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INITIAL MEASUREMENTS OF PETROPHYSICAL PROPERTIES ON ROCKS FROM THE LOS AZUFRES, MEXICO, GEOTHERMAL FIELD

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INTRODUCTION

Petrophysical properties of geothermal reservoir rocks are valuable information for many activities, including reservoir characterization, modelling, field test analysis and planning of exploitation techniques. Petrophysical data of rocks from geothermal reservoirs located in volcanic areas is in general very scarce. In particular, no petrophysical data of rocks from the Los Azufres geothermal field area has ever been published.

This work presents the results of initial petrophysical studies on outcrop rocks and drill core samples from the Los Azufres geothermal field. These studies are the first part of an ongoing experimental program intended to establish a data-base about physical properties of the Los Azufres rocks, in support of the many reservoir engineering activities which require of such information.

The experimental work carried out consisted of laboratory measurements of density, porosity, permeability, compressibility, thermal conductivity, thermal expansion, electrical resistivity and sonic wave velocities. Some of the experiments were aimed at investigation of the effects of temperature, pressure, saturation and other parameters on the physical properties of rocks.

DESCRIPTION OF SAMPLES

The specimens for this study were cut from outcrop rocks collected at eight sites in the Los Azufres area and drill core samples from the wells A1, A5, A9 and A19. Fig. 1 is a map showing the approximate location of the outcrop sampling sites, which are indicated by numbers 1 to 8, and the four wells.

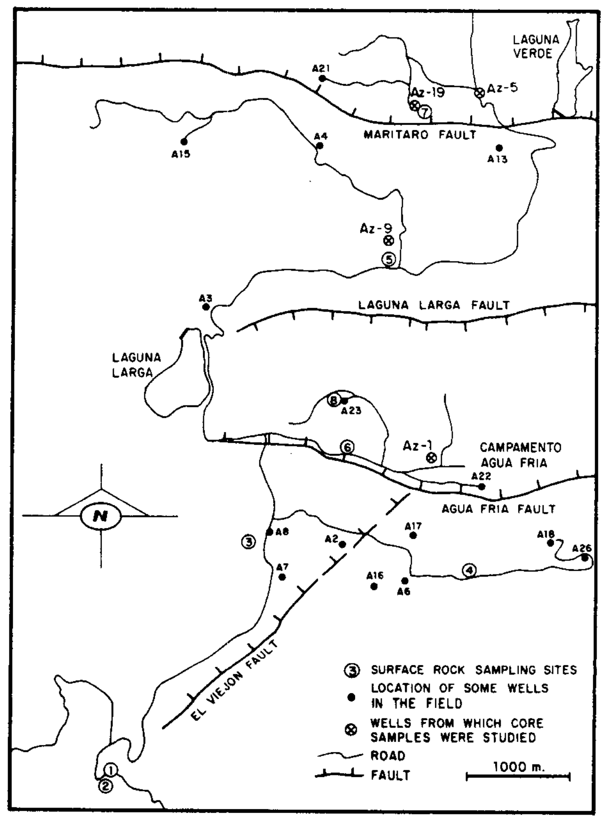

Fig. 1. Map of the Los Azufres Geothermal field area showing the approximate location of the outcrop sampling sites and wells.

Taking into account the geology of the area, the outcrop rocks were sampled from specific sites thought to be representative of the subsurface formations. Care was taken to avoid sampling outcrop rocks showing evidence of weathering processes. The drill core samples were provided by Comision Federal de Electricidad (CFE) from its valuable stock of cores retrieved during drilling operations.

The petrographic classification of the rocks and the depths from which drill core samples were cut are indicated in Table 1.

