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SEISMIC VELOCITIES AND ELECTRICAL RESISTIVITY OF RECENT VOLCANICS AND THEIR DEPENDENCE ON POROSITY, TEMPERATURE, AND WATER SATURATION

Abstract

Variation of P-wave velocities and electrical resistivities of several suites of water-saturated recent volcanics was investigated. Both P-velocities and resistivities exhibited strong dependence on porosity. Resistivity was also dependent upon degree of water saturation and temperature. P-wave velocities, while showing a strong dependence on porosity, appear to be independent of water saturation and temperature. Volcanics, in general, exhibit higher resistivities compared to other igneous rocks and sediments. Electric resistivity of fine-grained basalts is anomalously low, probably due to higher content of disseminated iron. Pyroclastics and volcanic breccia, on the other hand, exhibit higher resistivities in relation to fine-grained basalts.

Introduction

The interest in developing interrelationships between petro-physical properties of typical petroleum reservoir rocks is well documented in the literature. Established relationships between parameters, whether obtained by laboratory studies or from well logs, are effectively employed in the interpretation of geophysical well log data. Laboratory and well log studies demonstrate a strong dependence of acoustic velocity, electric, and thermal conductivities on porosity. Effects of temperature, pressure, texture, fluid saturation, among other factors, also prove to be significant.

Studies of the petrophysical properties of igneous rocks are not known to host significant hydrocarbon deposits. However, recent exploration efforts for geothermal energy demonstrated the importance of recent volcanic rocks as a source of geothermal energy. As the geothermal industry expands, unique technology will be developed for exploration, development, and recovery of energy from volcanic rocks. This effort will require a knowledge of the petrophysical properties of these rocks.

Crystalline rocks are the dominating form of volcanic rocks. In this group, porosity exists in the form of voids between individual crystals. This form of porosity, which has been named intermediate porosity, also exists in some sedimentary rocks such as marbles and limestones. Volcanic tuffs and breccia, on the other hand, are pyroclastics and their porosity is intergranular like clastic sedimentary rocks. Volcanic breccia may have both intercrystalline and intergranular porosity. Crack porosity is also common in all igneous rocks, including volcanics.

Limited studies of the petrophysical properties of volcanic rocks (Keller, et al., 1974) suggest that relations similar to those already developed for sedimentary rocks can be developed. These studies, however, revealed some unique characteristics of volcanic rocks. Resistivities of volcanic rocks were found to be several times higher than those of other crystalline or granular rocks. Also, the dependence of acoustic velocities on porosities were found to be weaker than in other rocks (Keller, 1960; Keller, et al., 1974).

We describe laboratory equipment and techniques for measuring the acoustic velocities and electrical resistivities of several suites of volcanic rocks at atmospheric pressure. Variations of these parameters with porosity, temperature, and water saturation are discussed and compared with similar relations obtained for other types of rocks.

Literature Review

Comprehensive studies of sedimentary rock established the dependence of formation factor on porosity. Archie (1942, 1947) pioneered this effort by suggesting his well-known empirical relationship $F = a\phi^{-m}$, where F is the formation factor, ϕ is porosity, m is a cementation factor, and a is a constant. Brace, et al. (1965), based on laboratory measurements on granites and limestones, suggested a value of 2.00 for m and implied that such a value will apply for a variety of rocks. Carothers (1968), based on laboratory measurements on sandstones and limestones, suggested values for the cementation factor varying between 1.3 to 2.15 for sandstones and 1.8 to 2.38 for limestones. The cementation factor was found to be 1.0 in the case of new fracture growth in stressed rocks (Brace and Orange, 1968). In some cases, Archie's law fails to apply due to the effect of factors other than porosity on resistivity. As an example, the presence of clay or iron minerals tends to lower resistivity below the value predicted by Archie's law (Keller, 1953; Patnode and Wyllie, 1950).

