

NOTICE CONCERNING COPYRIGHT RESTRICTIONS

This document may contain copyrighted materials. These materials have been made available for use in research, teaching, and private study, but may not be used for any commercial purpose. Users may not otherwise copy, reproduce, retransmit, distribute, publish, commercially exploit or otherwise transfer any material.

The copyright law of the United States (Title 17, United States Code) governs the making of photocopies or other reproductions of copyrighted material.

Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One of these specific conditions is that the photocopy or reproduction is not to be "used for any purpose other than private study, scholarship, or research." If a user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of "fair use," that user may be liable for copyright infringement.

This institution reserves the right to refuse to accept a copying order if, in its judgment, fulfillment of the order would involve violation of copyright law.

ABSTRACT

Permeabilities were measured as a function of temperature in 6 samples of sandstones from wells M-107, M-127 and M-129 in Cerro Prieto. We found that the dependence of permeability on temperature may be represented by the empirical expression $K=K_0(T/T_0)^{-b}$ with $b>0$. The expression was applied to different aqueous solutions. The magnitudes of K_0 and b depend on the composition of the solution. Through hypothetical examples, we demonstrated that the results of this research may have important consequences for interpreting long-term production results and for reinjection operations.

INTRODUCTION

Most of the petrophysical properties of interest to reservoir engineering vary significantly with confining pressure, pore pressure, temperature, pore fluid composition and degree of saturation (e.g. Sommerton, 1978). This has been partially verified by several authors with rock samples from the Cerro Prieto geothermal field (Sommerton, 1978; Martínez B., 1978; Abou-Sayed et al., 1979; Schatz, 1981).

One of the most important petrophysical parameters in reservoir engineering is permeability. Due to interest in geothermics and in secondary and tertiary recuperation, experimental studies have recently been carried out on the effect of temperature on permeability. Some of the most important studies are summarized below.

Casse and Ramey (1976) studies "Berea", "Boise" and "Bandera" sandstones using distilled water and mineral oil as permeability fluids. These authors concluded that: a) the effect of temperature on permeability depends on the nature of the saturating fluid; b) the effect of temperature is a function of confining pressure and c) the permeability of water decreases as the temperature increases in a basically reversible manner.

Aruna et al. (1977) conducted studies on "Masillon" consolidated sandstone, "Ottawa" unconsolidated sandstone and "Indiana" limestone. They found that there was a reduction in permeability in the "Masillon" and "Ottawa" sandstones when the temperature increased only when

water was used as the permeability fluid, but there was no variation when octanol or mineral oil was used, and that the effect of temperature on the permeability to water was basically reversible.

Gobran et al. (1980) used confined "Ottawa" sand with water as the permeability fluid and found that there was a reduction in permeability when the temperature increased, although the decrease was basically irreversible.

The permeability of sandstones in Cerro Prieto varies with temperature. Sommerton (1978) found that the permeability of sandstone in Cerro Prieto at 155°C was 30% less than at ambient temperature. Subsequently, Abou-Sayed et al. (1979) and Schatz (1981) reported that the permeabilities of four sandstones of Cerro Prieto were consistently lower at high temperatures (230°- 280°C) than at ambient temperature.

The studies mentioned in the preceding paragraph demonstrated the importance of measuring permeability at high temperatures in the specific case of Cerro Prieto, and indicate one possible range of variations in such permeability. In the present study, detailed research was conducted on the dependence of permeability on temperature in six samples of sandstones from wells M-107, M-127 and M-129 of the Cerro Prieto geothermal field and the effect of the aqueous fluid composition on the permeability of such rocks was explored. In the following sections, the equipment used for measuring and the testing procedures is described, the results are presented and the interpretation of the data is discussed. Finally, conclusions are set forth.

EQUIPMENT FOR EXPERIMENTS

The measurements were made at the IIE Petrophysical Properties Laboratory, which has an advanced system called the Geothermal Reservoir Simulator (GRS) for conducting experiments on rocks under controlled conditions of confining pressure, pore pressure, temperature and composition of the permeability fluid. Figure 1 shows a schematic diagram of the main components of this equipment. The GRS may be used to determine mechanical response, thermal properties and

permeabilities of rock samples. A list of the tests that are feasible with this equipment is presented in table 1, together with the related ranges of operation. Note that such ranges approximately cover those found in hydropressurized geothermal reservoirs. Further details regarding this equipment and complementary installations may be found elsewhere (Contreras, 1982).

The main aspects of the experiment system used to measure permeability are briefly described below. The sample to be tested is placed in a pressure vessel and the desired confining pressure and temperature conditions are produced. The confining pressure is produced and controlled with great precision through a servocontrolled pressure intensifier. The sample is heated and the temperature is controlled with an electric heater connected to the inside of the vessel with an automatic control. The pore fluid pressure is produced by accumulators pressurized with nitrogen, one placed upstream and the other downstream from the sample. The separating pistons of each accumulator are attached to a linearly variable differential transducer (LVDT), which sense the displacement of the pore fluid and make it possible to calculate the flow rate through the rock. The pressure gradient through the sample is obtained by establishing a difference in the nitrogen pressure of the accumulators; this difference is controlled with a precision regulator. The fall in pressure through the sample is measured with a diaphragm differential transducer and the pore pressures upstream and downstream from the sample are measured separately by each transducer. The temperature of the sample is measured inside the vessel with a thermocouple. The process of compiling data is carried out automatically under the control of a computerized system of which the central component is a MINC 11 computer.

TESTING PROCEDURE

The 6 samples studied were extracted from three drilling cores of the Cerro Prieto geothermal field. The cores were provided by the Coordinadora Ejecutiva of Cerro Prieto of the Comisión Federal de Electricidad. The wells for each core are identified in table 2 and their depths and locations are indicated. These wells are grouped toward the ENE part of the field near the dividing line between the portions called Cerro Prieto II and Cerro Prieto III. The distances between wells are on the order of 500 m. All the cores

are composed of sandstones typical of Cerro Prieto and M-107 presents a sandstone shale contact that is very well defined at one end. All of the cores show evidence of the invasion of drilling mud to different degrees.

