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RESEARCH ON THE PHYSICAL PROPERTIES OF GEOTHERMAL RESERVOIR ROCK

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DISCLAIMER

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RESEARCH ON THE PHYSICAL PROPERTIES OF GEOTHERMAL RESERVOIRS

ABSTRACT

A laboratory study of the P-wave velocity and electric resistivity has been undertaken on Cenozoic volcanic rocks collected from the Columbia Plateau volcanic basin (C) and the Jemeze volcanic field (NM). Electric resistivities of cylindrical samples saturated with 0.1 N NaCl solution were measured using a four electrode system and a 1.0 KHz frequency source. Seismic P-wave velocities were calculated from measured transit time of mechanical pulses generated and received by piezoelectric transducers. Measurements were performed at atmospheric pressure. Inductive heating of samples utilizing a microwave oven proved efficient in heating samples uniformly.

The electric resistivity of water saturated samples decreased as temperature increased to the boiling point of water. Above boiling point, resistivity increased rapidly as water changed to vapor. Resistivity is most sensitive to temperature changes between 35^oC - 65^oC. Resistivities of samples increased with decrease in saturation. The effect is more pronounced at lower temperatures. No dependence of seismic P-wave velocities on temperature has been observed.

Both resistivity and P-wave velocity depend on porosity. The increase in porosity results in a decrease in the resistivity formation factor. Assuming a relationship $FF = a\,\phi^{-m}$ (Archie's Law), where FF and ϕ represent the formation factor and porosity respectively, least squares indicate a variation of a between .5 and 2.0. The value of m varied between 1.2 to 1.7. Seismic velocities (v) decrease as porosity increases. Porosity appear to be linearly related to log v.

Several samples show anomalous relationship between porosity and resistivity. Most of these samples also show anomalous seismic velocities. The majority of these samples have coarse grains or large pores.

The effect of saturation on P-wave velocity is small and can be observed in few samples. In these samples, seismic velocities decrease with increase in saturation at high saturation (100%-85%), and show a reverse relationship at low saturation. Between 15% and 85% saturation in velocity is constant.

INTRODUCTION

Research on the physical properties of geothermal reservoir rocks at Colorado School of Mines has progressed in several areas:

1. Approximately 200 samples of pre-cenozoic volcanic rocks have been collected and samples prepared. At present, these samples are being prepared for saturation.

2. A system of simultaneously measuring seismic velocities and resistivities of rock samples at different temperatures has been built and tested.

3. Four suites of cenozoic volcanic rocks previously studied have been recorded, and measurements repeated on larger cores for comparison with previous results. These suites are the Columbian plateau, New Mexico Jemez Mountain, volcanics from south central Nevada, and Cascade range in Oregon. The new suites of samples which are being prepared for measurements are described in Appendix one.

EQUIPMENT AND PROCEDURES

Previous measurements were performed in sequence, with the electric measurements being carried out first at atmospheric pressure. Seismic velocities were then obtained using a pre-existing seismic system at low confining and pore pressures. To obtain seismic and electric data on samples under identical conditions, a system was designed and built for this purpose. This system permits simultaneous measurements of seismic velocity and resistivity both at different temperature and degree of saturation. Sample holder is shown in Figure 1. Circuit diagram is also shown in Figure 2.

The electric resistivity source, a sine wave generator, provides a 1.0 KHz signal to two brass discs which serve as current electrodes. These two discs also are the common ground electrode for the piezoelectric transducers in the seismic part of the system. Stainless steel needle voltage electrodes are brought into firm physical contact with the samples using plastic screws. Voltage across the electrodes is compared with the voltage across a standard resistor. Distance between voltage electrodes is 1.0 inch for short samples (2.0 inches in length) or 1.5 inches for long samples (3.0 inches long). Voltages are measured with Simpson digital multi-meters.

The seismic component of the system is composed of identical transmitting and receiving heads. Each is composed of a plastic housing which encloses a dilatational and shear wave transducers. These transducers are sealed in the transducing heads. Coaxial leads are used for transmitting energizing signal to source transducers and connecting receiving transducers to oscilliscope to minimize noise. A switching system has been included to permit a sequential switching from seismic velocities circuit to that of resistivity. With the sample clamped in place between transmitting and receiving heads, and voltage electrodes in place, the entire system can be placed in the microwave oven, thus permitting the study of variation of seismic velocities and electric resistivities at different temperatures.

Shear wave transducers are composed of shear cut prizoelectric cubes. The mechanical signal from the source produces flextural deformation in the sample. These signals are highly dispersive, and arrive later than the P-wave.