Mathematical modeling to prove the validity of an Archie-type relationship between porosity and formation factor has been carried out by Greenberg and Brace (1969), Kwon (1975), Madden (1976), and Towle (1962). However, simplistic geometric models of pore space restricted the degree of realism of such models. Satisfactory results, however, were obtained when pore structures were simulated by statistical distributions of sizes and shapes (Kwon, 1975; Madden, 1976). Laboratory studies such as those of Brace, et al., (1965) and Hilchie (1964) indicate an increase in conductivity with rise in temperature of water-saturated rocks. At temperatures above the boiling point of the electrolyte in the pore space, effects on the resistivity

of partial steam saturation have not yet been investigated.

Effects of liquid saturation on electrical resistivity have been cited in several publications (Keller, 1953; Brace and Orange, 1968, among others). Since most rocks are considered electric insulators when dry, most electrical conduction in saturated rocks takes place through motion of ions in the solution. An increase in electrolyte saturation, therefore, results in a decrease in electrical resistivity.

Acoustic wave velocity, like electrical resistivity, is also an important petrophysical rock parameter. It is sensitive to rock porosity, composition, and texture. The effect of porosity on P-wave velocities has been established by Wyllie, et al. (1956), Hardin, et al. (1963), Gardner, et al. (1963), Keller (1960), Keller, et al. (1974), and Overton and Smith (1966). Most of the results in volcanics showed a weaker correlation between porosity and P-wave velocity as compared to similar data in sedimentary rocks.

The effects of fluid saturation on acoustic wave velocities of sedimentary rocks, especially sandstone, have been thoroughly investigated by Domenico (1976), Gardner, et al. (1963), Born and Owens (1935), Oliphant (1950), Hughes and Cross (1951), King (1966), Wyllie, et al. (1956), Avchyan and Matveenko (1965), Nur and Simmons (1969), Hughes and Kelly (1952), Elliot and Wiley (1975), and Hughes and Jones (1951). Results of these studies do not yield a consistent conclusion. The interrelationship between fluid saturation and seismic velocities has been found to depend upon pressure under which measurements are carried out.

The effect of temperature changes on seismic velocities has not received as much attention as those of porosity, pressure, and saturation. Avchyan and Matveenko (1965) showed that change of P-wave velocities of fluid-saturated sandstones and clays with temperature parallels the changes of these

velocities in the saturating liquid with temperature. Hughes and Kelley (1952) showed that an increase in temperature of sandstones saturated with distilled water decreased P-velocities.

Apparatus and Method

In this study, a two-mode experimental set-up was designed for successive measurements of seismic P-wave velocity and electrical resistivity of water-saturated, cylindrical core samples at different temperatures without disturbing the sample. A four-electrode system was employed in measuring the electrical resistivity. Two separate transducer assemblies (source and receiver) were enclosed in waterproof Teflon housing. In each housing assembly, piezoelectric transducers were sandwiched between brass plates for energizing the sample. The inner brass plates also served as current electrodes in the electrical resistivity measurements, and they were in contact with faces of the sample. A vise system was constructed of two plates and four bolts for holding the sample in place between the transducer housings and for applying sufficient pressure (about 20 psi) to achieve mechanical coupling between sample ends and transducer assemblies. With the sample enclosed in a rubber jacket and placed between the source and receiver assemblies in the vise, the whole system can be placed in a microwave oven when carrying out measurements at different temperatures. Microwave oven heating of water-saturated samples proved to be efficient and less time-consuming compared to resistive heating. In this mode of heating, sufficient time must be provided to allow for uniform temperature distribution before carrying out measurements because dielectric heating takes place mostly in the water phase.

In the seismic mode of operation, square pulses energized the source transducer, and a double beam Tektronics scope (model 556) with time-delay measuring capability, was employed for transit time measurements. Transit times were reproducible to $\pm 0.10 \mu \text{ sec}$. Frequency content of the received signal was approximately 100 kHz.