Cylindrical samples 5.08 cm in diameter and 5.08 cm long were carefully cut from these cores in order to carry out permeability tests. Samples were extracted to measure horizontal permeability (identified with H) and vertical permeability (identified with V).

The samples were then submitted to a temperature of 105°C for 12 hours and were saturated in a vacuum with distilled water of brine. Subsequently the samples were properly prepared in accordance with the technique described in the paper by Ennis et al. (1979).

Distilled water was used as the permeability fluid in two cases and synthetic brine similar to that found in the reservoir was used in five cases. Table 3 shows the basic composition of the synthetic brine. At each temperature the silica content was equalled to the related solubility of quartz. After adding silica to the brine, the pH was adjusted to a value of 6.0.

The procedure adopted to conduct the tests consisted of measuring permeabilities at different temperatures, maintaining the confining pressure and average pore pressure constant. The tests were usually initiated at ambient temperatures; then the temperature of the sample was slowly increased (at 1.5°C/minute) until the new desired temperature was reached, after which there was a period of stabilization lasting at least half an hour before the following stage was initiated. The previous process was repeated until the maximum programmed temperature was reached. Finally, permeability was once again measured at ambient temperature in order to investigate reversibility. In certain cases, permeability was also measured at different confining pressures, maintaining the temperature constant.

During the tests, readings of all the parameters of interest were taken every three minutes. As the information was gathered, it was listed on computer printouts and simultaneously stored on magnetic disks. The information on the printouts was used to monitor the development of the test and the data stored on magnetic disks was used during the final stage when data was reduced and analyzed and results were calculated.

The results of these tests are presented in table 4-10. Errors calculated for the permeabilities reported do not surpass 3% and are generally less. In some cases, permeabilities varied during the measuring at constant temperatures, confining pressure and pore pressure. In such cases, the permeabilities measured at the beginning and at the end of the related stage are included in the tables and the initial permeability is always recorded above the final permeability.

DISCUSSION

The results presented in tables 4-10 indicate that permeability decreases as temperature increases. In some cases, this phenomenon is only observed between ambient temperature and intermediate temperatures (Tables 5 and 8). In most cases, however, this phenomenon occurs throughout the range, which goes from ambient temperature to high (>200°C) temperature (Tables 4, 6, 7 and 10). Such dependence of permeability on temperature was recognized in different sandstone by Casse and Ramey (1976) and by Aruna et al. (1977) and has been previously reported for sandstone in Cerro Prieto (Sommerton, 1978; Abou-Sayed et al., 1979; Schatz, 1981). In this section, we present evidence that, in the absence of irreversible phenomena that affect permeability, such as dissolution, scaling or sealing with fine particles, the permeability of Cerro Prieto sandstones varies with temperature in accordance with the formula:

$$K = K_0 (T/T_0)^{-b} \quad (1)$$

where $K(K_0)$ is the permeability at temperature $T(T_0)$, T_0 is an arbitrary reference temperature and b is a positive constant. If formula (1) correctly describes the relation between permeability and temperature, the plot of $\log K$ versus $\log T$ should be a straight line. Figs. 2 and 3 are the log-log graphs for samples M-107 V3 and M-129 V3, respectively. The points considered for adjusting the straight lines by the least squares method were those marked with the numbers 2, 3, 5, 6 and 7 for M-107 V3 and with numbers 1 to 5 for M-129 V3. The adjustment is excellent as may be seen by the related correlation coefficients: -0.984 and -0.989 respectively.

In the case of sample M-107 V3, points 1, 4 and 8 were excluded from the correlation because they correspond to confining pressures different from those

established for the test (see Table 6); point 9, a control point, indicates that an irreversible increase in permeability took place, attributable to dissolution, and it was also excluded from the correlation. Note that the reduction in permeability when the temperature increased was produced in spite of the (alleged) dissolution. By the same token, in the case of sample M-129 V3, points 6, 8 and 9 were excluded from the correlation because they did not correspond to the proper confining pressure (see Table 10); control points 7 and 10 showed irreversible decreases in permeability, attributable in increases in the confining pressure of the immediately preceding points (Table 10), so they were also excluded from the correlation.

The behavior of the two samples discussed in the preceding paragraph provides strong evidence that the proposed empirical expression (1) is valid at the approximate temperature interval from 20 to 280°C. In the following four paragraphs, the evidence available regarding the validity of expression (1) for narrower ranges of temperature is discussed, in addition to its possible extension to temperature on the order of 280°C or greater. Such ranges of validity, which are apparently narrower, are associated with water-rock interaction phenomena that cause irreversible changes in permeability. When the effects of irreversible changes in permeability can be removed, the potential law proposed (1) is valid, at least within the range of 20°C - 280°C, as is shown further on.

Figure 4 is the log-log diagram for sample M-107 V1. In this case, only points 1 -4 (23.5°C to 210°C) in Table 4 were taken into consideration in the correlation. During heating between point 4 and point 5 (210°C to 255°C), which was carried out without the passage of flow through the sample, an increase in permeability from 0.005 to 0.013 md was produced in approximately 1,700 seconds; immediately thereafter, during the run to 255°C, a new increase in permeability from 0.013 to 1.155 md was produced in approximately 6,700 seconds. The implied speed in permeability changes, 5×10^{-6} and 2×10^{-5} md/s, respectively, and the related flow conditions are consistent with the hypothesis that increases in permeability are caused by dissolution. Thus, points 5 -7 of Table 4 were excluded from the correlation. Control point 8, at 24°C, which supports the inference that an irreversible increase in permeability attributed to dissolution was produced throughout the test, could not be used in

the adjustment to the straight line either. The adjustment by the least squares method yielded a correlation coefficient equal to -0.994, which we consider excellent. Note that point 3 at 23°C, after having heated the sample from 23.5°C to 112°C (points 1 and 2, Table 4), presents strong evidence of reversibility in the absence of dissolution.