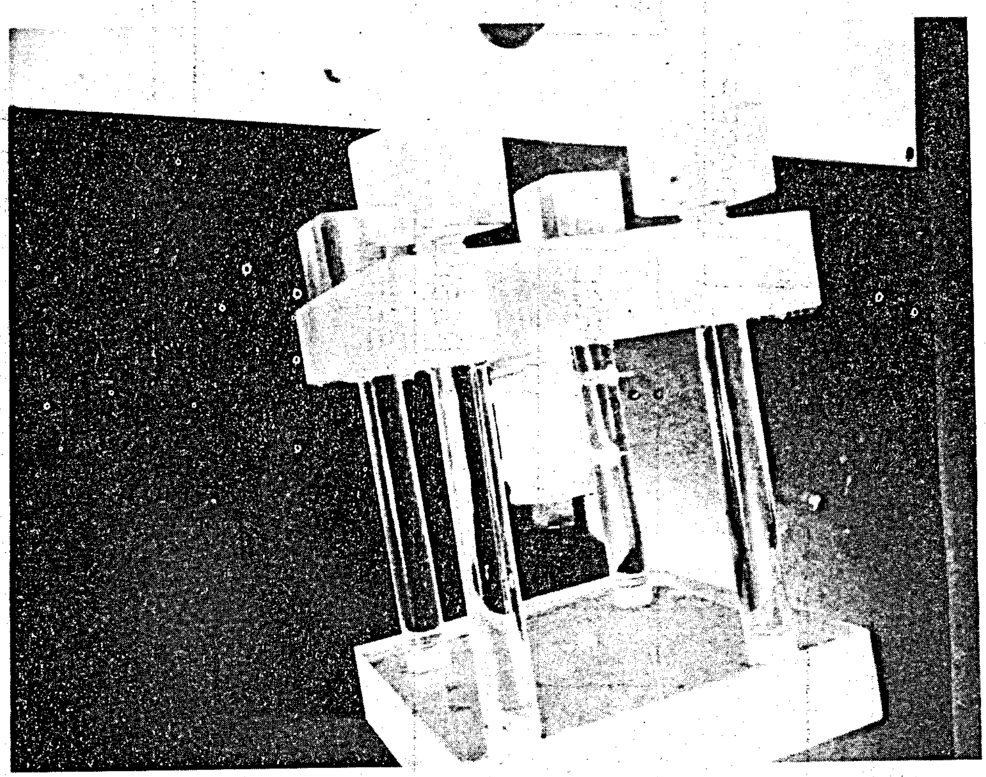

FIGURE I SAMPLE CHAMBER AND VISE

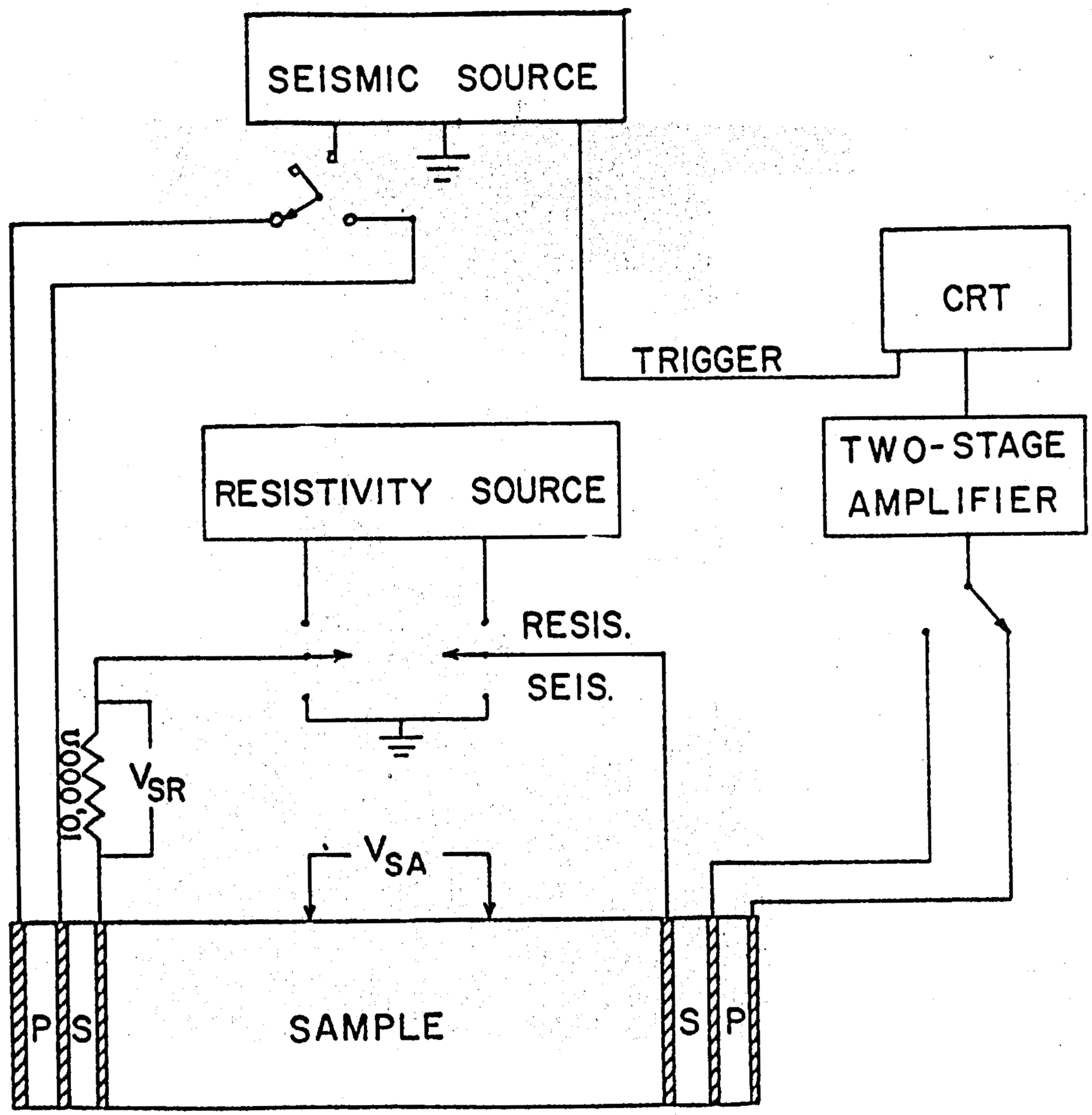

FIGURE 2. CIRCUIT BLOCK DIAGRAM

Their exact onset time is therefore harder to observe. Therefore at the present time shear transit times are not being read. However, a tortional seismic source and receiver is being built from shear cut crystals.

In some samples, good electric contact between voltage electrodes and the sample is hard to achieve especially in cases of low saturation. The sample holder will be re-designed and rubber jackets eliminated. Silver paint will be applied at two tiny spots where voltage electrodes will contact sample for better results. Modifications mentioned above will be incorporated in the system to be used for measurements in older volcanic rocks.

Porosities are calculated from the weight of dry and water saturated samples in air, and the saturated weight in water. A new electronic balance has been acquired for this purpose. Rock cores are prepared with a diameter of 3/4" and length of either 2 or 3 inches depending on sample physical dimensions. After cleaning with distilled water, samples are dreid at 105^{o}C until no significant change in their weight is observed. After measuring dry weight, samples are placed in vacuum jars, and pressure reduced to 0.05mm Hg. This vacuum is maintained for at least 24 hours, after which samples are immersed in a 0.1 NaCl solution. after which the pressure is changed to one atmosphere. Samples are then stored in separate containers in the same solution. This technique is believed to produce a high degree of saturation. A porosity meter is being designed to measure rock proosity using helium gas as a saturating liquid. Porosities obtained by this method will enable us to evaluate the effectiveness of the present method of saturation.