In the electrical resistivity mode of operation, a 1000 Hz source was employed, and the resistance of samples between two stainless steel potential probes was measured. This was accomplished by comparison of voltage between probes with that developed across a standard resistor connected in series with the sample. A schematic of the measuring circuit is shown in Figure 1.

Cylindrical core samples were drilled from several different suites of volcanic rocks (see the Appendix for sample location description). Samples were 3/4-inch diameter and ranged in length between 2 to 3 inches depending upon physical dimensions of rock specimens. End faces were ground flat and perpendicular to the axes of cylinders. Samples were boiled and washed several times in distilled water after preparation to rid them of ground rock fragments adhering to their surface as a result of coring. They were then dried at 105°C until constant weights were achieved. Saturation of samples with a 0.1 N sodium chloride solution (resistivity $1.0 \Omega\text{-m}$) was accomplished by maintaining the samples for at least 24 hours in a vacuum container under a reduced pressure of about 0.05 mm of mercury before flooding them. Porosities were calculated from weights of dry and saturated samples in air and their saturated weight suspended in the saturating solution.

Seismic P-wave velocities and electrical resistivities were measured for all samples at room temperatures and atmospheric pressure. Measurements at different temperatures and saturations were conducted on some of the samples. Different degrees of saturations were obtained by controlled evaporation in

air and heating in the microwave oven. Repeated weighing of samples was carried out to determine degrees of saturation.

Results and Discussion

The effect of temperature on the electrical resistivity of water-saturated recent volcanic rock is demonstrated in Figure 2 as a typical example. The figure indicates a decrease in electrical resistivity with rise in temperature. The rate of decrease is more significant at lower temperatures, while at about 70°C, resistivity is less sensitive to temperature variation. Above about 90°C, an increase in resistivity is typical of all highly saturated samples. When the measured resistivity of saturated samples at room temperature (22.5°C) in Figure 2 was employed in conjunction with Arps's equation relating resistivity of salt solution to temperature (Arps, 1953), the dotted curve in the figure was obtained.

The decrease in measured resistivity with temperature appears to follow an Arps-type relationship. However, measured resistivity which shows appreciable scatter at high temperatures tends to be lower than that predicted from his equation. The slower decrease at higher temperature range (70°C-90°C) probably takes place when the mobility of charge carriers reaches a limiting value due to liquid drag and more frequent collisions among the charge due to liquid drag and more frequent collisions among the charge carriers and between the charge carriers and rock matrix. The observed increase in resistivity above 90°C is possibly due to mass evaporation of water in the pore space of the rocks resulting in a decrease of water saturation and sharp increase in partial steam saturation. The phenomena of mass evaporation does not happen at lower saturation, possibly because residual water exists only in the smaller capillary pore space where a strong

FIG. 1. Circuit block diagram.

FIG. 2. Variation of resistivity with temperature and saturation.

FIG. 3. Relation between formation factor and porosity, OC suite.

FIG. 4. Variation of formation factor with porosity, NM suite.

FIG. 5. Variation of formation factor with porosity, C suite.

FIG. 6. Relation between formation factor and porosity for all suites.

capillary force resists sudden evaporation. This may explain the absence of resistivity rise above 90°C for low saturation.

Figure 2 also demonstrates the expected effect of saturation on the electrical resistivity in volcanic rocks. An increase in water saturation decreases resistivity. The diagram also indicates that resistivity is more sensitive to variations in saturations at lower temperatures. This is apparent from the convergence of different graphs representing different saturations at higher temperatures. Since low saturations were obtained by evaporating water from our samples, a decrease in saturation was produced since the number of charge carriers did not change. This, when accompanied by an expected decrease in ion mobility at higher salinity, may explain the apparent convergence of the resistivity-temperature curves at higher temperature.