The log-log diagram in figure 5 shows the permeability results for sample M-107 H4 obtained using distilled water as the fluid (Table 7). In the adjustment by the least squares method, points 1 to 3 (25°C to 200°C) were included. Point 4 at 265°C was excluded, because an irreversible increase in permeability was suspected. Point 5 was excluded because the confining pressure was twice as great as that considered for the rest of the points. In this manner, we obtained a correlation coefficient equal to -0.998. If point 4 is also included, the correlation coefficient is -0.853, which is still significant.

In order to study the effects of pore fluid composition on permeability, the permeability of M-107 H4 as a function of temperature was measured with brine. This test was difficult. The first point at ambient temperature was lost owing to an accidental problem in the data collecting system, which it was impossible to note before the end of the subsequent tests. Thus, the first point presented is that at 66°C (Table 8). In the three subsequent points, increases in permeability took place in the measurement taken at constant temperatures. At 94°C and 130°C the effect was not so severe. The significant increase in permeability recorded between 130°C and 186°C was considered irreversible because of the tendency observed in points 2, 3 and 4, and the irreversible increase in permeability shown by control point 7 at 66°C. Thus, only points 1, 2 and 3 were included in the adjustment by the method of least squares and the permeabilities measured initially in the respective runs were chosen for points 2 and 3 (see Table 8). A correlation coefficient of -0.989 was obtained in this manner. The related log-log diagram is shown in figure 6.

Another sample that presented difficulties was M-127 V2 (see Table 9). Between the point at 23°C and the point at 58°C, there was an initial decrease in permeability. The permeability measured at 58°C, however, increased over time until it reached 1.82 md, thus surpassing the permeability measured at 23°C. Similarly, when going from 2 to 3 and from 3 to 4, an initial reduction in permeability was produced, but the permeabilities at the

respective temperatures increased over time. Finally, control point 8 at ambient temperature indicated an irreversible increase in permeability, in comparison with point 1. In an attempt to separate reversible from irreversible effects, we assumed that the variation in permeability measured in relation to the initial point, is the same that would be produced in the absence of irreversible effects (presumably dissolution). On this hypothesis, corrections that appear in Table 11 were calculated using the following algorithm:

$$K_{j+1}^* = \{K_{j+1}(\text{initial})/K_j(\text{final})\} K_j^* \quad (2)$$

where K_j^* are the corrected values, K_j are the values measured and the words "initial" and "final" refer to the values measured at the beginning and end at each temperature. The corrected permeability at 270° is calculated as $K_7^* = (K_7/K_8)K_1^*$.

The log-log diagram of corrected permeabilities is presented in figure 7. For the data presented in the same figure, a correlation coefficient equal to -0.843 was calculated. The adjustment is quite good, considering the manipulations required by the correction process. The degree of agreement with the proposed potential law is such that it is difficult to consider it fortuitous. Thus, we believe that this case demonstrates that the proposed potential law is valid when the irreversible changes in permeability are removed.

The results obtained from sample M-107 H2 (Table 5) only contributed evidence of relatively poor quality regarding the dependence of permeability on temperature. Between 24°C and 108°C, there was a reduction in permeability and, at the end of a complete cycle, a similar decrease in permeability took place between points 5 and 6 (25°C and 110°C). The other data presented illustrate the difficulty experienced in interpreting experiments of this type.

Finally, the data of Sommerton (1978) provide independent experimental evidence that expression (1) represents the dependence of permeability on temperature for sandstones of Cerro Prieto when the irreversible effects are small. In figure 8, we have plotted the data presented by Sommerton for an unidentified sandstone of Cerro Prieto on a log-log diagram. Of the six original points, only the last, which indicates an irreversible reduction in permeability, was excluded. We obtained a correlation coefficient of -0.990 for these data.

The results discussed in the preceding paragraphs constitute a body of evidence that supports the proposed empirical equation (1). Note that this equation is applicable for different permeability fluids: distilled water (samples M-107 V3 and M-107 H4), brine (the rest of the samples measured in this study) and KCl solution (Sommerton's data). The permeability of brine, however, seems to be substantially better than distilled water, as indicated by the results obtained in samples M-107 H4 and M-107 V1. This characteristic is probably associated with the expansion of clays.

As mentioned above, the data were adjusted by the method of least squares using expression (1). In this manner, the values of K_0 were obtained, with K_0 arbitrarily defined as the permeability adjusted to 25°C, and values of b , the absolute value of the slope of the straight line in the log-log diagram. These values are summarized, together with the correlation coefficients, in Table 12. Sommerton's data were originally presented as the ratio between permeability at temperature T and at ambient temperature; thus, it was impossible to calculate the related value of K_0 .

The data in Table 12 show great variations in permeability in the core of well M-107. These variations are caused, in part, by the use of different permeability fluids (water and brine). For the samples measured using brine, the variations seem to be due to two factors: (a) the horizontal permeabilities tend to be notably greater than the vertical permeabilities; and (b) the petrology varies quite rapidly along the approximately 30 cm of the core. In the same core, it may be observed that the size of the grain decreases from sample M-107 V1 (typical sandstone), extracted from one end of the core, toward sample M-107 H4, which was extracted from the part closest to a sandstone-shale contact with very fine grain present in the opposite end of the core and similar to the grain of construction cement. The location of the other samples in the core is between samples M-107 V1 and M-107 H4 and is indicated by their numbers. The core of well M-107 studied in this project is a dramatic example of permeability variation in an area with facies changes.

