Proceedings Ninth Workshop Geothermal Reservoir Engineering
Stanford University, Stanford, California, December 1983
SGP-TR-74

THERMAL EXPANSION BEHAVIOR OF CERRO PRIETO SANDSTONES AND OTHER SEDIMENTARY ROCKS UNDER STRESS.

E. CONTRERAS

INSTITUTO DE INVESTIGACIONES ELECTRICAS. CUERNAVACA, MOR., MEXICO.

F. BERMEJO

COMISION FEDERAL DE ELECTRICIDAD. CERRO PRIETO, B.C., MEXICO.

ABSTRACT

This paper describes the experimental work and presents the results of a research program - carried out to investigate the thermal expansion behavior of sedimentary rocks under high stress conditions. The aspects that were investigated include the effects of temperature, temperature cycling, and confining pressure . Furthermore, the validity of the usual assumption on thermal expansion isotropy was investigated. On the other hand, the matrix thermal expansion concept is analyzed and its physical meaning and aplications are discussed. The effect of temperature on porosity is also a subject investigated regarding experimental methods for its estimation and comparison of earlier results.

The experiments carried out consisted basically of thermal strain versus temperature measurements on jacketed and unjacketed samples subjected to different confining pressures and covering the temperature range from 25°C to 280°C and the pressure range from 3.0 MPa to 34.4 MPa. A review of earlier work is included as a reference frame to discuss and compare the results of this work, as well as to emphasize the limited extent of the research on thermal expansion behavior of sedimentary rocks that had been accomplished.

Results are presented by means of thermal strain versus temperature curves and tabular data of thermal expansion coefficients. Several important conclusions for laboratory and field applications are reached from each of the aspects investigated.

The wide research scope of this work and the considerable amount of data reported may represent an important contribution to the knowledge of thermal expansion behavior of sedimentary rocks.

INTRODUCTION

The thermal expansion behavior of rocks is a subject of great interest in many reservoir engineering, geophysical, mining and similar underground applications where rocks are heated. The limited data available on thermal expansion of rocks are mostly bulk expansion data for low porosity rocks, the majority of which are igneous, generally corresponding to either atmospheric pressure and wide temperature ranges, or high pressure and narrow temperature range conditions. That is, very few results have been reported in which samples were subjected simultaneously to high stress and a wide range of temperature variations

It is well known that sandstones constitute the main producing-horizons in various geothermal fields; therefore, the importance of the thermal expansion behavior of sedimentary rocks in geothermal applications is self-evident. However, this subject has not yet been covered extensively.

In order to obtain a good knowledge about the thermal expansion behavior of rocks, it is mandatory to understand the effects of parameters such as temperature, temperature cycling, heating rate, stress, saturation, expansion anisotropy, and effect of temperature on porosity. Such an understanding is also necessary to plan the experimental measurements more adequately, thus reducing considerably the amount of experimental work required. Concerning sedimentary rocks, the effects of only some of the above mentioned parameters have so far been partially investigated. A brief review of the existing studies on this subject is included in the following.

Ashqar (1979), Somerton (1980) and Somerton et. al. (1981) reported the results of bulk thermal expansion of liquid-saturated specimens of Boise, Berea and Bandera sandstones that were subjected to 20.7 MPa confining pressure and 6.9 MPa pore pressure, while increasing the temperature from 30°C to 175°C at a rate of about 1°C/min. The samples were not subjected to temperature cycling, hence only heating strain-temperature curves were reported. These curves were compared with the strain-temperature curves for the same outcrop sandstones reported by Somerton and Selim (1961) run under dry and no confining or pore pressure conditions, and a fair agreement was found, indicating that thermal expansivities of Boise, Berea and Bandera sandstones were not strongly dependent of stress and fluid saturation.

Janah (1980), Somerton (1980) and Somerton et. al. (1981) reported results of a series of tests focused to investigate the influence of temperature on pore volume contraction for the same outcrop sandstones under stress. The specimens studied were subjected to 20.7 MPa confining pressure and 6.9 MPa pore pressure. Changes in pore volume were measured as temperature was increased from 30°C to 170°C. From their results, the authors concluded that the pore volume of liquid saturated sandstones under stress decreases with increasing temperature, and that the pore volume thermal contraction is a function of porosity, values decreasing with increased porosities. The fractional pore volume contractions reported by the authors for the Boise, Berea and Bandera sandstones for the 30°C to 170°C temperature range are 0.55%, 1.04% and 1.53%, respectively.

Janah (1980) also studied the effects of stress level on pore volume thermal contraction and noted that differences in confining stress level had little effect on it; on the other hand, increase in pore fluid pressure level had a marked effect, the pore volume contraction decreasing substantially with increased pore fluid pressure.

Greenwald et. al. (1982) presented a new set of results for exactly the same kind of experiments as carried out by Ashqar (1979) and Janah (1980) on bulk thermal expansion and thermal pore volume contraction of Boise, Berea and Bandera sandstones.

The strain-temperature curves reported by Greenwald et. al. (1982) differ to some extent from the ones obtained by Ashqar (1979), especially regarding Berea sandstone strain curves; the agreement for Boise and Bandera is fairly good. On the other hand, the fractional pore volume contractions reported by Greenwald et. al. for the Boise, Berea and Bandera sandstones for the 30°C to 170°C temperature increment are 3.0%, 3.7% and 4%, respectively, which compare badly to the 0.55%, 1.04% and 1.53% values reported by Janah (1980) and Somerton (1981). However no comments or explanations of these big dissimilarities were provided by the authors.

Assuming that all three sandstones are isotropic and thus, that the bulk volumetric strain is three times the axial strain, Greenwald et. al. (1982) combined their results of both pore volume contraction and axial thermal expansion measurements to calculate decrease in the original porosity. The results they reported are 3.0%, 3.8% and 4.4% porosity reduction for the 30°C -170°C temperature range for the Boise, Berea and Bandera sandstones, respectively. Greenwald et. al. (1982) concluded that the inclusion of bulk volume thermal expansion values in porosity determinations is a second-order correction, which led to the observation that the calculated fractional changes in porosity resulted very similar to their results for fractional pore volume changes. The authors of the present work would like to point out that such a conclusion is not always correct and would lead to significant errors in the cases where the fractional pore volume changes are of the same order of magnitude as the bulk volume thermal strain; such is the case if the pore volume contractions after Janah are considered instead of Greenwald's results.

Contreras et. al. (1982) measured the thermal strain of Berea sandstone and of a sandstone from Cerro Prieto Well M-94. The samples were tested at two different constant confining pressures of 3 MPa and 20.7 MPa, with the temperature being increased at a uniform rate of about 1.5°C/min. in the range from 20°C to 280°C. Thermal expansion measurements were made both on jacketed samples with no pore pressure, hence obtaining information about the usual bulk thermal strain, and on unjacketed samples with the confining fluid filling the rock pore volume, thus obtaining data about the so called "matrix thermal strain", a new concept that had not been introduced before in the scientific investigation on behavior of rocks. The results by Contreras et. al. (1982) showed that both, bulk and matrix thermal expansivities are dependent of the confining pressure applied to the rock. Further evidence was found that the bulk and the matrix thermal expansion coefficients depend of the temperature range itself. Furthermore, combining bulk and matrix thermal strain data and using a novel approach, Contreras et. al. (1982) presented estimates of the effect of temperature on porosity.

This short review of the existing literature clearly shows that there are several parameters whose influence on thermal expansion behavior of sedimentary rocks has not been investigated at all and that the effect of others has been investigated only in a very limited extension and mostly on outcrop sandstones.