Table 1. Origin and Petrographyc classification of samples

Sample No.	Sampling Site	Depth (m)	Petrographyc Classification
1	1	----	Microlitic Andesite
2	2	----	Pyroxene Andesite
3	3	----	Microlite Andesite
4	4	----	Porfiritic Andesite
5	5	----	Ignimbrite
6	6	----	Riolite
7	7	----	Microlitic Andesite
8	8	----	Riolite
A1	Well A1	1825	Pyroxene Andesite
A5	Well A5	1160	Porfiritic Andesite
A9	Well A9	1705	Porfiritic Andesite
A19	Well A19	1000	Microlitic Andesite

EXTENT OF THE STUDIES AND EXPERIMENTAL PROCEDURES

Dry bulk density and effective porosity were determined on five specimens of each outcrop sample and each drill core sample. Measurements were accomplished using a set of techniques recommended by the International Society for Rock Mechanics as "Suggested Method for Porosity/Density Determinations Using Mercury Displacement and Boyle's Law Techniques", (ISRM, 1972). Density and porosity values obtained using these techniques are accurate to within ±1 kg/m^3 and ±0.1 porosity percent, respectively.

Absolute permeability was measured on three specimens of the sample A5, five specimens of the sample A9 and five specimens of the sample A19. Measurements were carried out at room conditions using a Core Lab gas permeameter. Dry air and bottled nitrogen were used as permeating fluids. Gas permeability results were corrected to take into account the slippage Klinkenberg effect, thus obtaining equivalent liquid permeability values. Corrections were carried out using the charts recommended by Core Lab. It is estimated that permeability values are accurate to ±5% of the actual permeability.

Bulk compressibility was measured on two specimens of the sample from outcrop site number 1, one specimen of the sample A9 and two specimens of the sample A19. All the specimens were cylindrical, 2.5 cm diameter by 5 cm length, and were tested in dry condition. The specimens were jacketed with teflon tubing to prevent the confining fluid from entering the pore spaces. Hydrostatic stress was applied in the range from 0 to 420 bar and it was cycled at least three times to investigate hysteresis and repeatibility phenomena in the behavior of the rocks. The hydrostatic stress was varied at a uniform rate of about 40 bar/min. The linear compaction along the longitudinal axis of the specimens was continuosly measured as a function of the hydrostatic pressure. To investigate the effects of temperature on compressibility, measurements at 25°C and 250°C were carried out on some specimens.

Compressional and shear wave velocities were measured on a specimen from the sampling site number 7. The specimen, 5 cm diameter by 5 cm legth, was tested in dry and water-saturated conditions, and in both cases it was subjected to uniaxial compressive stress along its longitudinal axis. Starting at 25 bar, the stress was increased in 25 bar steps up to 150 bar. Wave-velocity measurements were carried out at every stress level in the direction of the longitudinal axis of the specimen. The testing temperature was 25°C. The velocities were measured with the pulse first-arrival technique, in which the time required for an elastic wave pulse to traverse a sample of known length is determined. The apparatus and the technique used have been described by King (1970). The accuracy of the velocity measurements is ±0.4%.

Electrical resistivity was measured on a specimen, 5 cm diameter by 5 cm length, from the sampling site number 7. The specimen was saturated using brines of two different concentrations. The testing temperature was 20°C. The specimen was subjected to four hydrostatic stress levels in the range from 7 bar to 100 bar. The electrical resistivity was measured at every stress level and for each of the saturating conditions as a function of frequency in the range 10 Hz to 100 KHz. The experimental method used is the two-electrode technique as it has been described by King (1977) and by Pandit and King (1979).

Thermal conductivity and diffusivity were measured on a specimen, 5 cm diameter by 10 cm length, of the drill core sample A19. Conductivity was measured at 25°C, 150°C and 250°C on the dry specimen subjected to 80 bar confining pressure. The technique used is the transient line heat source method as described by Woodside and Messmer (1961). Conductivity values determined with this technique are accurate to within ±5%. Diffusivity was only measured at 250°C. The technique used is based upon a classical heat transfer model presented by Carslaw and Jaeger (1959), which allows determinations to be carried out with an accuracy of ±5%.