The range of variation found for exponent b in this study is quite broad, between 0.085 and 2.4. The magnitude of b depends on the nature of the permeability fluid, as may be seen from the measurements taken with distilled water and with brine in sample M-107 H4 (Table 12). There are indications that the magnitude of b also depends on the confining pressure: if a

straight line is drawn between points 4 and 8 of figure 2, which correspond to confining pressures of 24 MPa (twice the value for points used in this study, Table 6), a decrease of 15% in the magnitude of b is found; furthermore, points 6 and 8 of figure 3, which correspond to a confining pressure 2.2 times greater than that adopted for the adjustment (Table 10), also suggest that increasing confining pressure tends to decrease the slope in the log-log diagram.

The data available are insufficient to investigate the possible correlation between values of K_0 and b . This correlation could be affected by different factors, including the permeability fluid, the confining pressure and whether the permeability in question is vertical or horizontal.

CONCLUSIONS AND SIGNIFICANCE

The main conclusion of this study is that, no measuring irreversible mechanisms, the permeability of the sandstones in Cerro Prieto varies with temperature, in accordance with the empirical expression $K = K_0 (T/T_0)^{-b}$, with $B > 0$, in the range of temperatures between 20°C and 280°C. This expression is valid for both horizontal and vertical permeabilities and may be applied equally to permeabilities measured with distilled water and with aqueous salting solutions. The potential law describes reversible changes in permeability; it is not applicable to irreversible changes in permeability such as those associated with dissolution or precipitation of minerals, the plugging of pore throats with fines or creep.

The magnitude of b depends on the composition of the permeability fluid and, probably, on the magnitude of the confining pressure. In the immediate area around the sandstone/shale contacts (some tens of centimeters) sharp permeability gradients are produced.

Finally, our results confirm previous observations that indicate that the permeability of sandstone in aqueous saline solutions is greater than in distilled water.

This type of dependence of permeability on temperature may significantly affect the productivity of certain horizons during exploitation and reinjection operations. During exploitation, the temperature of formations adjacent to the wells decreases (in Cerro Prieto falls in temperature up to 20°C have been recorded); for a

reduction from 320°C to 300°C, the permeability of a formation with the characteristics of sample M-107 V1 would increase 17%, with a consequent increase in production. In reinjection operations, which generally induce considerable decreases in temperature around the reinjection wells, the impact could be even more dramatic: for a reduction in temperature from 320°C to 170°C, the related increase in the permeability of a formation with the characteristics of sample M-107 V1 would be 356%. This indicates that the injectivity of reinjection wells may increase considerably as they become older because of the variation of permeability with temperature. Thus, it may be deduced that a desirable characteristic for reinjection horizons

is to have high b values.

ACKNOWLEDGEMENTS

The authors would like to thank Mr. Alfredo Mañón and Mr. F. Bermejo of the Coordinadora Ejecutiva de Cerro Prieto for their interest and encouragement in carrying out this study.

Martín Uribe F. collaborated in experimental work for the study and Adrián Patiño M. prepared the figures.

This work forms part of the Cooperation Agreement between the Instituto de Investigaciones Eléctricas and the Petroleum Engineering Department of Stanford University.

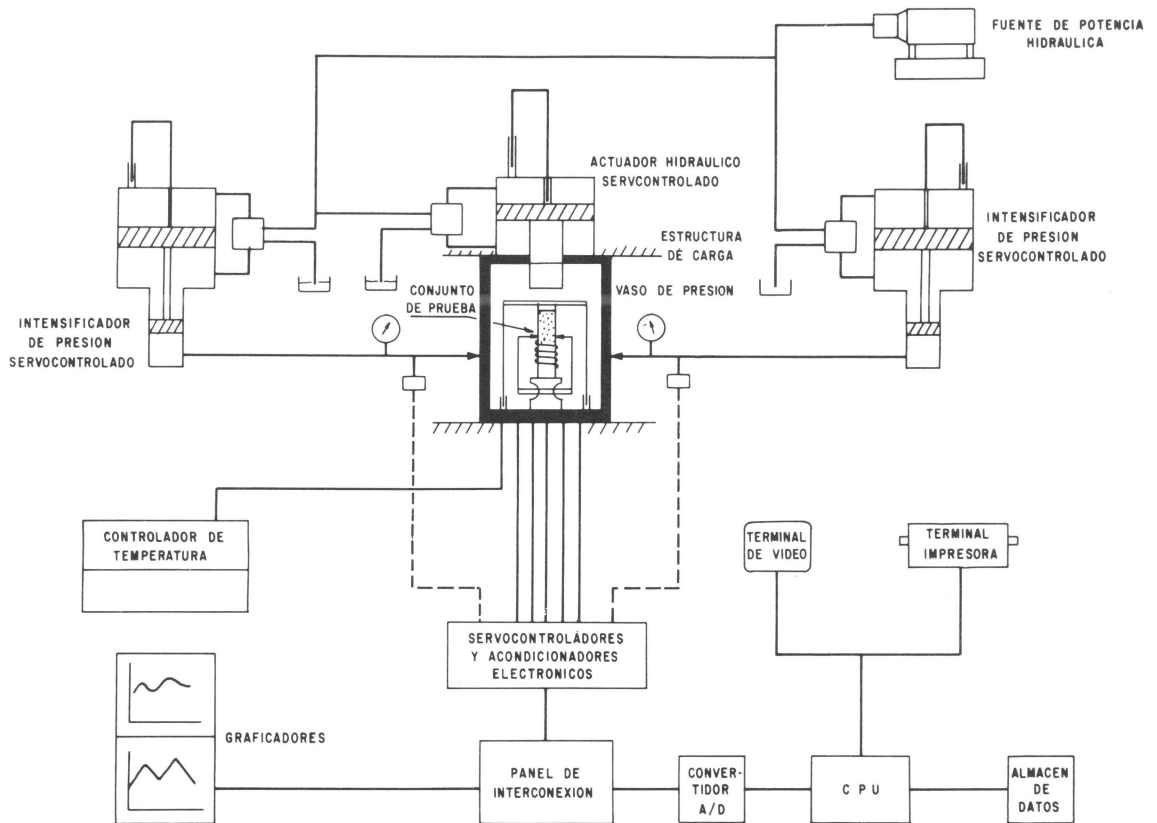


FIG. 1.- DIAGRAMA ESQUEMATICO DEL SIMULADOR GEOTERMICO.