The objectives of the present study were established to contribute to fill the main gaps of knowledge described above; consequently, in this work the following aspects are investigated in relation with thermal expansion behavior of sedimentary rocks: (1) effect of temperature cycling, (2) effect of heating rate, (3) effect of confining pressure, (4) effect of orientation with respect to the bedding plane, (5) comparison between bulk and matrix thermal strain and analysis of its significance, (6) effect of temperature on porosity. Furthermore, a big deal of data about thermal expansion coefficients of several sedimentary rocks is provided as another main result of the investigations accomplished. Unlike previous studies involving outcrop sandstones, the results presented in this paper correspond mostly to rocks from wells drilled in a very important geothermal region (the Cerro Prieto Geothermal Field area), thus increasing their importance for practical applications.

EXPERIMENTAL ASPECTS

The identification, origin and porosity at room conditions of the samples used in this work are given in Table 1. The porosities reported were measured using the liquid saturation under vacuum method. The three kinds of outcrop sandstones were chosen so as to cover a wide range of porosities. The geothermal samples were obtained from wells M-94, M-127 and M-149 drilled in the Cerro Prieto Geothermal Field, located in Baja California, México. These geothermal samples were cut perpendicular to their bedding planes from field cores using a 2.5 cm. diameter diamond drill bit, except the sample M-127-HA that was drilled out parallel to its bedding plane. After cutting the samples to a lenght of approximately 5 cm., their ends were ground flat and parallel to within 2.5 X 10^{-3} cm.

TABLE 1. Origin and Porosity of the Sandstones Studied.

SAMPLE IDENTIFICATION	WELL	DEPTH (METERS)	POROSITY (%)
M94-A	M94	2417	15.8
M94-B	M94	2417	15.8
M127-A	M127	2195	20.2
M127-HA	M127	2195	20.2
M149-A	M149	2160	15
KAYENTA K1	OUTCROP	----	18.6
KAYENTA K2	OUTCROP	----	18.6
KAYENTA K3	OUTCROP	----	18.6
BEREA 1	OUTCROP	----	18.8
BEREA 2	OUTCROP	----	18.8
COLTON 1	OUTCROP	----	10.9
COLTON 2	OUTCROP	----	10.9

In order to fulfill the objectives established for this work, four basic types of tests were planned and run. Their description is presented below.

Type A Tests. Intended to investigate the effect of temperature cycling on the bulk thermal strain. For these tests, a constant confining pressure of 8 MPa was applied on dry jacketed samples that were then subjected to two heating-cooling cycles in the range from 25°C to 280°C, with the temperature being changed both for the heating and cooling parts at a uniform rate of about 2°C/min. Strain and temperature were recorded during the temperature cycles once every minute. Type A tests were run on samples M127-A and M127-HA.

Type B Tests. Intended to investigate the combined effect of heating rate and temperature cycling on the bulk thermal strain. These tests were run on dry jacketed samples subjected to a constant confining pressure of 8 MPa. Each sample tested was subjected to three consecutive temperature cycles at 1, 2 and 3°C/min in the range from 25°C to 280°C. Strain and temperature were recorded during the three cycles once every minute. Type B tests were run on samples M149-A and KAYENTA K1.

Type C Tests. Intended to investigate the effect of confining pressure and temperature cycling on the bulk thermal strain. These tests were run on dry jacketed samples subjected at two or three temperature cycles in the range 25°C to 280°C; for each consecutive cycle a different confining pressure was applied to the rock, keeping the heating and cooling rates constant at 2°C/min. The values of confining pressures chosen for these tests were 3, 17.2, 20.7 and 34.4 MPa. Samples M94-A and KAYENTA K2 were subjected to temperature cycles at 3, 17.2 and 34.4 MPa. Samples BEREA 1 and COLTON 1 were subjected only to heating from 25°C to 280°C at 3 and 20.7 MPa. Strain and temperature were recorded during the tests once a minute.

Type D Test. Intended to investigate the concept of matrix thermal expansion and determine the influence of confining pressure and temperature cycling on it. These tests were run on unjacketed samples, thus enabling the confining fluid to fill the rock pore volume. The samples tested were subjected to temperature variation in the range from 25°C to 280°C at two different confining pressures. Samples M94-B and KAYENTA K3 were subjected to temperature cycles at 3 and 34.4 MPa. Samples BEREA 2 and COLTON 2 were subjected only to heating from 25°C to 280°C at 3 and 20.7 MPa. Strain and temperature were recorded during the tests once a minute.

A summary of the tests description and the experimental work accomplished is shown in Table 2.

The experimental equipment used is shown schematicaly in Fig. 1. It consists primarily of the pressure vessel, a servocontrolled pressurizing system, an automatized heating system, strain and temperature sensors and transducers and a computer based data acquisition system.

Linear thermal expansion for both jacketed and unjacketed samples was measured along their axis by means of high resolution LVDT's (linearly variable differential transducers) attached to the top of the test specimen by quartz rods. Deformation of up to 2.5 X 10^{-2} cm. can be measured with an accuracy of ± 6.2 X 10^{-5}cm. Averaging the outputs of the two LVDT's removes any false strain due to tilting. More details

TABLE 2. Summary of Testing Conditions and Experimental Work Carried Out.

TEST TYPE (SAMPLES TESTED)	SAMPLE CONDITION	CONFINING PRESS MPa	TEMPERATURE VARIATION(°C)	HEATING RATE °C/MIN.
A (M127-A,M127-HA)	JACKETED	8	25-280-25 25-280-25	2 2
B (M149-A,KAYENTA K1)	JACKETED	8 8 8	25-280-25 25-280-25 25-280-25	1 2 3
C (M94-A,KAYENTA K2)	JACKETED	3 17.2 34.4	25-280-25 25-280-25 25-280-25	2 2 2
C (BEREA 1,COLTON 1)	JACKETED	3 20.7	25-280 25-280	2 2
D (M94-B,KAYENTA K3)	UNJACKETED	3 34.4	25-280-25 25-280-25	2 2
D (BEREA 2,COLTON 2)	UNJACKETED	3 20.7	25-280 25-280	2 2

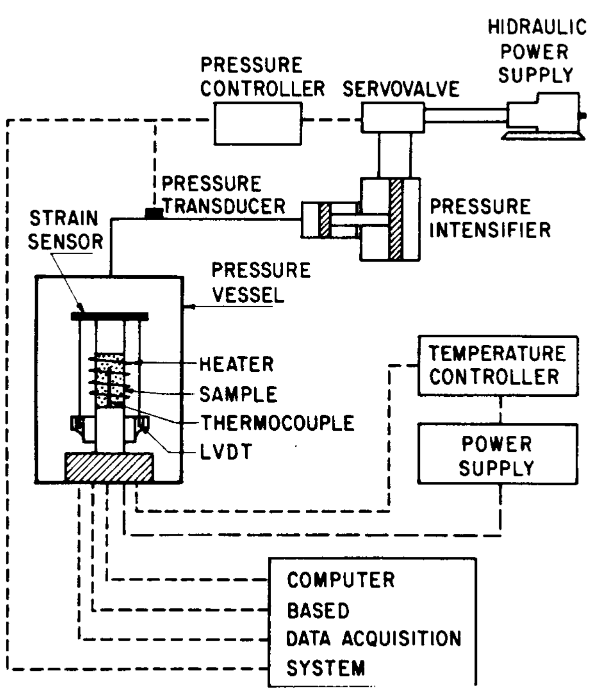

Figure 1. Schematic of experimental equipment.

on the experimental configuration used are given by Ennis et. al. (1979).

The temperature cycles and heating rates were tailored by means of a Honeywell programmable controller that regulated the power to an electric heater located inside the pressure vessel around the sample. By using the servocontrolled pressurizing system, confining pressure was kept constant at the chosen values within ± .01 MPa.