Linear thermal expansion was measured on a specimen, 2.5 cm diameter by 5 cm length, from sampling site number 1. The specimen was subjected to a 50 bar confining pressure and was jacketed with teflon tubing to prevent the confining fluid from entering the pore spaces. Temperature was increased from 20°C to 280°C at a uniform rate of 1.5°C/min. The linear thermal expansion was continuosly measured along the longitudinal axis of the specimen as a function of temperature. The overall accuracy of the measurements is ±5%.

RESULTS AND DISCUSSION

Table 2 shows the density and porosity results. The reported figures are the mean values of the individual determinations carried out on five specimens of each sample. The standard deviation of the individual determinations is also indicated in Table 2.

Fig. 2 shows the relationship between the mean values of the porosity and density results, along with a density-porosity correlation for Cerro Prieto sandstones reported by Contreras (1983), which is presented here for comparison purposes. The Cerro Prieto rocks data shows an excellent linear correlation. On the basis of the conceptual relations between porosities and densities of rocks, this correlation can be interpreted as indicating that Cerro Prieto sandstones feature uniform grain density and non-isolated porosity. On the other hand, the Los Azufres rocks data disperses significantly from the linear correlation defined by its best fit line, although a general trend of correlation is observed. The deviations from the linear correlation probably are a cosequence of isolated porosity and variations in grain density in the Los Azufres rocks.

Table 2. Results of Dry Bulk Density and Effective Porosity Measurements

	Density (gr/cm^3)		Porosity (%)	
	Mean Value	Std. Dev	Mean Value	Std. Dev
1	2.67	0.03	1.8	0.3
2	2.46	0.02	9.3	1.0
3	2.83	0.03	2.6	0.4
4	2.25	0.01	8.0	0.9
5	1.53	0.02	20.5	1.5
6	2.05	0.01	8.7	1.1
7	2.65	0.02	1.7	0.3
8	2.25	0.03	3.5	0.4
A1	2.72	0.01	2.1	0.4
A5	2.40	0.02	12.0	1.2
A9	2.66	0.03	3.2	0.3
A19	2.31	0.03	16.8	1.2

Table 3 shows the results of the permeability measurements. Regardless of their medium to high porosities, the specimens of the samples A5 and A19 gave low permeability values. For most of the Cerro Prieto sandstones of comparable porosities, permeabilities are two to three orders of magnitude higher, which suggests poor pore conectivity in the Los Azufres rocks. The specimens of the low-porosity sample A9 also gave low permeabilities, excepting the specimen A9-3 for which the measured permeability was unexpectedly high. Close examination of this specimen shown a microfracture from one side to another along the direction of the applied flow, thus explaining the higher permeability and illustrating the relative importance that pores and fractures may have in the process of fluid conduction through a fractured rock mass.

Table 3. Permeability Results

Specimen	Porosity (%)	Permeability (microdarcy)
A5-1	9	94.0
A5-2	10.2	179.0
A5-3	10.1	181.0
A9-1	2.1	2.8
A9-2	---	< 1.9
A9-3	2.8	2224.0
A9-4	3.1	< 1.9
A9-5	1.0	< 1.9
A19-1	14.7	3.8
A19-2	15.1	41.0
A19-3	15.2	11.0
A19-4	15.2	4.2
A19-5	14.2	< 1.9