Results of this study also show an apparent dependence of electrical resistivity of volcanic rocks on porosity. This dependence is shown for three suites of volcanics in Figures 3, 4, and 5 as examples. Figure 3 shows the dependence of formation factor on porosity for the Cascade Range volcanics (denoted as OC). Several samples show anomalous resistivities. Samples 1, 2, 17, 31, 50, and 51 have anomalously higher electrical resistivities than indicated by the least square lines. Samples 50 and 51 are red tuff, while 2 and 17 are volcanic breccia. On the other hand, samples 33, 28, 30, and 55 are extremely fine-grained, massive basalt ranging in color from dark gray to black. Their noticeable low resistivity may be caused by the presence of disseminated iron sulfide and oxides. Similar results are shown in Figure 4 for the New Mexico suite (NM). In this suite sample 2 showed anomalously low resistivity values. It is composed of very fine-grained, massive black basalt, which is probably rich in highly conductive iron minerals. Samples 28

and 37 are siliceous tuff; and highly porous, frothy, silicic pumice, respectively. Both samples show higher resistivity values.

The Columbia Plateau suite (C) showed a narrower range of porosity variations and least scatter of points around the least-square line in the porosity-formation factor graph (Figure 5). In all suites fine-grained basalts generally exhibit lower resistivity compared to volcanic tuff and breccia. All suites except that of the Columbia Plateau show appreciable deviation from the least-square lines. Additional data may reveal two separate trends; a low-resistivity trend representing fine-grained volcanic rocks high in disseminated iron minerals and a high-resistivity typical of tuffs and breccia.

Figure 6 is a compilation of the least-square lines representing the porosity-formation factor relationships for the three suites. A tabulation of the cementation factors is also listed in the overlay table. For all suites studied, m is smaller than 2.0, a value reported for crystalline rocks by Brace and Orange (1968). It is generally smaller than the range of 0.8-2.4 reported for Paleozoic limestone by Carothers (1968).

It is apparent from the data presented that Archie's law applies to recent volcanics. However, variation in lithology causes a scatter of points and deviation from this law. With the addition of more data, it is possible that an Archie-type equation may emerge for each lithology. Also, it must be pointed out here that the cementation factors for recent volcanics tend to be smaller than those reported for limestones and other crystalline igneous rocks. This indicates higher resistivities, a conclusion of Keller, et al., (1974). This higher resistivity could be caused by the abundance of "dead end" porosity and a more tortuous pore space configuration.

It was shown by Towle (1962) that the cementation factor varies with rock

age and lithology. This leads us to conclude that relations presented here will not necessarily apply to other igneous rocks. Preliminary laboratory results obtained by the authors for pre-Cenozoic volcanics indicate drastically reduced porosities and suggest different petrophysical relations when compared with those presented in this paper.

Integration of similar data on volcanics of different ages and locations will eventually result in the development of more general interrelationships between petrophysical properties of volcanic rocks. Such relations will take into consideration the effects of parameters such as age and lithology and would represent a universal tool for borehole log interpretation.

Dilatational wave velocity measurements on volcanic rocks also revealed dependence on porosity. Results for three suites are shown in Figures 7 through 9. In all suites, P-wave velocity decreased with increase in porosity. In Figure 7, OC samples 50 and 51, which displayed higher resistivities, appear to have higher velocities also. In Figure 8, NM samples 2 and 55 exhibit higher velocities than expected for their porosities. NM2, which is an extremely fine-grained dark gray basalt, also showed a higher electrical resistivity than would be predicted on the basis of its porosity.

FIG. 7. Variation of *P*-wave velocity with porosity, OC suite.

FIG. 8. Variation of *P*-velocity with porosity, NM suite.

FIG. 9. Variation of *P*-velocity with porosity, C suite.

FIG. 10. Relation between grain density and *P*-velocity, C suite.

The effect of porosity on the P-wave velocities of the Columbia Plateau (C) is shown in Figure 9. Experimental points of this suite appear to result in two relationships represented by two parallel lines. This suggests that the Columbia Plateau suite has two distinct groups, a high-velocity group and a low-velocity group. No readily noticeable distinction in texture or composition between the two groups is apparent. The relationship between grain density and P-wave velocity for this suite is shown as a scatter diagram in Figure 10. It is apparent that a clear-cut dependence of P-wave velocities on densities is absent. The high-velocity and low-velocity samples form separate clusters of points in this figure. Apparently, grain density, which reflects chemical composition, is not the cause of the existence of two distinct velocity groups in this suite of volcanics. A detailed petrographics study of the samples is underway to investigate differences in texture and pore configuration of the two groups.