Data collected during the tests consisted of deformation output from the two LVDT's, sample temperature and confining pressure. Data was collected once every minute and stored by means of a computer based acquisition system.

In order to take into account the thermal expansion of the measuring system, calibration tests were run using fused quartz as the standard.

RESULTS AND DISCUSSION

Effect of Repeated Temperature Cycles on Bulk Thermal Expansion:

The results of type A tests carried out to investigate the effect of two consecutive temperature cycles on the bulk thermal expansion of sandstones are shown graphically in figures 2 and 3 by means of strain versus temperature curves. Description of the test conditions were given before and are also included as inset in the figures. The general strain-temperature behavior exhibited by the samples M127 - Ā and M127-HA is very similar, as it can be inferred from figures 2 and 3. Several interesting features of the strain-temperature curves can be appreciated and will be analyzed and discussed in the following.

For both samples, the heating and cooling strain-temperature curves of the first cycle show significant differences, with the cooling curve lying below the heating curve almost for the whole temperature range, resulting in a negative strain or compaction at the end of the first cycle. On the other hand, the strain-temperature behavior for the second cycle is highly reversible, since the discrepancies between its heating and cooling curves are almost inexistente; further, the compactions observed after completion of the second cycle are smaller than the ones for the first cycle. Using the strain marks drawn on figures 2 and 3, it is also noted that for both temperature cycles, the sum of the heating thermal strain, ε_T, and the corresponding compaction, ε_C, is almost a constant value, ε, for each sample. The parameter ε physically represents the cooling thermal strain experimented by the rock.

From these observations, we can draw an important conclusion, although still somewhat preliminary, concerning the strain-temperature behavior of sandstones. It appears that after a few temperature cycles, the rock will become thermomecanically stabilized, and that further recycling will not cause additional compaction in it. Under these circumstances, bulk thermal strain of sedimentary rocks would be reversible provided the rock has been previously subjected to a few temperature cycles. More experimental evidence supporting the conclusion of reversibility will be presented in the forthcoming subsection.

Further, since the parameter ε is the cooling thermal strain experimented by the rock, and such a parameter has the same value for both cycles as was noted before, it would be reasonable to propose that the thermal strain versus temperature curve of the cooling part of the temperature cycle does not depend on the thermal history of the rock, (as oppossed to the heating strain-temperature curve that does depend on the thermal history). The validity of the above proposed concept is strong-

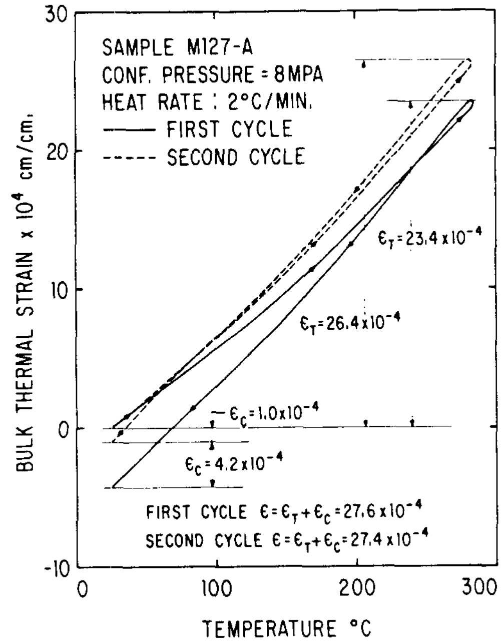

Figure 2. Effect of repeated temperature cycles on bulk thermal expansion of sample M127-A.

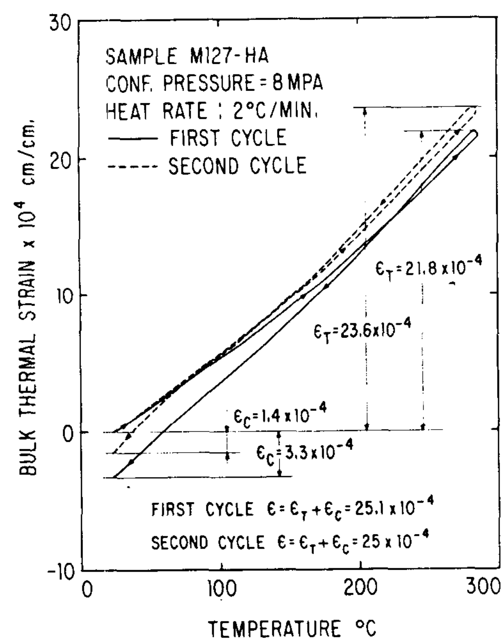

Figure 3. Effect of repeated temperature cycles on bulk thermal expansion of sample M127-HA.

ly supported by the experimental evidence that will be presented later in this work.

Combining the concept about the invariability of the cooling strain-temperature curve with the conclusion on the reversibility of the bulk thermal strain after a few temperature cycles, it is possible to determine the bulk thermal strain versus temperature behavior of a thermomecanically stabilized rock from the knowledge of any cooling strain curve, even the one corresponding to the first cycle. The importance of this conclusion is evident for the planning of experimental measurements as well as for analysis and application of results.

Effect of Heating Rate and Temperature Cycling on Bulk Thermal Expansion.

The results of type B tests carried out to investigate the effect of different heating rate values are shown in figures 4 and 5 for the samples M149-A and KAYENTA K1, respectively. Again, it is observed that for both samples the heating strain and the cooling strain versus temperature curves of the first cycle differ to a large extent, and a considerable compaction results at the end of this cycle. However, this compaction is more noticeable for sample KAYENTA K1 than for sample M149-A.

Both the latter strain-temperature cycles (two and three) differ markedly from cycle one. However, discrepancies between the cycles two and three are nearly indistinguishable from each other, thus providing evidence that the change in heating rate from 2°C/min to 3°C/min does not affect the strain-temperature pattern.

Furthermore, thermal expansion for cycles two and three is highly reversible upon cooling; the heating and cooling curves show only a small hysteresis loop, which can be related to the existence during the heating period of a lag of the inside-the-sample temperature with respect to the temperature sensed by the thermocouple attached to the external surface of the sample. The opposite phenomenon occurs during the cooling period. This observation is supported by the fact that the hysteresis loop is wider for the 3°C/min heating rate than for the 2°C/min heating rate.

The notorious similarity between cycles two and three provides enough evidence so as to reasonably conclude that their discrepancy from cycle one is not due to the different heating rates, but to the compaction mechanism, which was discussed before. Therefore, it can be concluded that differences in heating rates in the range from 1°C/min to 3°C/min do not affect the thermal strain-temperature behavior of sedimentary rocks nor do they produce irreversible structural damage. As it is noted, the actual value of the heating rate influences only the extension of the hysteresis loop. A 2°C/min heating rate is recom-

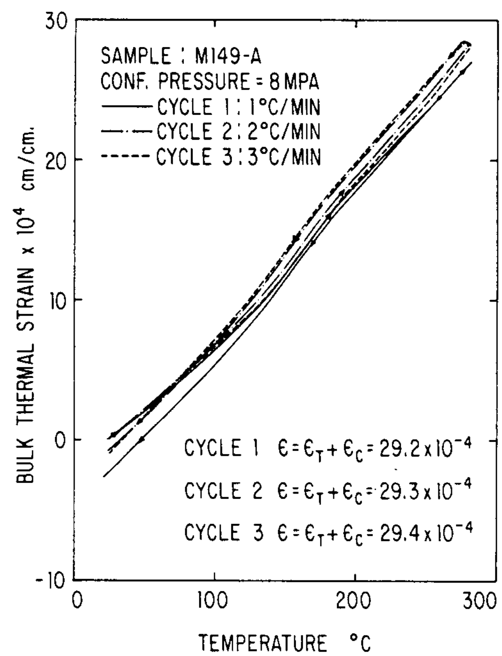

Figure 4. Effect of heating rate and temperature cycling on bulk thermal expansion of sample M149-A.