TABLA I.- CAPACIDAD DEL SIMULADOR GEOTERMICO

		RANGOS DE OPERACION		
	TIPO DE PRUEBA	TEMPERATURA °C	PRESION DE CONFINAMIENTO MPa	PRESION DE PORO MPa
COMPORTAMIENTO MECANICO	TRIAxIAL	20 - 380	0 - 104	0 - 104
	COMPRESION SIMPLE	20 - 380	0 - 104	0 - 104
	COMPRESION HIDROSTATICA	20 - 380	0 - 104	0 - 104
PROPIEDADES TERMICAS	EXPANSION TERMICA	20 - 380	0 - 104	0 - 104
	CONDUCTIVIDAD TERMICA	20 - 380	0 - 104	0 - 104
	DIFUSIVIDAD TERMICA	20 - 380	0 - 104	0 - 104
PERMEABILIDAD	METODO DE REGIMEN PERMANENTE BOMBA DE DESPLAZAMIENTO CONSTANTE Y MEDIDOR DE FLUJO. (1 mD - 1 D)	20 - 300	0 - 104	0 - 104
	METODO DE REGIMEN PERMANENTE PRESURIZACION CON ACUMULADORES HIDRAULICOS. (10 yD - 10 mD)	20 - 300	0 - 104	0 - 41
	METODO DE REGIMEN TRANSITORIO (.1 yD - 200 yD)	20	0 - 104	0 - 104
	CONDUCTIVIDAD DE FRACTURAS { HASTA 10 D HASTA 500 D	20 - 300	0 - 104	0 - 104 0 - 41

El ajuste es excelente, como lo atestiguan los correspondientes coeficientes de correlación: -0.984 y -0.0989 respectivamente.

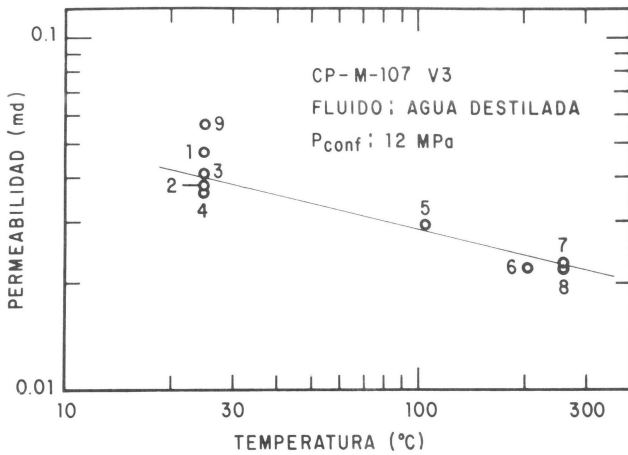


Fig.2. Diagrama log-log para la muestra M-107 V3.
Log-log diagram for sample M-107 V3.

En el caso de la muestra M-107 V3 los puntos 1, 4 y 8 fueron excluidos de la correlación por corresponder a presiones de confinamiento distintas a la establecida para la prueba (ver Tabla 6); el punto 9, de control, indica que se produjo un aumento irreversible de permeabilidad atribuible a disolución, y fue también excluido de la correlación.

Nótese que la disminución de la permeabilidad con el aumento de la temperatura se produjo a pesar de la (supuesta) disolución. Similarmente, en el caso de la muestra M-129 V3 los puntos 6, 8 y 9 se excluyen de la correlación por no corresponder a la tensión de confinamiento apropiada (ver Tabla 10); los puntos 7 y 10, de control, mostraron disminuciones irreversibles de permeabilidad atribuibles a los incrementos experimentados por las tensiones de confinamiento en los puntos inmediatamente precedentes (Tabla 10), y fueron por ello excluidos de la correlación.

El comportamiento de las dos muestras discutidas en el párrafo anterior provee fuerte evidencia de que la expresión empírica propuesta (1) es válida en el intervalo aproximado de temperatura 20 -

280°C. En los cuatro párrafos siguientes discutimos la evidencia disponible acerca de la validez de la expresión (1) en rangos de temperatura más estrechos, y su posible extensión hasta temperaturas del orden de 280°C o más. Estos rangos de validez aparentemente más estrechos, y su posible extensión hasta temperaturas del orden de 280°C o más. Estos rangos de validez aparentemente más estrechos están asociados con fenómenos de interacción agua-roca que causaron cambios irreversibles de permeabilidad. Cuando se pueden sustraer los efectos de cambios irreversibles de permeabilidad la ley potencial propuesta (1) es válida al menos en el rango 20°C - 280°C, como se demuestra más abajo.

La figura 4 es el diagrama log-log correspondiente a la muestra M-17 V1. En este caso se tuvieron en cuenta en la correlación únicamente los puntos 1 - 4 (23.5°C a 210°C) de la Tabla 4. Durante el calentamiento entre punto 4 y el punto 5 (210°C a 255°C), que se realizó sin que pasara flujo a través de la muestra, se produjo un incremento de permeabilidad de 0.005 a 0.013 md en aproximadamente 1700 segundos; inmediatamente después, durante la corrida a 255°C, se produjo un nuevo incremento de permeabilidad, de 0.013 a 1.155 md, en aproximadamente 6700 segundos. Las velocidades de cambio de permeabilidad implicadas, 5×10^{-6} y 2×10^{-5} md/s respectivamente y las correspondientes condiciones de flujo son consistentes con la hipótesis de que los incrementos de permeabilidad son debidos a disolución. Por ello los puntos 5 - 7 de la Tabla 4 fueron excluidos de la correlación. El punto de control 8, a 24°C, soporta la inferencia de que a lo largo de la prueba se produjo un aumento irreversible de permeabilidad atribuible a disolución, y tampoco pudo ser utilizado en el ajuste de la recta. El ajuste por cuadrados mínimos arrojó un coeficiente de correlación igual a -0.994 , que consideramos excelente. Nótese que el punto 3 a 23°C después de haber calentado la muestra desde 23.5°C hasta 112°C (puntos 1 y 2, Tabla 4) presenta fuerte evidencia en favor de la reversibilidad en ausencia de disolución.