In a typical run, after mounting sample in the sample holder between the seismic transmitter and receiver, the entire assembly is placed in the microwave oven. Resistivity and seismic transit time is then obtained at room temperature. Temperature is then increased in steps, and measurements of seismic velocity and resistivity is repeated in each step, until the boiling point. The sample is then removed from the sample holder and allowed to cool to room temperature. It is then re-weighed and the volume of water remaining in the sample is calculated. The degree of saturation is calculated by dividing the volume of water remaining by the total volume of the space in the sample. The sample is then placed in sample holder between transducers in oven and a series of resistivities and seismic velocities is obtained as a function of temperature. This procedure could be repeated until sample is dry.

To calculate seismic velocities from the transit time, the delay time of system must be evaluated. The corrected transit time is calculated from the measured time by subtracting the delay time caused by the finite thickness of transmitter and receiver. The delay time is obtained by measuring signal transit time in several steel cylinders of different lengths. Transit time length graph produces a straight line which intersects time axis at a value equal to delay time. It is apparent from Figure 3 that delay time is 4.2 and 5.1 seconds without and with filter in circuit respectively. From the graph, it is also apparent that transit time can be calculated with an accuracy of $\pm$ 0.15 μ sec.

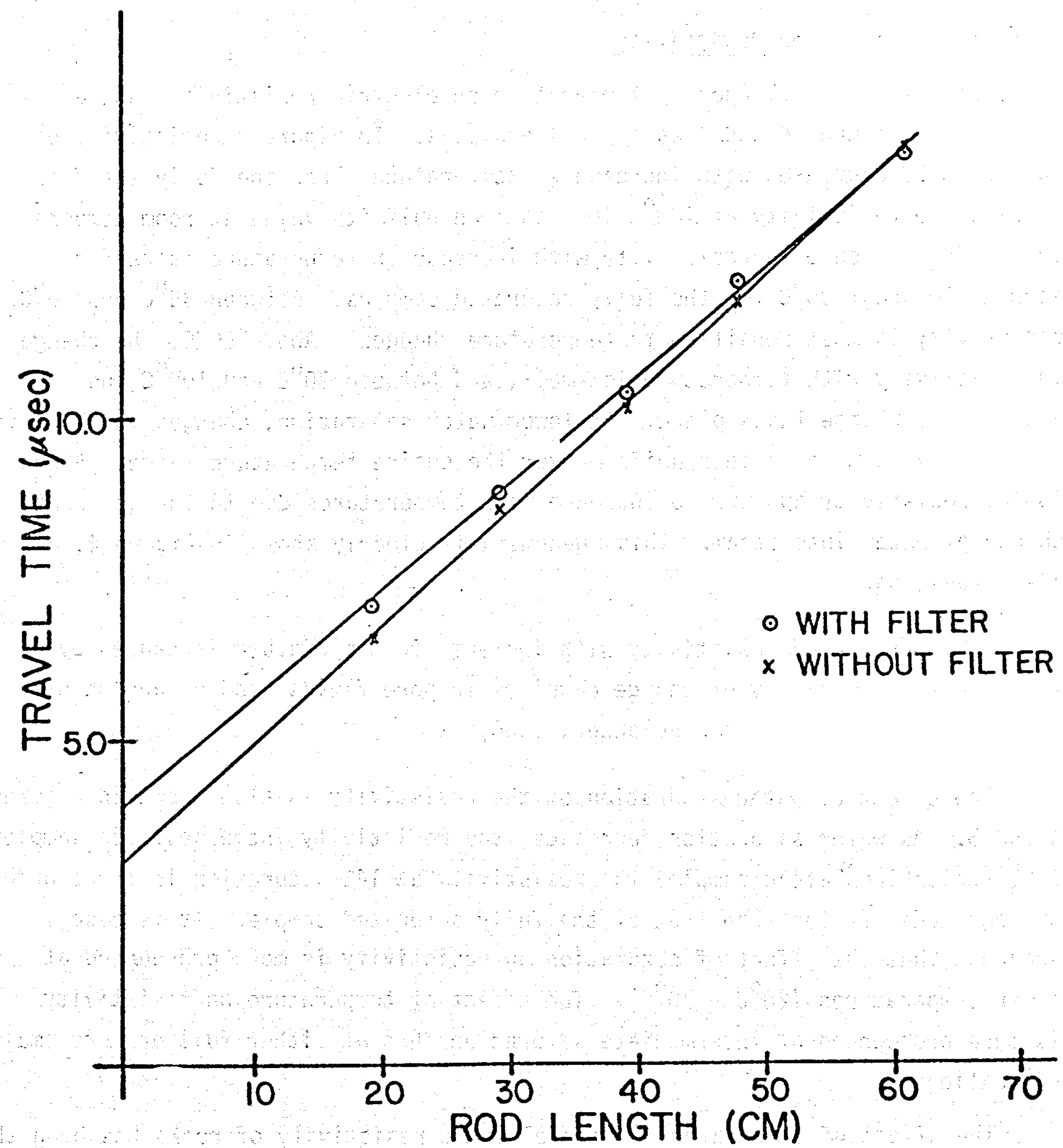

FIGURE 3. CALIBRATION OF VELOCITY CIRCUIT USING STEEL CYLINDERS

RESULTS

Temperature Effect on Resistivity

The effects of changes in temperature on electric resistivity can be observed in Figures 4 and 5 as typical examples. In Figure 4 resistivity of sample NM 58 decreases with increase in temperature. For the fully saturated sample, the resistivity at 100°C is less than half its value at room temperature. The decrease in resistivity with increase in temperature is rather slow up to about 35°C for the fully saturated samples. Between 35°C and 60°C, resistivity is most sensitive to temperature changes. Above 60°C, the change in resistivity with temperature is small, and between 90°C and 100°C, no appreciable change takes place. At lower water saturation, changes in electric resistivity is more or less uniform over the entire temperature range. Above 100°C, resistivity appears to increase with temperatures due to the apparent change of water into steam. This phenomena is clearly shown in Figure 4, at 50% saturation.