When P-wave velocity-porosity graphs for the three suites of volcanics are combined (Figure 11), we begin to realize the emergence of two distinct velocity classes of volcanics. The low-velocity class is composed of the New Mexico suite and the low-velocity group of the C suite. The high-velocity class is composed of the OC and the high-velocity group of the Columbia Plateau volcanics. The P-wave velocity least-square lines for the high-velocity volcanics appear to converge to the same velocity at zero porosity, thus suggesting similar matrix velocity. The convergence to the same velocity at zero porosity for the low-velocity volcanics is not apparent. This lack of convergence may be caused by slight inaccuracy in defining the least-square lines as evidenced by the appreciable scatter in the NM suite velocity-porosity graph.

A measurable increase in seismic-velocity with temperature (up to 100°C) was observed in water-saturated samples (Table 1). The effect of variation of water saturation on P-wave velocities has been studied on a limited number of samples. No measurable effect of saturation variation on P-velocities has been observed (Table 1). For most samples studied, matrix P-wave velocities are significantly higher than the P-wave velocity in salt water in the pore space of samples. Therefore, seismic energy transmitted partially through salt water in pores is expected to arrive later than energy traveling through the rock matrix alone, and the corresponding signal is usually masked by noise.

Conclusions

Seismic P-wave velocities and electrical resistivities of recent volcanics saturated with salt solution depend strongly on porosity. Recent volcanics have higher resistivity than sedimentary and other crystalline

rocks, but they appear to divide into two distinct classes depending on P-wave velocities - a low- and a high-velocity class. Electrical resistivity of the suites studied decreased with increase in temperature and water saturation. The electric resistivity is more sensitive to temperature changes at lower temperature. Seismic P-wave velocities appeared not to depend upon saturation or temperatures.

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$$\phi = -A \log V + B$$

SUITE	B	A
CI	5.09	1.35
C2	4.80	1.35
OC	3.76	1.0
NM	3.26	0.90

FIG. 11. Relation between *P*-wave velocity and porosity for all suites.

Table 1. Effects of saturation and temperature on *P*-wave velocity sample number C13.

100% saturation		70% saturation		62% saturation		50% saturation	
Temp (°C)	P T* (μsec)	Temp (°C)	P T (μsec)	Temp (°C)	P T (μsec)	Temp (°C)	P T (μsec)
23	17.2	57	17.6	19	17.0	19	17.0
28	17.2	62	17.6	25	17.0	32	16.9
49	16.4	66	17.6	36	16.8	40	16.8
52	16.4	71	17.6	46	16.9	54	17.0
53	15.9	76	17.6	54	17.0	60	17.0
65	16.0	81	17.8	66	17.0	71	17.0
71	15.8	85	17.8	76	17.0	83	16.9
76	15.7	92	17.7	84	17.1	91	17.0
82	15.6			94	17.3	97	17.3

*PT is *P*-wave transit time.

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Appendix

Cenozoic volcanic rock samples in this study were collected from three localities, as listed below. Fresh unweathered field samples ranged between one and three kilograms. Sample selection procedure was designed to allow a representative, vertical and lateral, coverage of the volcanic sections samples.

- (1) Columbia Plateau suite, designated as C. Samples collected from Columbia Plateau volcanic basin in southeastern Washington, northeastern Oregon, and western Idaho. Basalt lava flows dominate this suite with some interbedded clastics.
- (2) Jemez volcanic field, North Central New Mexico, designated NM Pliocene-Quaternary rhyolites and basalts.
- (3) Cascade Range volcanics, Oregon, designated OC. Miocene-Quaternary mainly lava flows.