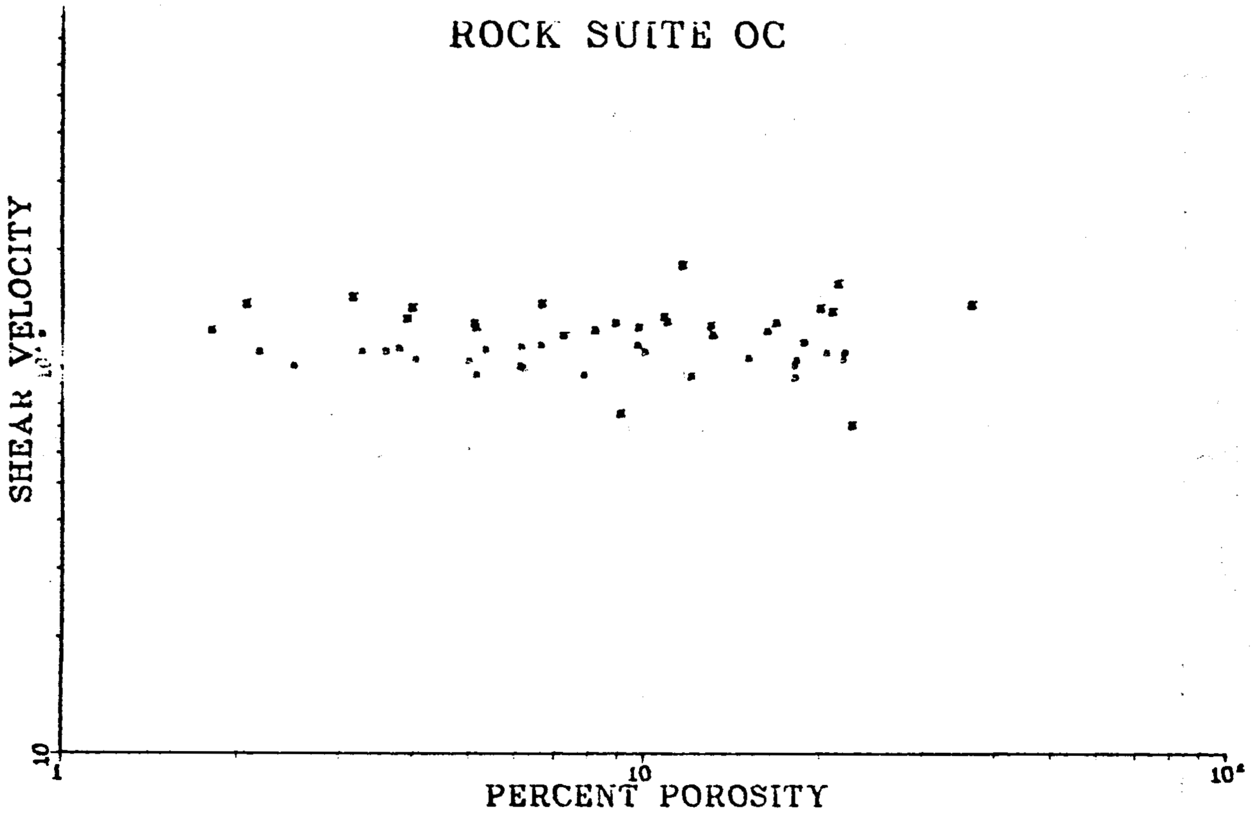

Figure 14. Scatter plot of shear wavespeeds and porosities for samples from the Cascade Range of Oregon. The vertical scale is in microseconds per foot.