The decrease of resistivity with increase in temperature is caused by an increase in mobility of charge carriers in pore fluids, and expansion of rock matrix and pore space (Helander, 1966).

The effect of water saturation on the resistivity is also shown in Figures 4 and 5. As water saturation decreases, the resistivity increases. In sample C 28 (Columbia Plateau sample) the resistivity at 14% saturation is three orders of magnitude greater than that of the fully saturated sample. It is also apparent that the effect of saturation on resistivity is more pronounced at lower temperatures (20°C - 70°C). The effect of temperature on resistivity is more pronounced at intermediate saturation than at either full or very small saturations.

The effect of temperature on the electric resistivity of rocks has been the subject of many investigations (Hilch, 1960; Coster, 1948). An increase in temperature results in an increase in mobility of charge carriers of ions in electrolytes and rock skeleton. When saturated with salt water, rocks with high porosity show a bulk resistivity variation with temperature characteristic of the electrolyte. On the other hand, variations of resistivity with temperature in case of rocks with extremely low porosity is similar to that of the solid framework (Parkhomenko, 1967).

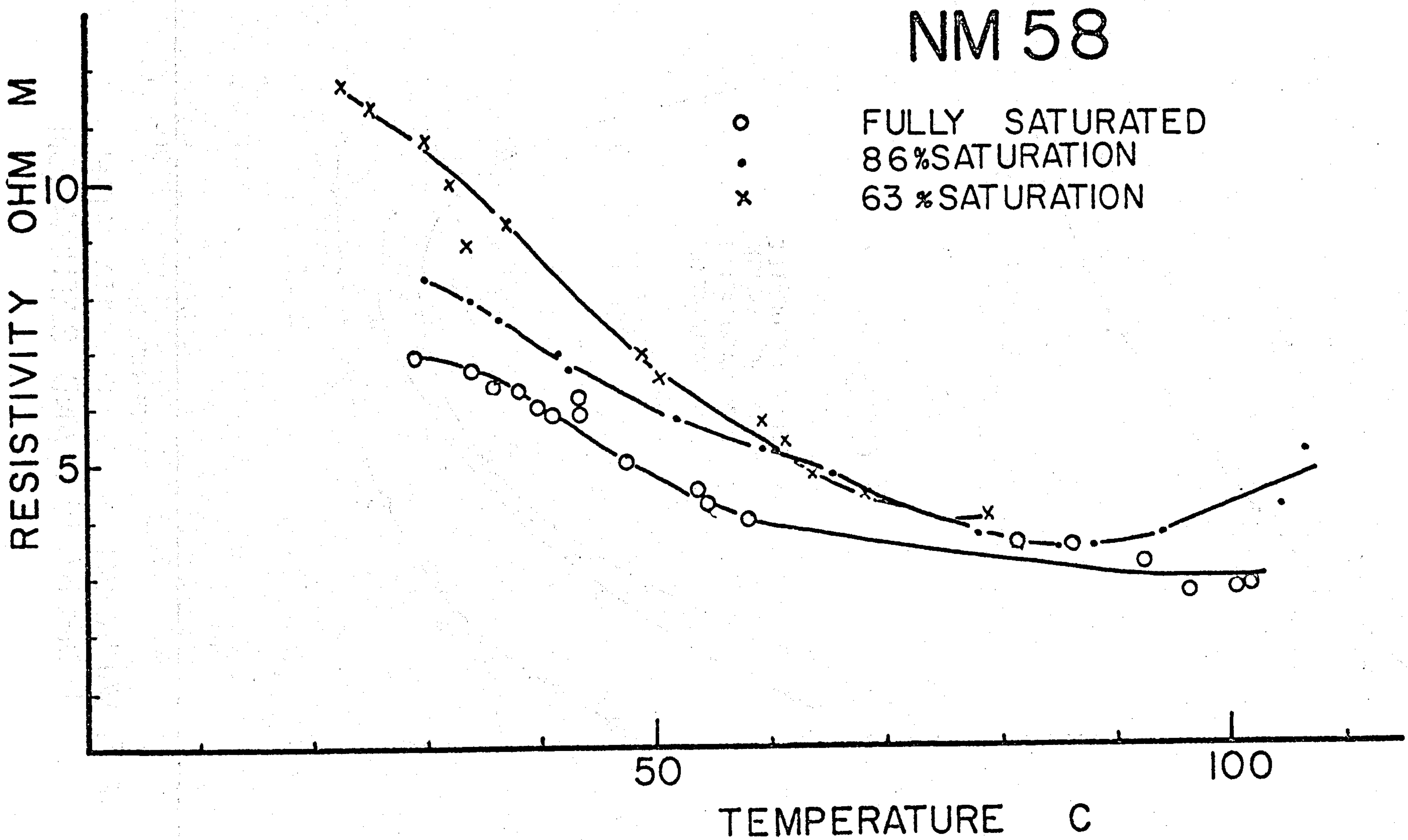

FIGURE 4. VARIATION OF RESISTIVITY WITH TEMPERATURE AND SATURATION

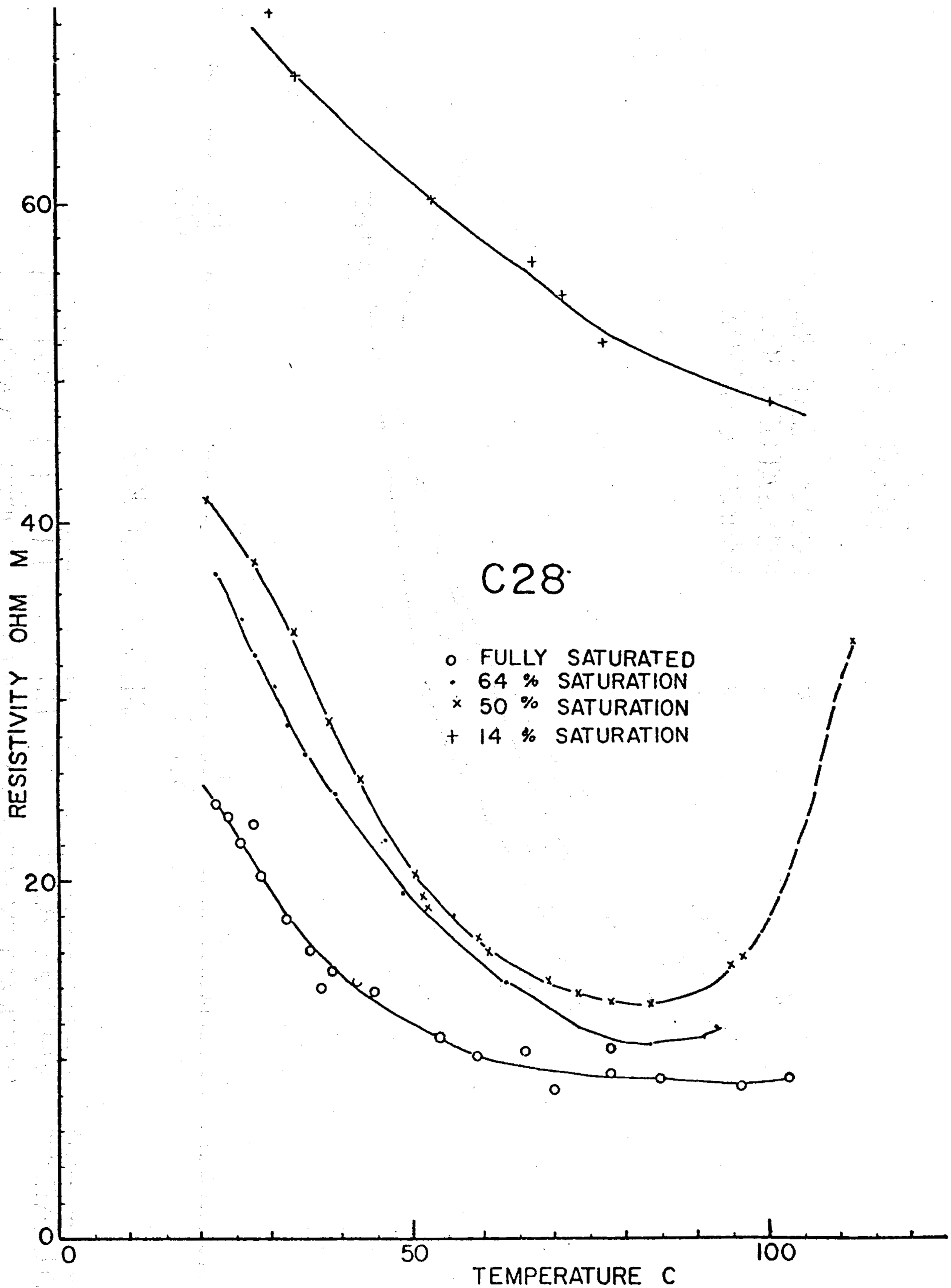

FIGURE 5. VARIATION OF RESISTIVITY WITH TEMPERATURE AND SATURATION

Effect of Porosity on Electric Resistivity