En la figura 5 se presenta el diagrama log-log correspondiente a las determinaciones de permeabilidad de la muestra M-107 H4 realizadas usando agua destilada como fluido (Tabla 7). En el ajuste por cuadrados mínimos se incluyeron los puntos 1 a 3 (25°C a 200°C). El punto 4, a 265°C, fue excluido por sospecharse un aumento irreversible de permeabilidad. El punto 5 fue excluido por corresponder a una presión de confinamiento dos veces mayor que la considerada para el resto de los puntos. De este modo obtuvimos un coeficiente de correlación igual a -0.998 ,

Incluyendo también el punto 4 se obtiene un coeficiente de correlación igual a -0.853, que continúan siendo significativo.

Para estudiar los efectos de la composición del fluido de poro sobre la permeabilidad, medimos con salmuera la permeabilidad de la muestra M-107 H4 en función de la temperatura. Esta prueba resultó dificultosa. El primer punto a temperatura ambiente se perdió por un problema accidental sufrido por el sistema recolector de datos, que no pudo ser notado antes de la finalización de las pruebas subsiguientes. Por ello el primer punto presentado corresponde a 66°C (Tabla 8). En los tres puntos subsiguientes se manifestaron incrementos de permeabilidad durante las mediciones realizadas a temperaturas constantes. A 94°C y 130°C este efecto no fue severo. El significativo aumento de permeabilidad registrado entre 130°C y 186°C fue considerado irreversible considerando la tendencia manifestada en los puntos 2, 3 y 4, y el aumento irreversible de permeabilidad evidenciado por el punto de control 7, a 66°C. De este modo sólo se incluyeron en el ajuste por cuadrados mínimos los puntos 1, 2 y 3 de estos dos últimos se eligieron las permeabilidades medidas inicialmente en las respectivas corridas (ver Tabla 8). Encontramos de este modo un coeficiente de correlación igual a -0.989. El correspondiente diagrama log-log se muestra en la figura 6.

Otra muestra que presentó dificultades es la M-127 V2 (ver Tabla 9). Entre el punto a 23°C y el punto a 58°C hubo inicialmente una disminución de permeabilidad. Sin embargo, la permeabilidad medida a 58°C fue incrementándose con el transcurso del tiempo hasta alcanzar 1.82md, sobrepasando así la permeabilidad medida en el punto a 23°C. Similarmente, al pasar de los puntos 2 a 3 y 3 a 4 se produjeron disminuciones iniciales de permeabilidad, pero las permeabilidades a las temperaturas respectivas se incrementaron con el tiempo. Finalmente, el punto de control 8 a temperatura ambiente indicó, por comparación con el punto 1, un aumento irreversible de permeabilidad. En un intento por separar los efectos reversibles de los irreversibles, supusimos que la variación de permeabilidad, relativa al punto inicial, que se midió en cada incremento de temperatura es la misma que se produciría en ausencia de los efectos irreversibles (presumiblemente disolución). Sobre esta hipótesis se computaron las correcciones que aparecen en la Tabla 11 con el siguiente logaritmo:

$$K_{j+1}^* = (K_{j+1} \text{ (inical)} / K_j \text{ (final)}) K_j^*$$

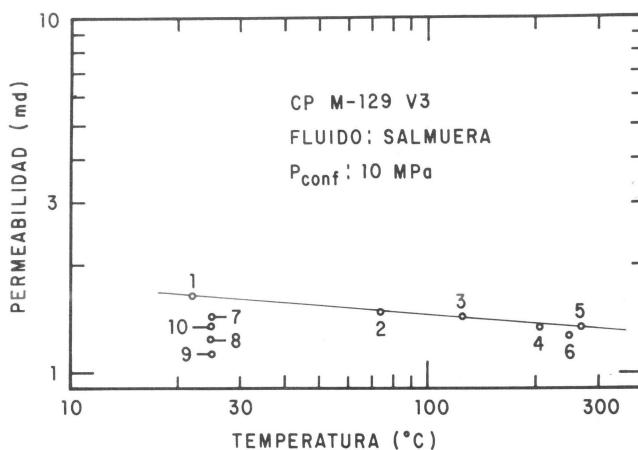


Fig.3. Diagrama log-log para la muestra M-129 V3.
Log-log diagram for sample M-129 V3.