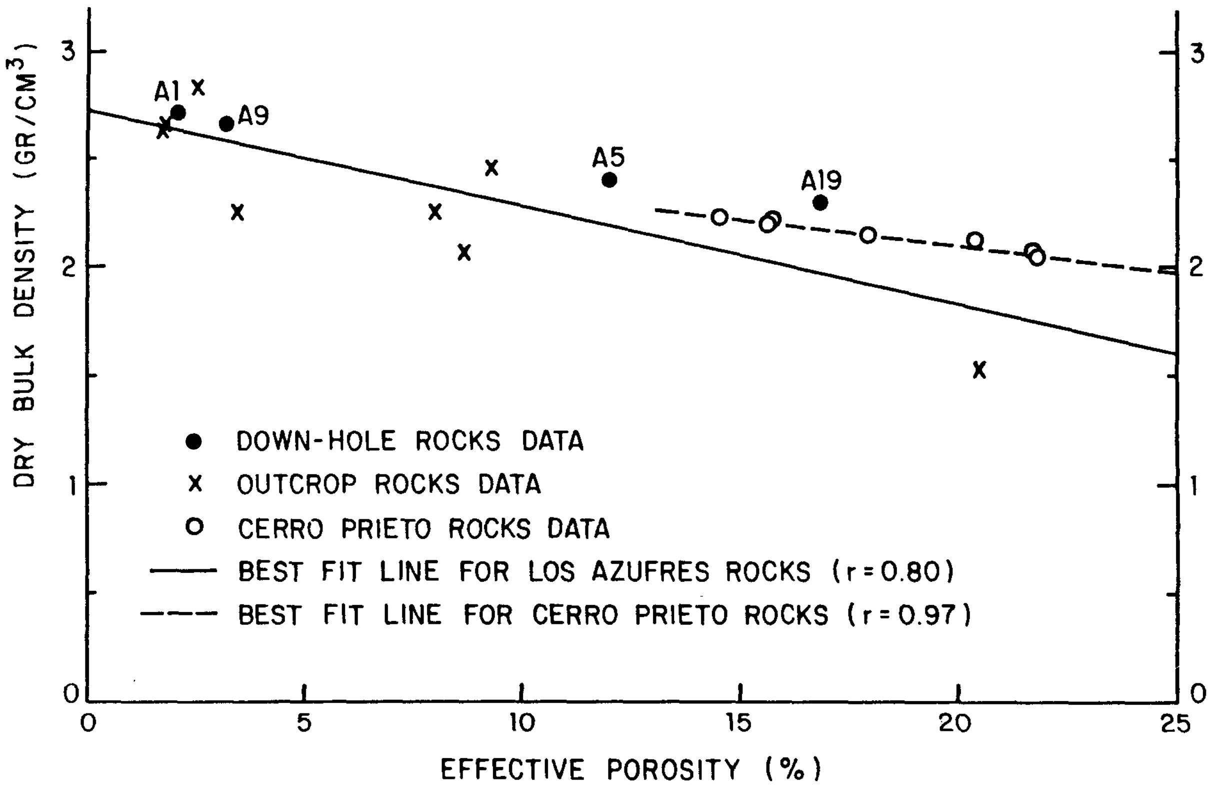

Fig. 2. Relationship between effective porosity and dry bulk density for Los Azufres and Cerro Prieto rocks.

The results of the acoustic velocities are shown in Fig. 3. Compressional and shear wave velocities were observed to increase slighty with increase in axial stress for both the dry rock and the saturated rock. Saturating the specimen resulted in slightly higher compressional-wave velocities and slightly lower shear-wave velocities. The slight effects of the axial stress and the saturation on the acoustic velocities were in agreement with the low porosity of the specimen tested (1.2%).

Compressibility results are shown in Fig. 4, wherein the volumetric bulk compressibility coefficients of the specimens tested are plotted as a function of hydrostatic pressure. The volumetric compressibility coefficients were calculated as three times the corresponding linear compressibility coefficients, which in turn were determined as the slopes of the linear compaction against hydrostatic stress plots. As it was expected, the more porous rocks were also the more compressible. Compressibility decreased with increasing pressure; this effect being more pronounced for the specimens with higher porosity.