The effect of porosity on electric resistivity can be demonstrated in Figures 6 and 7. In both Figures, the formation factor is proportional to porosity and appear linear on a log-log graph. Assuming the relation $FF = a\,\phi^{-m}$ (Archie's law, Archie, 1942, 1947), least square lines give a value of 2.0, and 0.48 for the constant a in sample N M and C 28 respectively. The corresponding m values are 1.17 and 1.70. It is apparent from diagram that appreciable number of samples have anomalous formation factor-porosity relationship. Most of these samples appear to have large grains or large vugy porosity.

The apparent scatter of points in Figures 6 and 7 is not surprising since resistivity of water saturated rocks depends on a multitude of factors in addition to porosity (Helender, 1966). These factors include:

1) shape, packing, and sorting of grains
2) degree of cementation
3) type of pore system, pores could be intergranular, intercrystalline, or vuggy
4) tortuosity of pores
5) constrictions in pore systems
6) presence of conductive inclusions
7) compaction due to overburden pressures
8) thermal expansion.

Patnode and Wyllie (1950) stressed the effect of clay in increasing conductivity, and Keller (1953) showed that different wettabilities yield different electric conductivities in same rock at the same saturation.

Archie's Law applies to sedimentary rocks such as limestones and sandstones (Wyllie, 1963; Greenberg and Brace, 1969). The cementation factor, m in such cases was found to be 2.0. Brace and Orange (1968b) arrived at a value of 1.0 for m in case of rocks under pressure where new crack porosity developed.

Effects of Temperature, Saturation and Porosity on Seismic Velocities

Seismic wave velocities in porous rocks depend on porosity, fluid saturation, cementation, grain size, matrix composition, temperature, and pressure. The effect of porosity on seismic velocities has been treated in several articles. Watkines, (1972), and Gardner, (1964), showed a linear relationship of the form