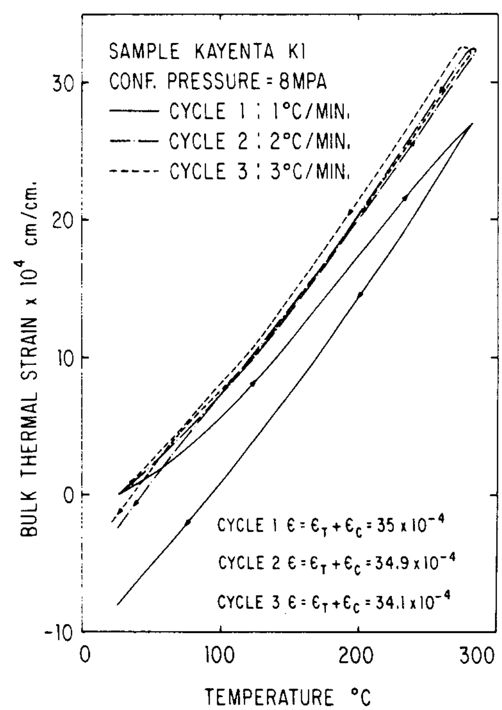

Figure 5. Effect of heating rate and temperature cycling on bulk thermal expansion of sample KAYENTA K1.

mended by the authors of this work, since the hysteresis loop associated to it is small enough so as to avoid significant experimental errors.

Concerning the heating and cooling thermal strains for the three cycles, it is interesting to note that for each sample the cooling thermal strain associated to the total temperature range covered is practically constant, regardless of the cycle considered. The same conclusion was drawn in the earlier subsection as well. The numerical values of the cooling thermal strain for the three cycles of both samples studied, M149-A and KAYENTA K1, are shown on figures 4 and 5, respectively.

Invariability of the Cooling Thermal Strain-Temperature Curve.

The observations that have been made regarding the constant value exhibited by the cooling thermal strain in the total temperature range for a given sample, regardless of its thermal history, strongly suggest the possibility that, provided the stress conditions on the rock are kept constant, the cooling thermal strain versus temperature curves exhibit the same pattern independently of the thermal history of the rock. In order to confirm such an assumption, the cooling strain-temperature curves of the cycles shown in figures 2 - 5 were redrawn using a common origin at 280°C, and the results are shown in figures 6 - 9, which provide enough experimental evidence in favor of the proposed concept about the invariability of the cooling thermal strain.

A practical application of this concept, as it was mentioned before, is the inferrence of the thermal expansion behavior corresponding to a stabilized rock from the cooling thermal strain-temperature curve of any cycle. This means that all the information regarding the thermal expansion behavior of a rock subjected to a given confining pressure, can be obtained from a single first cycle, but not from the heating thermal strain versus temperature curve only, since this curve is dependent on the thermal history of the rock. Another application of the invariability of the cooling thermal strain-temperature curve will be shown in the next subsection.

Effect of Confining Pressure on Bulk Thermal Expansion.

Type C tests were carried out to investigate the effect of confining pressure on bulk thermal expansion behavior. Information on the experimental conditions and the samples tested was given before and is summarized in table 2. The results for samples M94-A and KAYENTA K2 are shown in figures 10 and 11, respectively. The bulk thermal strain versus temperature cycles for the confining pressures of 3 MPa, 17.2 MPa and 34.4 MPa are plotted using a common origin at 25°C.

The problem involved in analizing the effect of confining pressure on bulk thermal expansion from figures 10 and 11, is that the heating strain-temperature curves are influenced by the previous thermal tratment underwent by the rock sample. Thus, the differences that may exist between any two heating curves are the sum of the influence of confining pressure itself plus the effect associated to the thermal history of the rock. Therefore, an analysis of the effect of confining pressure from heating strain-temperature curves requires that these effects be separated. On the other hand, the invariability of the cooling strain-temperature curves with respect to the thermal history was demonstrated before; thus, any observable discrepancies between cooling strain curves can be attributed to the effect of the confining pressure only. Using this approach and taking into account that for a thermomecanically stabilized rock at a given pressure, the heating strain curve is very similar to its corresponding cooling strain curve (see figures 2 - 5), the isolated effect of confining pressure on bulk thermal expansion can be estimated by plotting the cooling strain-temperature curves from a common origin at 25°C. Applying this method to the cases under study, samples M94-A and KAYENTA K2, the results shown in figures 12 and 13 were obtained. For sample M94-A, the effect of confining pressure on bulk thermal expansion in the range from 3 MPa to 34.4 MPa is rather small and erratic. On the other hand, for sample KAYENTA K2 the effect of increasing confining pressure is to reduce the thermal strain at a given temperature. At high temperatures (> 150°C), this effect is more significant for the 3 MPa to 17.2 MPa interval than for the 17.2 MPa to 34.4 MPa interval.

Bulk thermal expansion measurements at 3 MPa and 20.7 MPa were also carried out on samples BEREA 1 and COLTON 1 in the range from 25°C to 280°C with no temperature cycling. The results of these measurements are presented in table 3 by means of average thermal expansion coefficients for the 25°C to 280°C range, from which the effect of confining pressure on bulk thermal expansion can be inferred.

The Matrix Thermal Expansion Concept:

In the following, the concept of matrix thermal expansion introduced by Contreras et. al. (1982) is analyzed with relation to its physical significance and applications. It has been pointed out by some authors, Somerton et. al. (1981) among others, that it is the expansion of mineral grains into the pore space that causes the decrease in pore volume with increased temperature, since there is less resistance to grain expansion into the pore space than to displacing adjacent grains. From this observation it can be inferred that for a confined sample, that is a jacketed sample subjected to a confining pressure higher than a pore pressure, the observable bulk thermal expansion should be

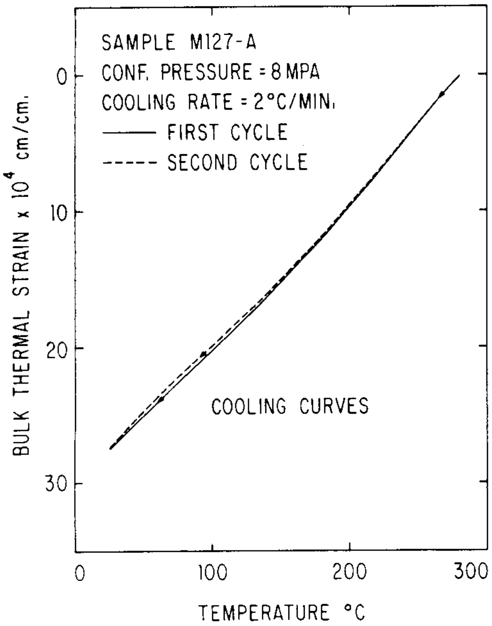

Figure 6. Strain-temperature cooling curves of sample M127-A. (Redrawn from Fig.2 using a common origin at 280°C).

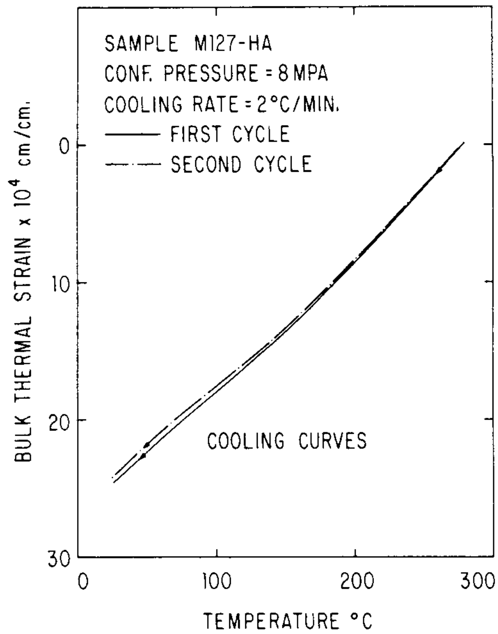

Figure 7. Strain-temperature cooling curves of sample M127-HA, (Redrawn -- from Fig.3 using a common origin at 280°C).