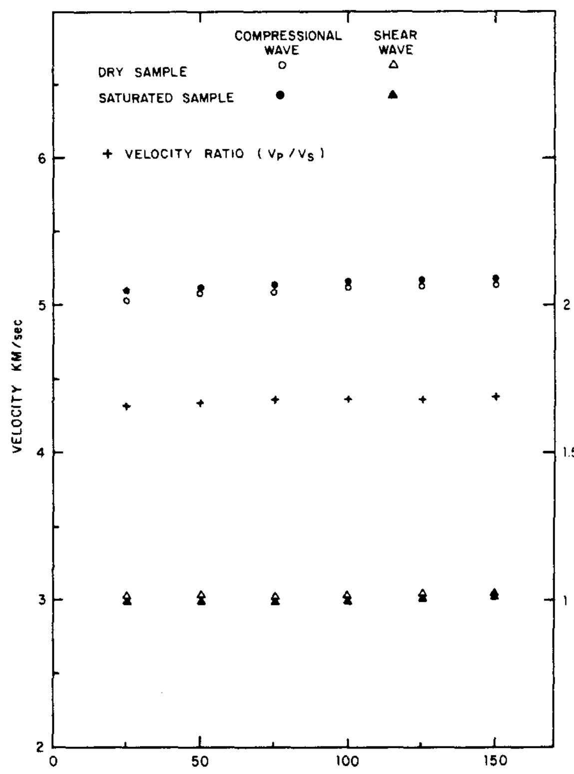

Fig. 3. Compressional and shear-wave velocities as functions of axial stress and saturation for a microlitic andesite specimen from sampling site number 7.

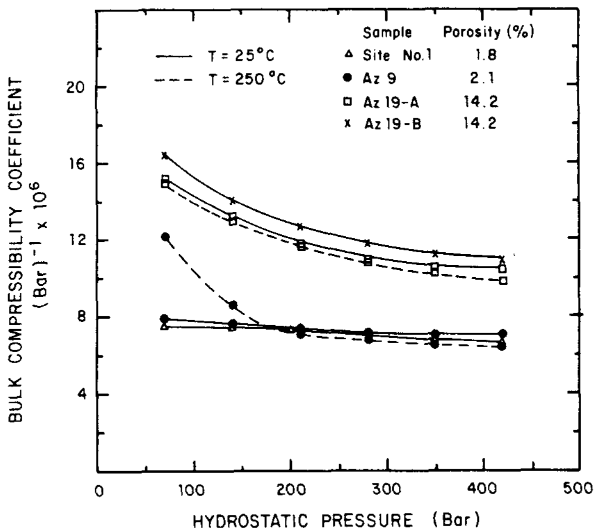

Fig. 4. Bulk compressibility coefficients of the Los Azufres rocks as functions of hydrostatic pressure.

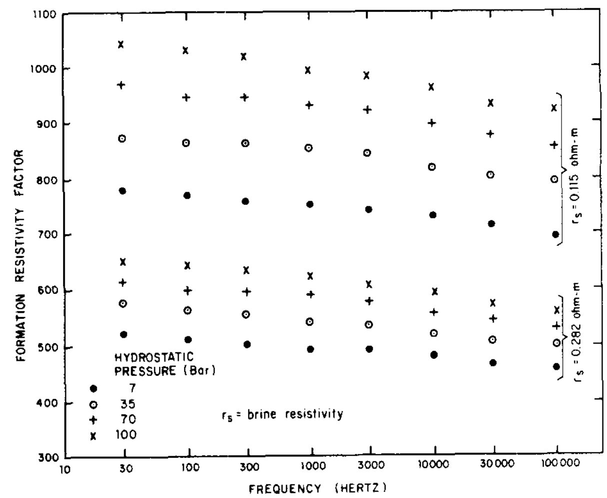

Fig. 5. Resistivity formation factor of a microlitic andesite specimen as function of frequency, hydrostatic pressure and saturating brine resistivity.

For the specimen of the sample A9, increasing the temperature from 25°C to 250°C resulted in higher compressibility only at low pressure values. No temperature effect was observed on a specimen of the sampling site number 1. Regarding the effects of hydrostatic stress cycling, for all of the specimens tested a very repeatable behavior was observed, with no compaction remaining upon completion of the loading-unloading cycles.

However, hysteresis loops were observed in all the cases, more pronouncedly for the more porous rocks.