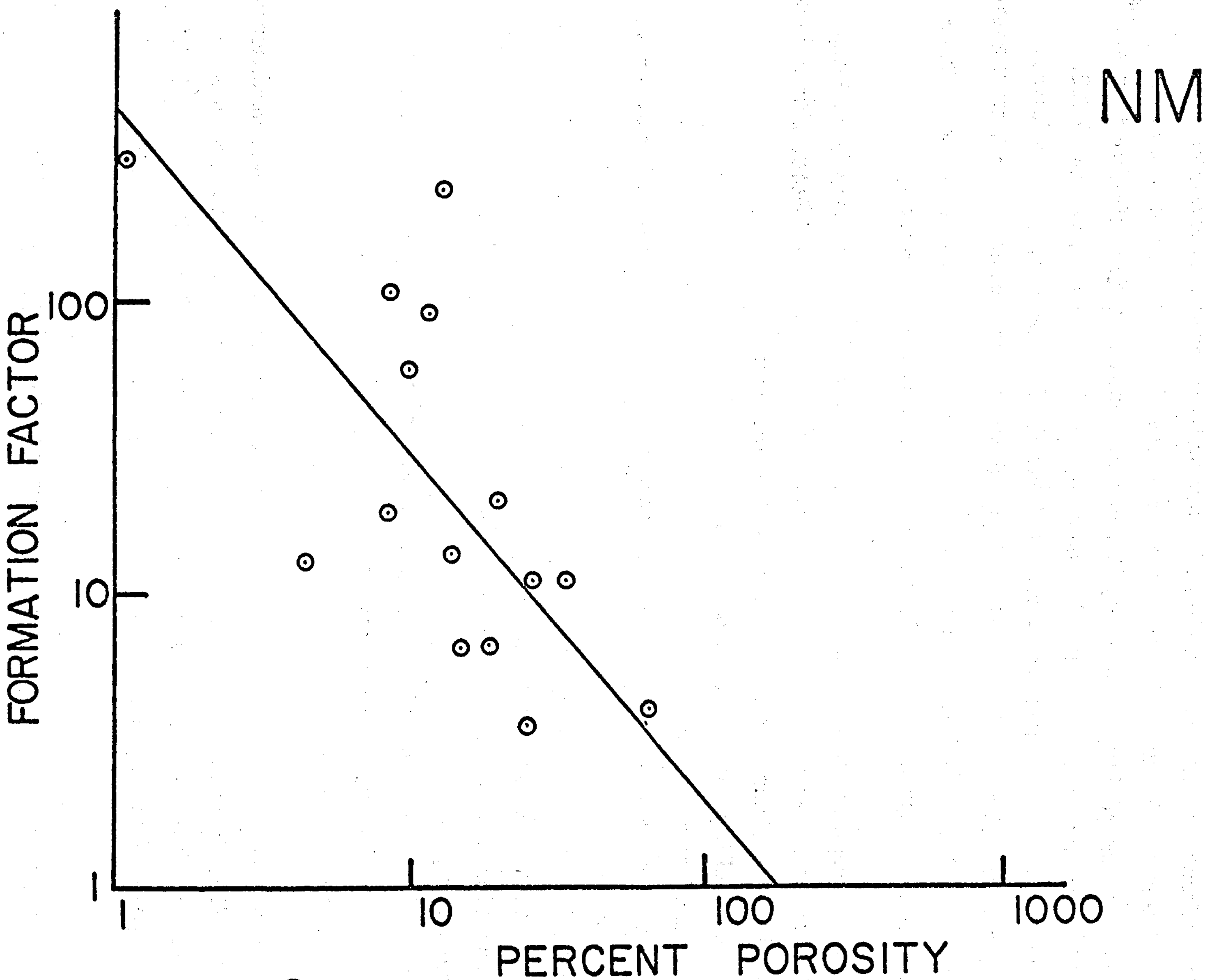

FIGURE 6. VARIATION OF FORMATION FACTOR WITH POROSITY

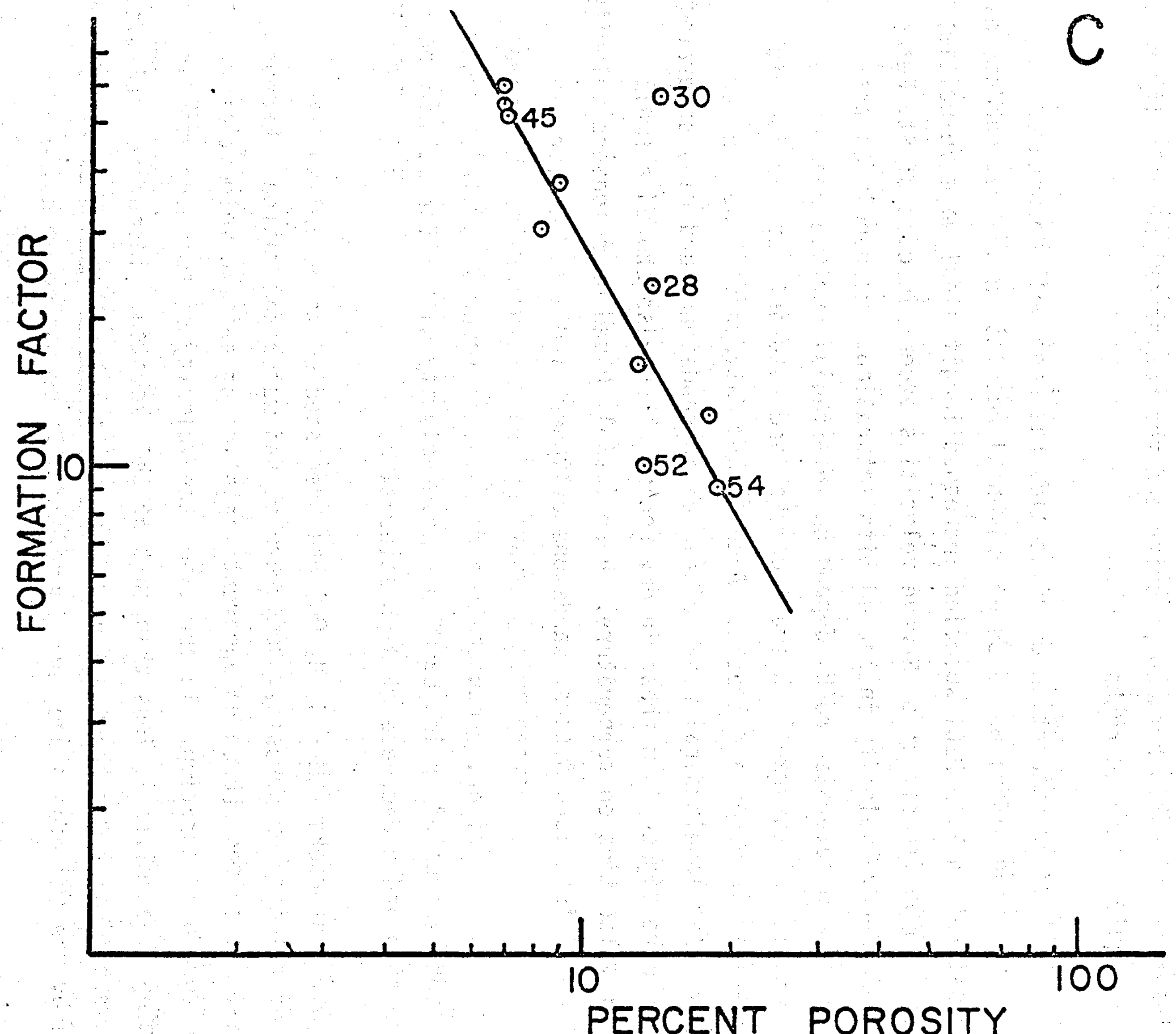

FIGURE 7 VARIATION OF FORMATION FACTOR WITH POROSITY

log V = a ϕ, where a is a constant, v is velocity, and ϕ is porosity. Wyllie (1956) and Hughes and Jones (1950) developed the time average equation relating velocity to porosity. Realistic mathematical models relating porosity to velocity have been developed by Biost (1956), Gassman (1951), Geertsma and Smith (1961), White and Sengbush (1953), Brandt (1935), and Hicks and Berry (1956). Geertsma showed a linear relationship between porosity and the reciprocal of velocity for both dry and liquid saturated rocks.

The effect of water saturation on velocities has been well documented in literature also. King (1966) based on experimental results on several sandstones, showed that saturation with NaCl solution increased longitudinal wave velocities while having an opposite effect of S-wave velocities except in case of St. Peter sandstone where S-wave velocity increased with saturation. He concluded that velocities in liquid saturated rocks depend on interfacial surface phenomena, relaxation behavior of saturants in small cracks, and saturant interaction with detrital materials in pores and cracks. Avchyan and Matveenko (1965) showed experimentally that longitudinal wave velocities in sandstones and clay saturated with kerosene were higher than those in dry rocks. They also showed a small dependence of velocities on temperature. Born (1935), based on resonance velocity measurement on 94 inch long Amherst sandstone cylinder, indicated a decrease in velocity with moisture at atmospheric pressure and room temperature. He showed that this decrease is primarily caused by a decrease in Young's modular. Hughes and Kelly (1952) indicated an increase in P-wave velocity with water saturation at low saturation and a decrease at high saturation.

Four suites of rocks (NM < C, N, OC) has been studied to establish the dependence of velocity on porosity, temperature, and water saturation. Except in few cases, all suites showed no apparent variation of seismic velocities with temperature or saturation. In our case, the velocity of seismic waves in the saturating electrolyte is less than that of the skeleton. Therefore, seismic energy transmitted part way through fluid will arrive later than energy being transmitted by the skeleton alone, and therefore will be masked by noise.

The effect of porosity on seismic wave velocities is demonstrated in Figures 8 and 9. These Figures show a decrease in velocity with porosity. In the NM and C suites, porosity have a greater effect on velocity than in the OC or N suites.