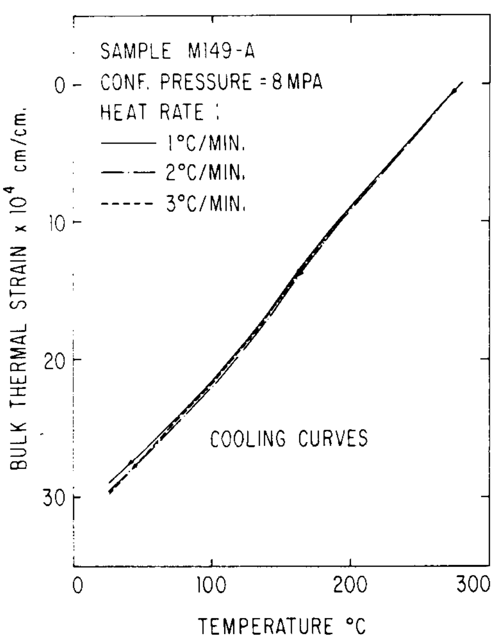

Figure 8. Strain-temperature cooling curves of sample M149-A. (Redrawn from Fig.4 using a common origin at 280°C).

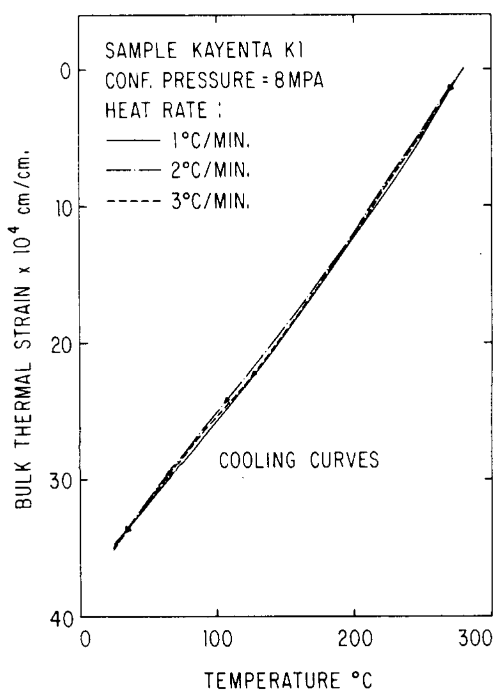

Figure 9. Strain-temperature cooling curves of sample KAYENTA K1. (Redrawn from Fig.5 using a common origin at 280°C).

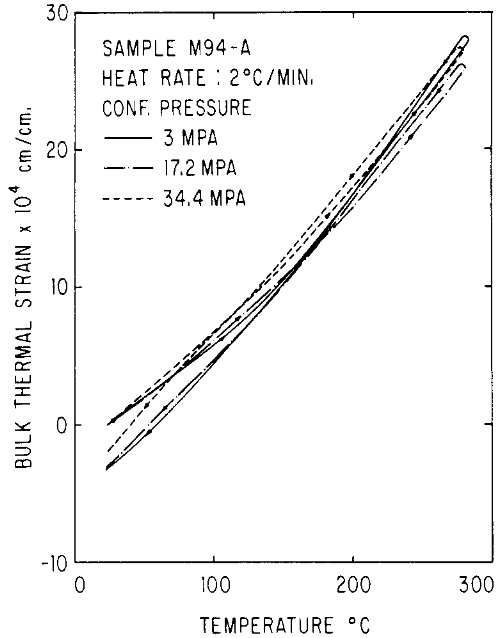

Figure 10. Combined effect of confining pressure and temperature cycling on bulk thermal expansion of sample M94-A.

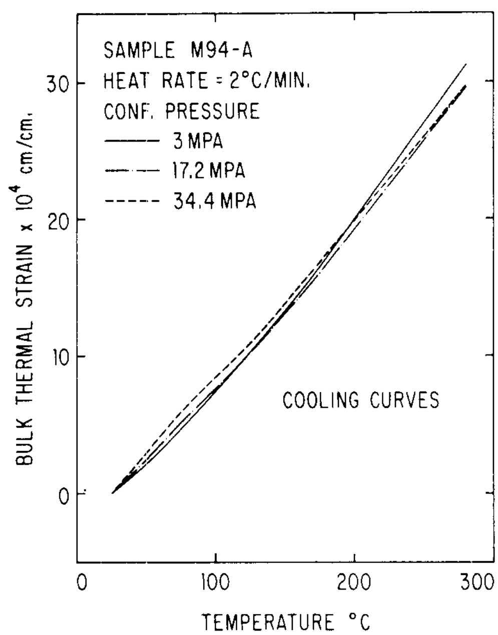

Figure 12. Isolated effect of confining pressure on bulk thermal expansion of sample M94-A.(As inferred - from strain-temperature cooling cur-- ves).

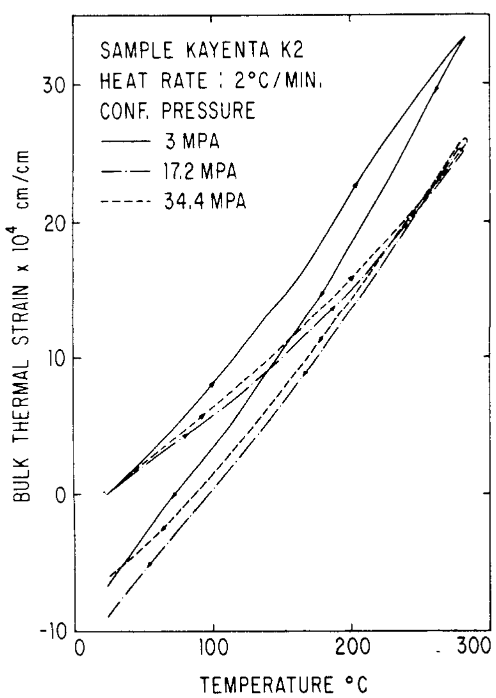

Figure 11. Combined effect of confi-- ning pressure and temperature cycling on bulk thermal expansion of sample KAYENTA K2.

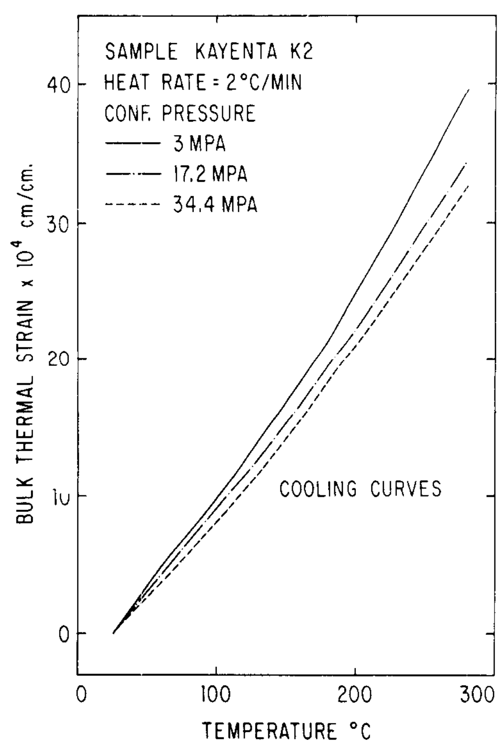

Figure 13. Isolated effect of confining pressure on bulk thermal expansion of sample KAYENTA K2.(As infe-- rred from strain-temperature cooling curves).

smaller than the thermal expansion experimented by the solid material or rock matrix.