The electrical resistivity results are shown in Fig. 5, wherein resistivity formation factors calculated from the resistivities measured are plotted as function of frequency. The formation factor exhibits an inverse frequency dependence, which can be interpreted as indicating the existence of a reactive resistivity component caused by either a ionic double layer at charged clay surfaces or mineral metallic components distributed in the rock. A consistent increase in the formation factor with increased hydrostatic pressure was also observed. This can be originated by alterations in the paths through which the electrolytic conduction takes place. Regardless of the low porosity of the specimen tested (1.2%), the effect of pressure on electrical resistivity is remarkable. This phenomenon suggests that even moderate stress variations on the rocks can significantly modify the pores and fractures and originate changes in other related properties such as permeability. The formation factor was also observed to depend upon brine saturant resistivity. This phenomenon is a separate evidence that suggests the ocurrence of electrical conduction through a way different to the electrolytic way. The increase in formation factor with brine resistivity is probably due to the lesser importance of the effect of mineral surface conductivity as the brine saturant resistivity decreased.

Table 4 shows the thermal conductivity and diffusivity results. Conductivity was observed to decrease moderately with increasing temperature. The conductivity values reported here are within the range of the conductivities at 20°C reported by Clark (1966) for a wide variety of igneous rocks (1.6 to 4.0 Watt/m-°C). The specific heat

Table 4. Thermal Properties

Temperature °C	Conductivity Watt/m-°C	Diffusivity cm^2/sec	Specific Heat cal/gr-°C
25	2.00	----	----
150	1.80	----	----
250	1.75	0.66	0.28

value reported in Table 4 was calculated from the conductivity and diffusivity data at 250°C and the dry bulk density at room conditions.

Fig. 6 shows the result of the thermal expansion test. The linear thermal strain measured along the longitudinal axis of the specimen is plotted against temperature. It was observed that the linear thermal expansion coefficient, as given by the slope of the strain against temperature plot, exhibits a significant dependence upon temperature.

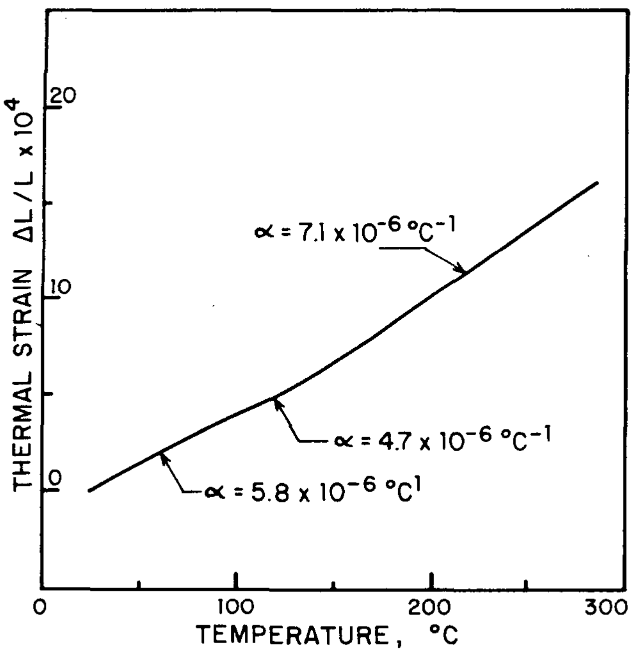

Fig. 6. Linear thermal expansion of a microlitic andesite specimen.

CONCLUSIONS

In this work, the first laboratory-determined data about physical properties of rocks from the Los Azufres geothermal field area has been presented. Due to the limited extent of some of the measurements carried out, no claim can be stated about the representativity of the values reported. However, these results can be useful, at least, as indicators of the orders of magnitude that can be expected for the values of the physical properties of the Los Azufres rocks.

The density, porosity, permeability and compressibility results indicate that the values of the physical properties of the Los Azufres rocks range between wide limits.

It was observed, corroborating similar observations already published elsewhere, that temperature, pressure, saturation as well as other parameters affect most of the physical properties of rocks. Thus, it must be emphasized that to obtain reliable results on specific applications such as interpretation of geophysical data, well logs and pressure tests, it is necessary that the required data about rock properties be obtained from tests on local rocks, and that measurements be carried out on samples subjected to in-situ conditions.

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