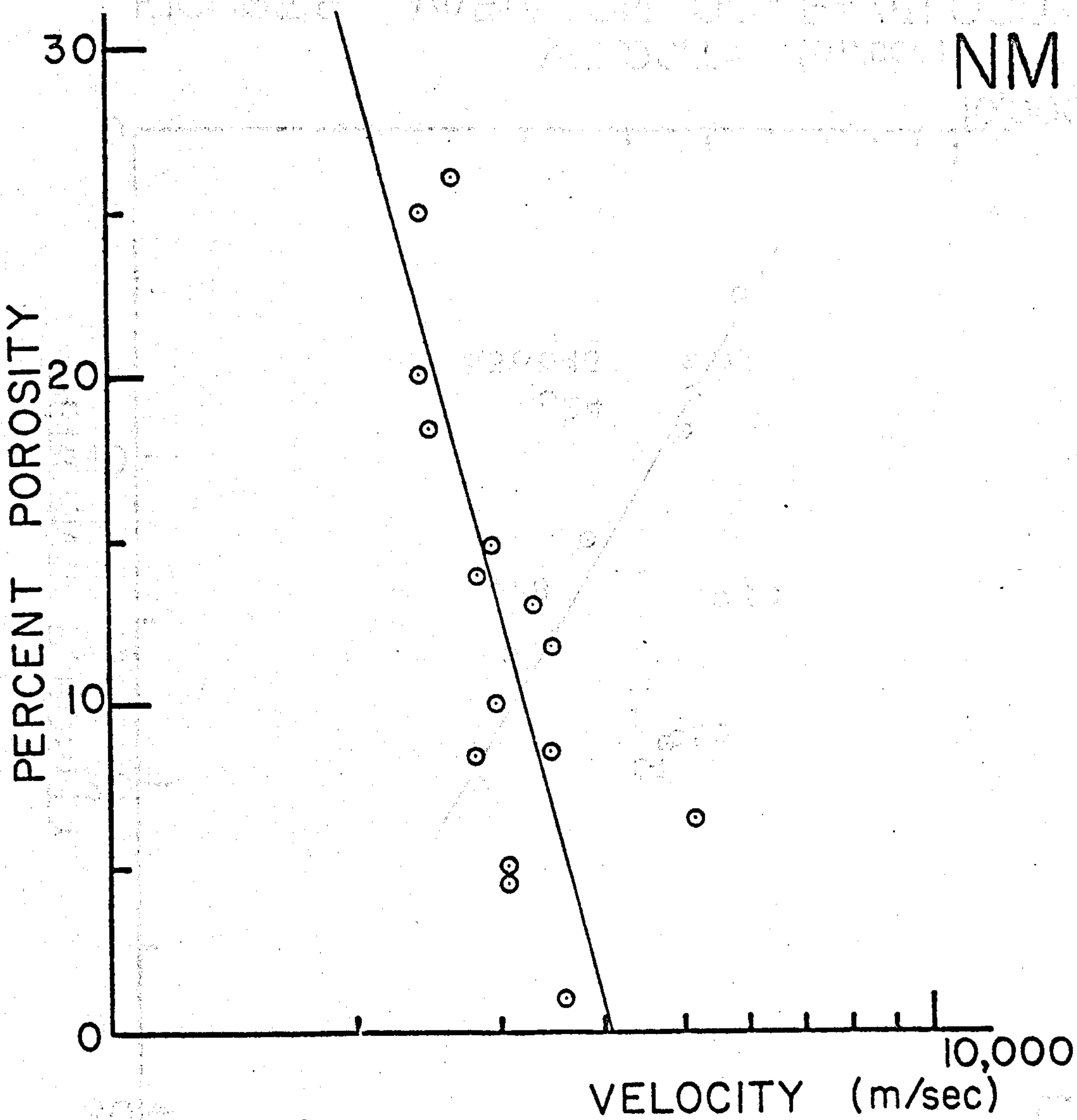

FIGURE 8. VARIATION OF P VELOCITY WITH POROSITY

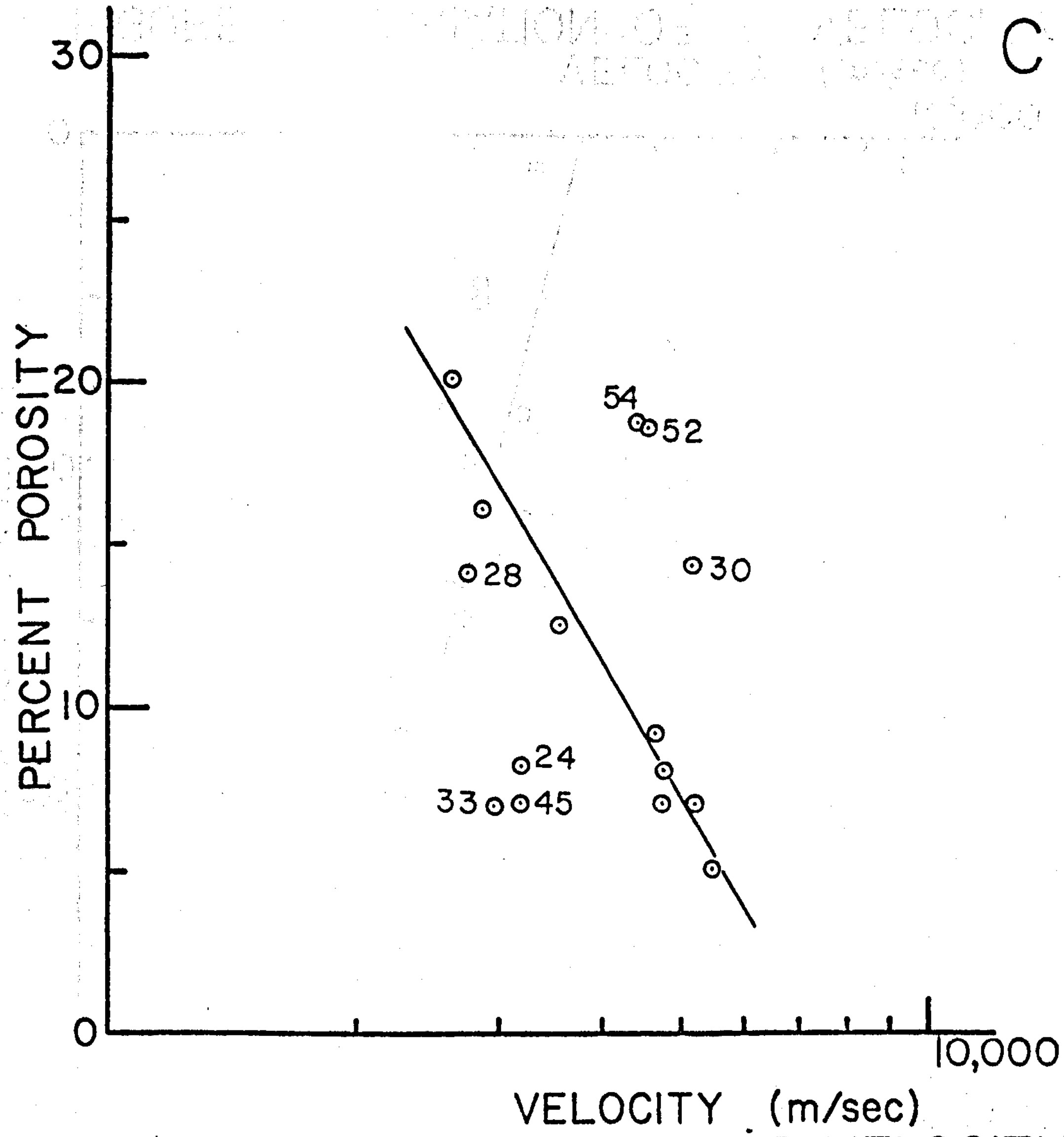

FIGURE 9. VARIATION OF P-VELOCITY WITH POROSITY

CONCLUSIONS

A strong dependence of seismic velocity and resistivity of cenozoic volcanic rocks on porosity has been demonstrated in four suites of rocks. Several samples in each suite show anomalous resistivities and seismic velocities corresponding to porosity. This anomalous behavior is due to peculiarities in grain size, pore volume distribution, anistropy, and cementation. It is suggested that further studies be conducted on the effect of these variables on seismic velocities and resistivities of volcanic rocks.

While resistivities decrease with increase in temperature (20^oC - 110^oC) and degree of saturation, seismic velocities seem to be constant.

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Drs. G.V. Keller and G.R. Pickett availed themselves for consultations. However they have not charged any of their time to the project. Dr. A.W. Ibrahim, a post-doctoral fellow, devoted full time (3 man-months) to the project and was responsible for carrying out laboratory measurements. L.T. Grose spent part of the 1977 summer collecting rock specimens. Three graduate students were involved in this project. These students are: Koji Tsuliata, Jose Suto, and Bill Silk. Each contributed 1.5 man-months to the project.

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