In order to evaluate the matrix thermal expansion of a confined rock subjected to given confining pressure P_c and pore pressure P_p, it is required to supress the preferential expansion of the mineral grains into the pore space by making the resistance opposed to the expansion of grains equal towards any direction. This can be accomplished if a pressure equal to the mean isotropic stress in the rock is applied in the pore space in such a way that the isotropic stress is kept constant to avoid any stress difference which could affect the matrix thermal expansion to be determined. It can be shown that these conditions are achieved by increasing both the confining pressure and the pore pressure up to a common value P_o given by

$$(1) \quad P_o = \frac{P_c - \phi P_p}{1 - \phi}$$

where ϕ is the porosity of the rock. Therefore the matrix thermal expansion behavior of a rock subjected to P_c and P_p can be inferred from thermal expansion measurements carried out either on the jacketed rock subjected to $P_c' = P_p' = P_o$ or on the unjacketed rock subjected to a hydrostatic pressureequal to P_o.

The matrix thermal expansion behavior of some sandstones was determined by running tests type D. In order to provide a comparison frame to analyze differences between matrix and bulk thermal expansions, matrix tests were run on samples obtained from the same piece of rock as the samples used for type C bulk tests. The effect of temperature cycling and confining pressure on matrix thermal expansion behavior of samples M94-B and KAYENTA K2 is shown in figures 14 and 15 respectively. It is interesting to note that at the end of the first temperature cycle (confining pressure = 3 MPa) a permanent positive strain results, which is probably indicative that some kind of irreversible microestructural alteration occurs in the rock. On the other hand, the thermal strain versus temperature behavior for the second cycle (confining pressure = 34.4 MPa) is highly reversible. This suggests that the assumed microestructural damage is temperature-dependent only.

Matrix and bulk thermal strain-temperature curves for the heating part of temperature cycles are shown in Fig. 16 for samples M94-A (matrix data) and M94-B (bulk data). The differences that exist between matrix strain and bulk strain for the same confining pressure at given temperature, provide evidence in favor of the concept that preferential expansion of the mineral grains occurs towards the pore space. To this point, it has to be pointed out in accordance with the discussion of the latter subsection, that to accomplish a better comparison with bulk thermal expansion data for 3MPa and 34.4 confining pressure matrix thermal expansion measurements should have been carried out at 3.6 MPa and 40.9 MPa respectively.

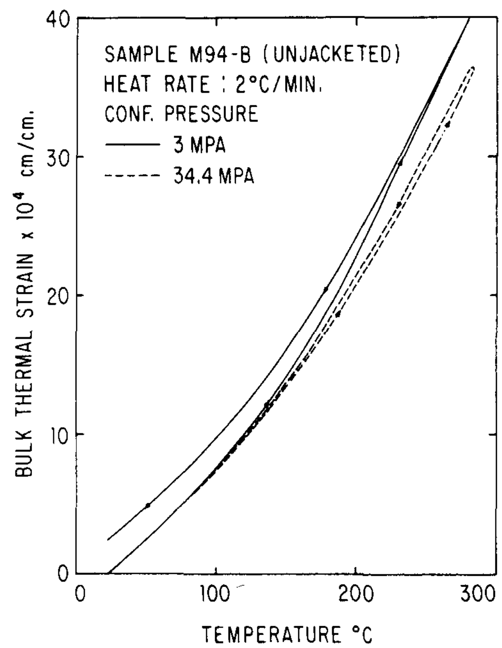

Figure 14. Effect of confining pressure and temperature cycling on matrix thermal expansion of sample M94-B.

Estimation of the Effect of Temperature on Porosity from Bulk and Matrix Thermal Expansion Measurements.

Determination of the effect of temperature on porosity is a subject of interest because of its practical implications in reservoir engineering. The traditional approach proposed to investigate this effect consists of calculating the fractional change in porosity $\Delta\phi/\phi_o$ from experimental data on fractionalchange in bulk volume $\Delta V_B/V_B$ (normally considered to be three times the linear bulk strain) and fractional change in pore volume $\Delta V_P/V_P$. The basic equation used is

$$(2) \quad \frac{\Delta\phi}{\phi_o} = 1 - \frac{1 - \frac{\Delta V_P}{V_P}}{1 - \frac{\Delta V_B}{V_B}}$$

Greenwald et. al. (1982) used this method to calculate the effect of temperature in the range from 40° to 170°C on fractional porosity change for Boise, Berea and Bandera sandstones under 20.7 MPa confining pressure and 6.9 MPa pore pressure. The result reported by Greenwald for the Berea sandstone is shown in Fig. 17. Further, from data on linear thermal expansion and pore volume contraction for the same outcrop rock by Somerton (1980) and Somerton et. al.

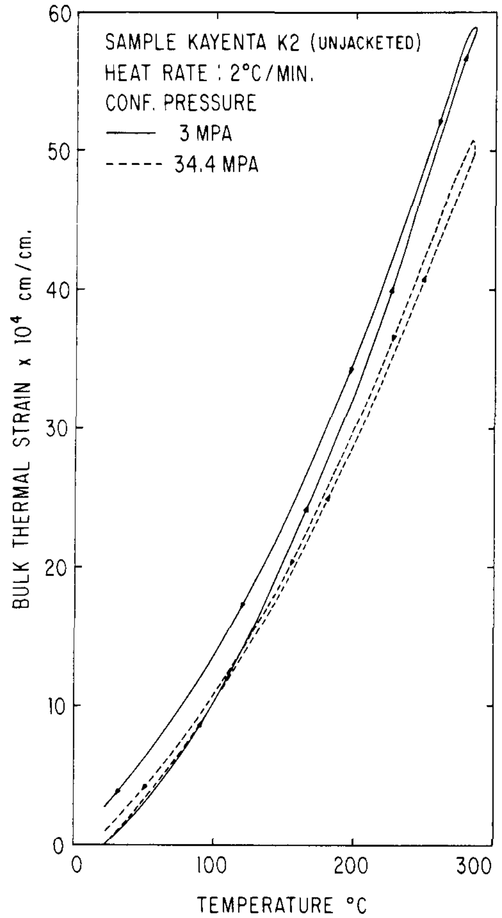

Figure 15. Effect of confining pre-- ssure and temperature cycling on matrix thermal expansion of sample -- KAYENTA K2.

(1981), we calculate the effect of temperature on porosity and the result is also shown in Fig. 17. The discrepancy exhibited by the results shown arises from the differences between the pore volume contraction data used by Greenwald and the data presented by Somerton. This matter was referred to in the literature review of the present work.

On the other hand, provided the rock is isotropic, the effect of temperature on porosity may also be expressed mathematically as

$$(3) \quad \left(\frac{\phi_T}{\phi_{T_o}}\right) = \frac{1}{\phi_o} \{1+(\phi_o - 1)\ e^{3(E_s - E_B)}\}$$

where:

ϕ_T = Porosity at temperature T

ϕ_{T_o} = Porosity at temperature T_o

E_s = Linear matrix thermal strain at temperature T

E_B = Linear bulk thermal strain at temperature T.

Using matrix and bulk linear thermal expansion data obtained from type C and D tests, we calculated through equation (3) the effect of temperature on porosities for sandstones BEREA and KAYENTA and the results are presented in Figs. 17 and 18 respectively. Our results for BEREA sandstone show a fair agreement with the values we calculated from Somerton's data, but they differ considerably from the results reported by Greenwald.