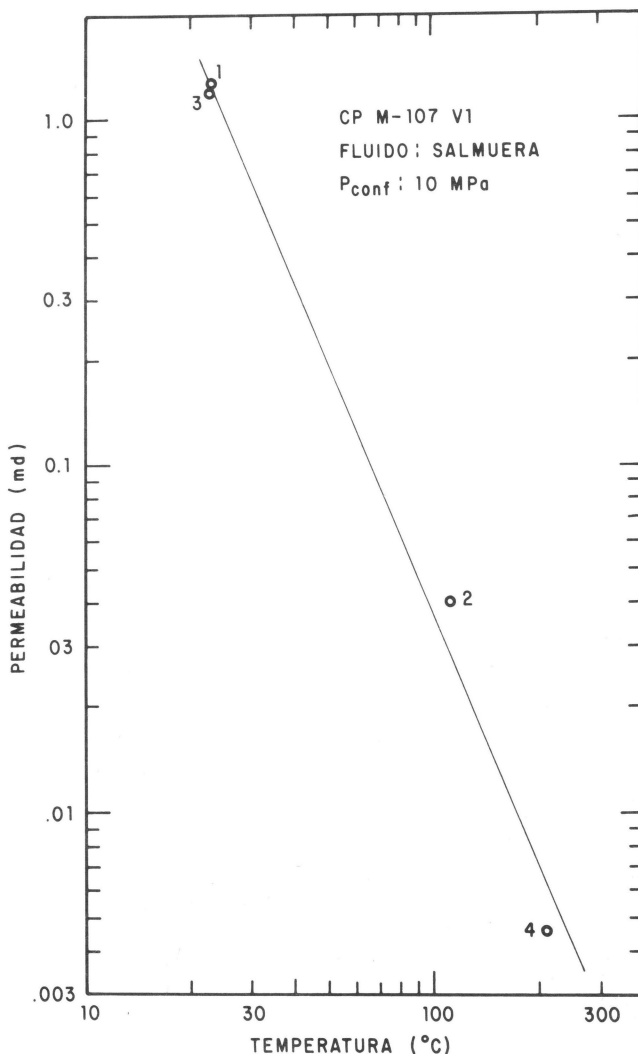


Fig.4. Diagrama log-log para la muestra M-107 V1.
Log-log diagram for sample M-107 V1.

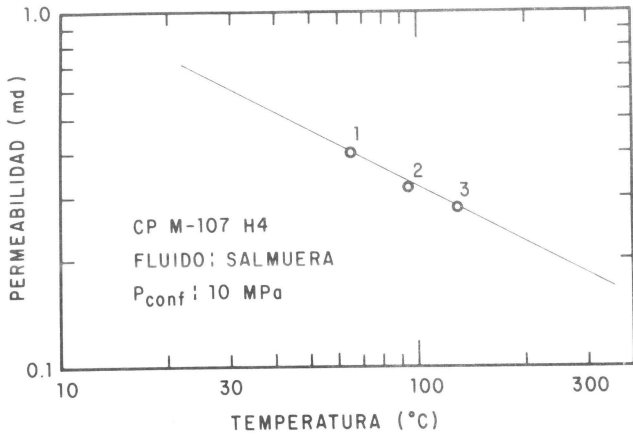


Fig.6. Diagrama log-log para la muestra M-107 H4 con salmuera.
Log-log diagram for sample M-107 H4 with brine.

Donde las K_j^* son los valores corregidos, los K_j los valores medidos, y las palabras "inicial" y "final" se refieren a los valores medidos al principio y al final respectivamente, a cada temperatura. La permeabilidad corregida para 270°C se calculó como $K_j^* = (K_j/K_8) K_1^*$.

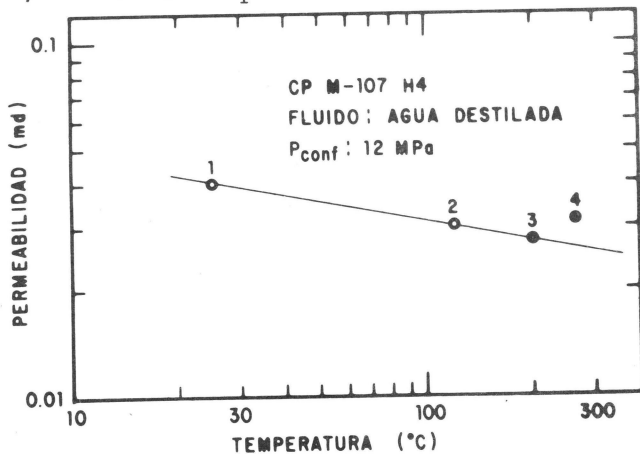


Fig.5. Diagrama log-log para la muestra M-107 H4.
Log-log diagram for sample M-107 H4.

El diagrama log-log de las permeabilidades corregidas se presenta en la figura 7. Para los datos presentados en la misma computamos un coeficiente de correlación igual a -0.843. El ajuste es muy bueno considerando las manipulaciones requeridas por el proceso de corrección. La calidad de la concordancia con la ley potencial propuesta es tal que se hace difícil imaginar que sea fortuita. Por ello interpretamos que este caso demuestra que la ley potencial propuesta es válida cuando se sustraen los cambios irreversibles de permeabilidad.

Los resultados obtenidos de la muestra M-107 H2 (Tabla 5) sólo contribuyen evidencia de relativamente poca calidad en cuanto a la dependencia de la permeabilidad con la temperatura. Entre 24°C y 108°C se presentó una disminución de permeabilidad, y al cabo de un ciclo completo nuevamente se presentó entre los puntos 5 y 6 (25°C y 110°C) un decremento similar de la permeabilidad. El resto de los datos presentados es ilustrativo de las dificultades encontradas en la interpretación de este tipo de experimentos.

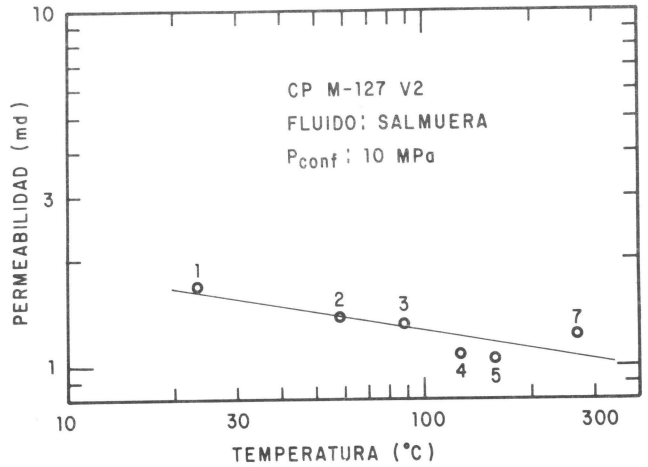


Fig.7. Diagrama log-log para la muestra M-127 V2.
Log-log diagram for sample M-127 V2.