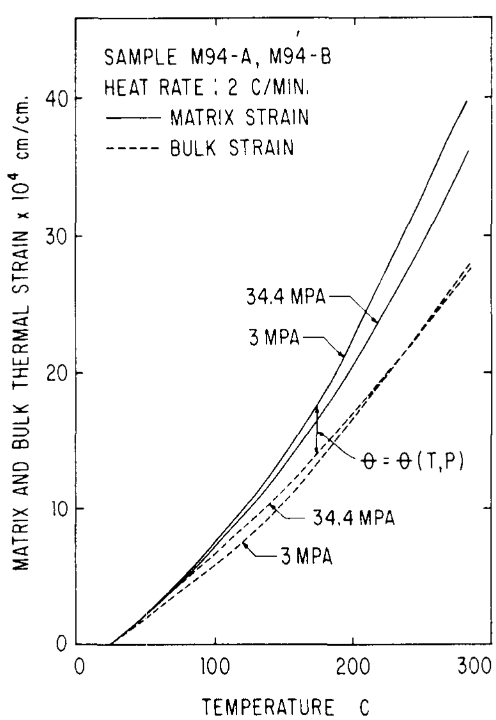

Figure 16. Comparison between matrix and bulk thermal strain of samples M94-A and M94-B.

Results of Research on Thermal Expansion Isotropy:

The assumption that sedimentary rocks are isotropic concerning thermal expansion behavior is very frequently adopted; for example when it is considered that the volumetric strain equals three times the linear strain. The validity of

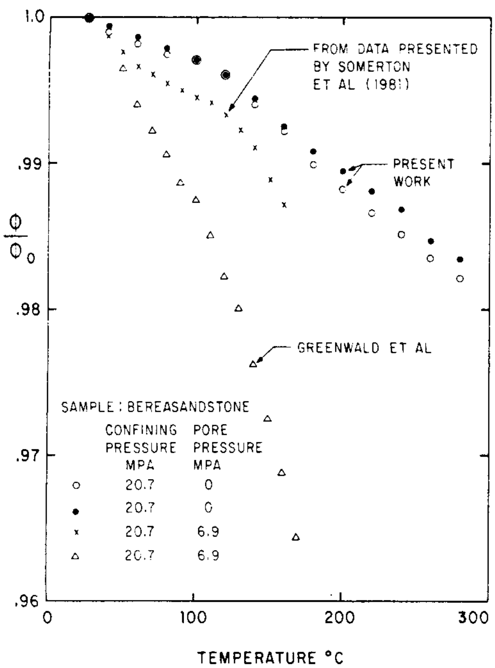

Figure 17. Effect of temperature on porosity of Berea sandstone as reported by different authors.

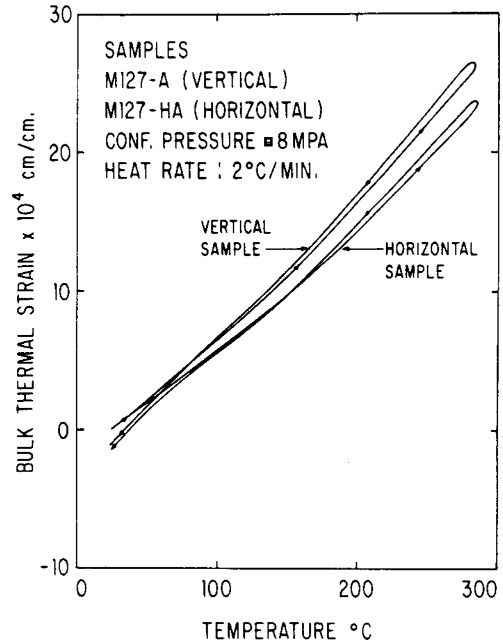

Figure 19. Effect of orientation with respect to the bedding plane on bulk thermal expansion. (From data presented in Figs. 2 and 3).

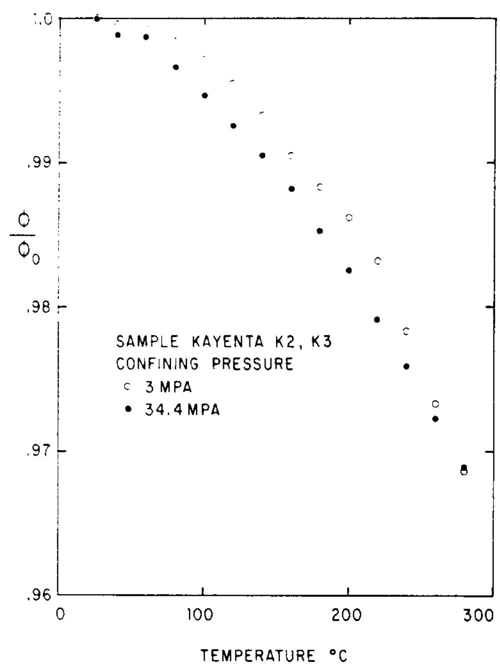

Figure 18. Effect of temperature on porosity of sample KAYENTA K2,K3.

this assumption was investigated in the present work by measuring the bulk thermal expansion of two twin samples obtained from the same piece of rock; one of them was cut parallel to the bedding plane (sample M127-HA) and the other one was cut perpendicular to the bedding plane (sample M127-A). These samples were also used to investigate temperature cycling effects and the results obtained were presented before (see Figs. 2 and 3). Overlapping the thermal strain versus temperature curves for the second cycles of samples M127-A and M127-HA, as taken from Figs. 2 and 3, the result shown in Fig. 19 is obtained. The thermal strain exhibited by the vertical sample is higher than the thermal strain exhibited by the horizontal sample at a given temperature, thus suggesting that the thermal expansion isotropy assumption for sedimentary rocks may not be a good approach to simplify analysis. Of course, more investigation has to be conducted to determine the extent of thermal expansion anisotropy in sedimentary rocks.

Thermal Expansion Coefficients:

The results of some of the tests carried out are not presented explicitly by means of thermal strain-temperature curves. However, thermal expansion coefficients were calculated from al strain versus temperature data for all of the tests carried out. The results are presented in Table 3.

TABLE 3. Thermal Expansion Coefficients of the Samples Tested.

SAMPLE	CONFINING PRESSURE MPa		LINEAR THERMAL EXPANSION COEFFICIENTS °C^{-1} x 10^6							
			BULK				MATRIX			
			TEMPERATURE INTERVAL °C				TEMPERATURE INTERVAL °C			
			40–70	140–170	240–270	AVG(25–280)	40–70	140–170	240–270	AVG(25–280)
M94–A (1)	3	H–2	7.2	12.3	13.5	10.8				
		C–2	9.9	12.8	14.3	12.3				
	17.2	H–2	8.2	10.5	12.7	10.0				
		C–2	10.7	11.7	13.0	11.5				
	34.4	H–2	9.0	10.7	12.7	10.7				
		C–2	11.9	11.7	12.2	11.7				
M94–B (2)	3	H–2					10.1	15.9	20.6	
	34.4	H–2					9.4	13.6	19.7	
M127–A (3)	8	H–2	7.8	9.4	10.3	10.0				
		C–2	9.7	10.9	12.9	10.7				
		H–2	8.9	10.2	11.3	8.1				
		C–2	10.7	10.6	12.3	9.7				
M127–HA (4)	8	H–2	7.5	8.2	9.4	8.1				
		C–2	9.5	9.7	11.3	9.7				
		H–2	7.9	8.3	9.8	8.9				
		C–2	9.4	9.4	11.1	9.7				
M149–A (5)	8	H–2	8.3	13.5	10.9	10.5				
		C–2	9.9	13.8	10.9	11.5				
		H–2	8.7	14.0	12.0	11.0				
		C–2	11.3	13.8	11.9	11.6				
		H–3	8.7	13.3	12.6	11.0				
		C–3	11.6	14.7	11.0	11.7				
KAYENTA K1 (6)	8	H–1	7.7	12.1	11.3	10.6				
		C–1	12.0	14.3	16.1	13.8				
		H–2	9.0	14.3	12.1	12.4				
		C–2	13.1	14.0	15.9	13.7				
		H–3	9.9	14.2	15.3	12.6				
		C–3	13.0	14.1	16.1	13.8				
KAYENTA K2 (7)	3	H–2	10.9	14.6	11.7	12.9				
		C–2	14.2	15.1	20.1	15.5				
	17.2	H–2	7.9	10.3	13.0	9.9				
		C–2	12.8	13.8	15.2	13.5				
	34.4	H–2	8.8	10.4	12.2	10.1				
		C–2	10.7	13.5	14.9	13.0				
KAYENTA K3 (8)	3	H–2					13.5	24.3	33.4	22.1
	34.4	H–2					12.6	20.2	25.1	18.9
BEREA 1 (9)	3	H–2	10.2	14.5	15.4	12.8				
	20.7	H–2	10.6	13.0	15.8	12.5				
BEREA 2 (10)	3	H–2					12.1	21.9	20.5	18.0
	20.7	H–2					13.1	19.6	18.4	17.3
COLTON 1 (11)	3	H–2	10.9	17.1	16.3	14.8				
	20.7	H–2	9.8	12.5	13.6	11.7				
COLTON 2 (12)	3	H–2					12.7	18.5	14.8	15.9
	20.7	H–2					12.7	14.8	17.2	14.3

Note: H and C in the confining pressure column indicate whether the reported data in the row correspond to the heating or to the cooling part of the temperature cycling respectively.

Thermal expansion coefficients were calculated both for heating and cooling curves in the intervals of 40°C to 70°C, 140°C to 170°C and 240°C to 270°C, using a linear regression scheme with at least ten experimental data points for each interval. The correlation coefficient was higher than 0.99 in all the cases. Furthermore, average thermal expansion coefficients for the total temperature range covered (25°C to 280°C) were also calculated and the results are also reported in Table 3.

SUMMARY AND CONCLUSIONS

An extensive experimental program focused to investigate the thermal expansion behavior of sedimentary rocks has been carried out. The significant findings and conclusions from this work can be summarized as follows:

1. At a given confining pressure, after a first irreversible thermal strain-temperature cycle samples become thermomecanically stabilized and further cycles are almost reversible, repeteable and with no considerable hysteresis. However, a rock sample stabilized at a given pressure will again exhibit an irreversible thermal strain-temperature behavior if the confining pressure is increased up to a new value. This suggests that the compaction experimented by the rock arises from a combined effect of temperature and pressure.

2. Differences in heating rates in the range from 1°C/min to 3°C/min do not affect the thermal expansion behavior of the sedimentary rocks studied.

3. At a given confining pressure, the cooling thermal strain versus temperature curves show the same pattern independently of the thermal history of the rock (as opposed to the heating curves that exhibit thermal hystory dependence).

4. The bulk thermal expansion behavior that a stabilized rock at a given pressure would exhibit, can be inferred from the cooling thermal strain-temperature curve of any cycle, even the first one, but not from the first heating strain temperature curve.

5. The effect of confining pressure on bulk thermal expansion is significant and well behaved for one of the two samples studied, but is rather small and erratic for the other sample. More investigation on this aspect has to be carried out to obtain further evidence to support some sort of conclusion.

6. The matrix thermal expansion behavior corresponding to a rock subjected to given confining pressure P_c and pore pressure P_p, can be inferred by measuring the thermal expansion of the rock subjected to confining pressure P_c^* and to a pore pressure P_p^* given by

   $$P_p^* = P_c^* = \frac{P_c - \phi P_p}{1-\phi}$$

   where ϕ is the porosity of the rock.

7. For a rock subjected to given pressure conditions, the matrix thermal strain is higher than the bulk thermal strain at a given temperature; this is in agreement with the concept of preferential thermal expansion of mineral grains into the pore space.

8. The matrix thermal expansion behavior exhibited by the samples studied shows that strain remains in the rock after completion of the first temperature cycle. On the other hand, for the second cycle the thermal strain versus temperature behavior is highly reversible and with no hysteresis, even though a different confining pressure was applied on the samples during the second cycle. This suggests that the remaining strain of the first cycle arises because of structural damage caused by differential thermal expansion of the mineral grains when are heated during the first cycle. This structural damage is temperature dependent and occurs during the first temperature cycle only. Furthermore, it can be noted that the effect of increased confining pressure is to reduce the matrix thermal expansion at a given temperature.

9. The effect of temperature on porosity was estimated from matrix and bulk thermal expansion data for two sandstones and results were compared with earlier available data calculated from pore volume contraction and bulk thermal expansion data. Although the observed effect is rather small, more investigation on this particular subject should be conducted to establish ranges of porosity change as well as to determine a pattern of influence upon variable confining pressure.

10. Thermal expansion isotropy for sedimentary rocks is an assumption that should be adopted cautiosly

11. A big deal of data about thermal expansion coefficients of the samples tested is reported. Information concerning magnitudes and variation ranges of this parameter may be useful for reservoir engineering calculations that involve the thermal expansion behavior of sedimentary rocks.

ACKNOWLEDGEMENTS

We wish to thank Ing. Alfredo Mañón M. at Comisión Federal de Electricidad, Coordinadora Ejecutiva de Cerro Prieto, for his interest in this work. We also thank Ing. Sergio Mercado G., at Instituto de Investigaciones Eléctricas, for his permission to accomplish the experimental program leading to this paper as part of project IIE-1663. Martín Uribe collaborated in the experimental work, Adrián Patiño drafted the figures and Mrs. María Eugenia Calderón and Mrs. Ma. de Lourdes Calderón made the typing; their participation is duly acknowledged.

REFERENCES

Ashqar, P. I., (1979), "Thermal Expansion of Poous Rocks Under Stress". Master of Science Project Report, University of California, Berkeley, December 1979.

Contreras, E., Iglesias, E.; Bermejo, F. (1982), "Effects of Temperature and Stress on the Compressibilities, Thermal Expansivities, and Porosities of Cerro Prieto and Berea Sandstones to 9000 psi and 280°C". Proceedings 8th Workshop on Geothermal Reservoir Engineering. Standford, California, December 14-16, 1982.

Ennis, D. O., Butters, S. W., Lingle, R., Van Buskirk, R. G., Prater, F. R. (1979). "Capabilities to Measure Geothermal Material Properties at Simulated In-Situ Conditions". Terratek Report TR79-49.

Greenwald, R. F., Ashqar, P. I., Somerton, W.H., (1982). "Thermal Expansion Behavior of Porous Rocks Under Stress". Proceedings of the Thermal Expansion Conference N° 7. Plenum Press, 1982. David C. Larsen, Editor.

Janah, A., (1980). "Pore Volume Variation with Temperature for Porous Rocks Under Stress". M. S. Report, University of California, Berkeley. Department of Mechanical Engineering.

Somerton, W. H., Selim, M. A., (1961). "Additional Thermal Data for Porous Rocks-Thermal Expansion and Heat of Reaction". 31st Annual California Regional Meeting of SPE, Octobre 21-22, 1961.

Somerton, W. H., (1980). "The Behavior of Rock-Fluid Systems at Elevated Temperatures and Pressures". Annual Report 1981, Earth Sciences Division, Lawrence Berkeley Laboratory, University of California.

Somerton, W. H., Janah, A. H., Ashqar, P. I., (1981). "Thermal Expansion of Fluid Saturated Rocks Under Stress". SPWLA Twenty-Second Annual Logging Symposium. June 23-26, 1981.