Finalmente los datos de Sommerton (1978) aportan evidencia experimental independiente en cuanto a que la expresión (1) presenta la dependencia de la permeabilidad con la temperatura para areniscas de Cerro Prieto, cuando los efectos irreversibles son pequeños. En la figura 8 hemos graficado los datos presentados por Sommerton para una arenisca de Cerro Prieto no identificada en un diagrama log-log. De los seis puntos originales sólo se excluyó el último que indica una disminución irreversible de permeabilidad. Para estos datos encontramos un coeficiente de correlación igual a -0.990.

Los resultados discutidos en los párrafos anteriores constituyen un cuerpo de evidencia que soporta la ecuación empírica propuesta (1). Nótese que dicha ecuación es aplicable para distintos flúidos de permeabilidad: agua destilada (muestra M-107 V3 y M-107 H4), salmuera (el resto de las muestras medidas en este trabajo) y solución de KCl (datos de Sommerton). Sin embargo, la permeabilidad a la salmuera parece ser substancialmente mayor que el agua destilada, como lo

indican los resultados, obtenidos con las muestras M-107 H4 y M-107 VI. Esta característica está probablemente asociada a la expansión de arcillas.

Como se menciona más arriba, se ajustaron los datos por cuadrados mínimos usando la expresión (1). De este modo se obtuvieron los valores de K_0 , que se eligió arbitrariamente como la permeabilidad ajustada a 25°C, y de b, el valor absoluto de la pendiente de la recta en el diagrama log-log. Estos valores se resumen, conjuntamente con los coeficientes de correlación, en la Tabla 12. Los datos de Sommerton fueron presentados originalmente como la razón entre la permeabilidad a la temperatura T y la permeabilidad a temperatura ambiente; por ello no fue posible calcular el valor de K_0 correspondiente.

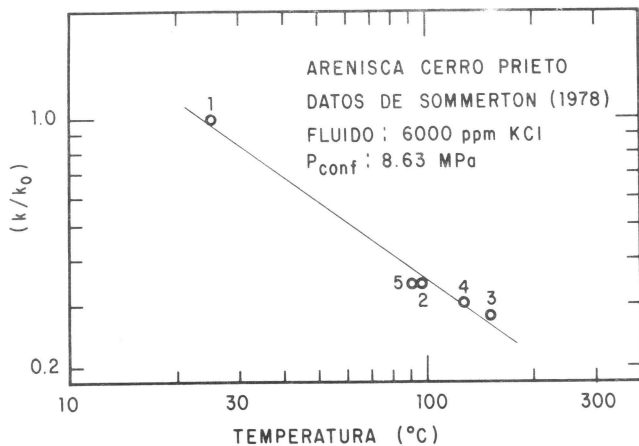


Fig.8. Diagrama log-log para una arenisca de Cerro Prieto no identificada. Datos de Sommerton (1978).
Log-log diagram for an unidentified sandstone of Cerro Prieto. Data from Somerton.

Los datos de la Tabla 12 indican grandes variaciones de permeabilidad en el núcleo del pozo M-107. Estas variaciones son debidas en parte a la utilización de distintos flúidos de permeabilidad (agua y salmuera). Para las muestras que se midieron utilizando salmuera las variaciones parecen obedecer a dos razones: (a) las permeabilidades horizontales tienden a ser sensiblemente mayores que las verticales; y (b) la petrología varía muy rápidamente a lo largo de los aproximadamente 30cm del núcleo. En el mismo se observa que el tamaño del grano decrece desde la muestra M-107 VI (arenisca típica), extraída de un extremo del núcleo, hacia la muestra M-107 H4, que fue extraída de la parte más cercana a un contacto arenisca-lutita que presenta el núcleo en el extremo opuesto, y que revela un grano muy fino, similar al de un cemento de construcción. La ubicación del resto de las muestras en el núcleo es

intermedia entre las muestras M-107 VI y M-107 H4, y corresponde con su numeración. El núcleo del pozo M-107 estudiado en este trabajo constituye un drámatico ejemplo de variación de la permeabilidad en la vecindad de un cambio de facies.

Tabla 11. Muestra M-127 V2. Correcciones por disolución.
Sample M-127 V2. Corrections for dissolution.

Prueba (#)	Temp. (°C)	K inicial (md)	K final (md)	K_{j+1}^i/K_j^f	K^* (md)
1	23	1.68	1.68	—	1.68
2	58	1.38	1.83	—	1.38
3	87	1.76	1.90	0.9617	1.327
4	128	1.57	1.70	0.8263	1.096
5	158	1.65	1.65	0.9706	1.063
7	270	3.02	2.02	0.7319	1.229
8	215	2.76	2.76	—	—

Tabla 12. Resumen de parámetros de permeabilidad.
Summary of permeability parameters.

Muestra	Fluido	Coef. Corr.	K_0 (md) ⁺	b
M-107 V1	Salm.	-0.994	1.093	2.40064
M-107 H2	Salm.	—	12.2*	—
M-107 V3	Agua	-0.984	0.0397	0.24754
M-107 H4	Agua	-0.998	0.0399	0.17432
M-107 H4	Salm.	-0.989	0.654	0.51294
M-127 V2	Salm.	-0.843	1.588	0.16473
M-129 V3	Salm.	-0.989	1.634	0.08457
Sommerton	Sol. KCl	-0.990	—	0.72888

+ K_0 es la permeabilidad ajustada a 25°C.

* Permeabilidad medida a 24°C.

El rango de variación encontrado para el exponente b en este trabajo es bastante amplio, entre 0.085 y 2.4. La magnitud de b depende de la naturaleza del fluido de permeabilidad, como se desprende de las mediciones realizadas con agua destilada y con salmuera en la muestra M-107 H4 (Tabla 12). Existen indicaciones de que la magnitud de b también depende de la presión de confinamiento: trazando una línea recta entre los puntos 4 y 8 de la figura 2, que corresponden a presiones de confinamiento de 24 MPa (el doble del valor correspondiente a los puntos usados en el ajuste, (Tabla 6), se encuentra un decremento de 15% en la magnitud de b;