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EFFECTS OF TEMPERATURE AND STRESS ON THE COMPRESSIBILITIES, THERMAL EXPANSIVITIES, AND POROSITIES OF CERRO PRIETO AND BEREA SANDSTONES TO 9000 PSI AND 280°C

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ABSTRACT

We measured matrix and bulk compressibilities and thermal expansion coefficients of Berea sandstone and of a sandstone from Cerro Prieto well M-94. Furthermore, we developed and demonstrated a novel technique for computing porosities as functions of effective stress or temperature from uniaxial compression and thermal expansion measurements respectively. Unlike previous results, which are limited to temperatures below 200°C, our measurements cover the range from ambient temperature to 280°C. Our data for Berea sandstone generally agree with previous results. The matrix and bulk compressibilities of the Cerro Prieto sandstone are considerably greater than those of two Imperial Valley sandstones, reported in the literature, indicating significantly greater subsidence potential for Cerro Prieto. The porosities of the rocks studied decrease with increasing effective stress; our results indicate that porosity reductions due to pore pressure drawdown in sandstone dominated geothermal reservoirs are probably small. Porosities decrease also with increasing temperatures because the grains expand at the expense of the pore volume. Porosity increases due to thermal drawdown are likely to be small in sandstone geothermal reservoirs, but greater porosity relative changes are expected for tighter sandstones.

INTRODUCTION

Most physical properties of rocks vary with temperature and stress. Knowledge of the corresponding dependences and of their magnitudes is important for geothermal reservoir assesment and interpretation. Among the petrophysical properties of major interest for the geothermal industry are porosity, compressibilities and thermal expansivities. Sandstones constitute the main producing horizons in the extense Mexicali/Imperial Valley geothermal region. Understanding the behavior of these sedimentary rocks at reservoir conditions is therefore economically important. However, the information available about the stress and temperature dependences of porosities, compressibilities and thermal expansivities of these rocks is scarse. This information is briefly reviewed in the next paragraph.

Compressibilities of several sandstones to high pressures (~16,000 psi) and to medium temperature (~200°C) were measured by Lobree (1968), Von Gonten and Choudhary (1969), and Somerton et al (1974); they found that bulk matrix compressibilities generally increased with increasing temperature, despite some erratic behavior of matrix compressibilities. Thermal expansivities of Berea, Boise, and Bandera sandstones to 160°C were presented recently by Somerton et al (1981); these results indicate that thermal expansivities are nearly independent of stress and of the amount of fluid saturation. Porosity variations with stress in sandstones to ~10,000 psi were investigated by Somerton (1978) who drew on data by Fatt (1953), Somerton et al (1974), and Von Gonten and Choudhary (1969); it was found that porosity reductions with stress are greater at higher temperatures. Variations of pore volume versus temperature to 170°C for three sandstones were reported by Somerton et al (1981); these authors showed that pore volumes of liquid saturated sandstones under stress decrease with increasing temperature, and that the pore volume thermal contraction is a function of porosity, values decreasing with increased porosities.

This paper focuses on the magnitudes and on the temperature and stress dependences of the compressibilities, thermal expansivities and porosities of Cerro Prieto and Berea sandstones. Berea is a well-known rock used extensively in laboratory investigations, and as such, valuable for comparison purpouses. Apart from its obvious importance for characterization of the Cerro Prieto reservoir itself, knowledge of the properties of Cerro Prieto sandstones provides valuable information concerning the whole Mexicali/Imperial Valley geothermal area. We have measured bulk and matrix compressibilities and thermal expansivities as functions of stress and temperature. From these measurements we computed porosities as functions of stress and temperature by means of a novel technique devised by us for this purpouse. Unlike previously published data, which are limited to temperatures below 200°C, our measurements cover the range from ambient temperature to 280°C.

EXPERIMENTAL METHODS

From each of the samples studied in this work (Berea sandstone and a sandstone from Cerro Prieto well M-94) four specimens were obtained. Two of them were dry jacketed for bulk compressibility and thermal expansion measurements; the rest were used unjacketed for matrix compressibility and thermal expansion measurements. The specimens were cilindrical, 2.54 cm in diameter by 5.08 in length; their ends were ground flat and parallel to within 2.54 x 10^{-3} cm.

Linear thermal expansion and linear compaction were measured along the specimens axis by means of high resolution LVDT's (linearly variable diferencial transformers) attached to the top of the test specimens by quartz rods. Thermal and mechanical induced deformations of up to 2.5 x 10^{-2} cm can be measured in our equipment 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 on the test configuration used are given by Ennis et al (1979).

During the compressibility tests, confining pressure was changed at a uniform rate of 785 psi/min (5MPa/min). The specimen was subjected to loading-unloading cycles, until no permanent strain was detected, to insure reproducibility. Compressibilities were computed from the loading portion of the cycle. Temperature was kept constant at the test value with an accuracy of ± 1°C.

When running thermal expansion tests, the sample temperature was increased at a uniform rate of about 1.5°C/min. The heating rate chosen, according to our own experience, is low enough to prevent large irrecoverable microestructural damage in the rock sample. Confining pressure was kept constant with an accuracy of ± 1 psi.

A computer based data aquisition system which allows sampling of the channel transducers involved in the test with a frequency of up to 180/minute was used. In the compressibility tests data were collected every 10 seconds; while in the thermal expansion tests the frequency was once every minute.

The initial porosity ϕ_o of each sample, used in our computations of porosity as a function of effective stress or of temperature, was determined by averaging the porosities of the corresponding four specimens. These porosities were measured using the liquid vacuum saturation method.

RESULTS AND DISCUSSION

Matrix compressibilities

These were computed assuming isotropy from uniaxial compression measurements on unjacketed samples at constant temperature with hydrostatic confining pressures ranging from o to 9000 psi. The corresponding results are shown in Table 1. The linearity of the uniaxial compression data with hydrostatic stress

TABLE 1. Matrix compressibilities

	BEREA		CERRO PRIETO	
Temp. (°C)	Compress. (psi^{-1})	Corr. coeff.	Compress. (psi^{-1})	Corr. coeff.
20	1.46×10^{-7}	0.9975	1.59×10^{-7}	0.9999
280	2.39×10^{-7}	0.9997	3.06×10^{-7}	0.9991

is excellent, as indicated by the magnitudes of the corresponding correlation coefficients.

Our results for Berea sandstone are in good agreement with those by Somerton et al. (1974) as shown in Fig. 1. Pooling together our results with Somerton et al's we find that the matrix compressibility of Berea sandstone increases with temperature at a constant rate equal to 3.26 x 10^{-10} psi^{-1} $°C^{-1}$. The corresponding correlation coefficient equals 0.9477.

Comparison of our results for Cerro Prieto sandstone from well M-94 at a depth of 6900 feet with Somerton et al's results for an Imperial Valley sandstone denominated W823, from a depth of 5073 feet (Fig. 1) shows that the corresponding matrix compressibilities differ significantly from each other, and that the matrix compressibilities of both rocks increase with temperature at nearly the same

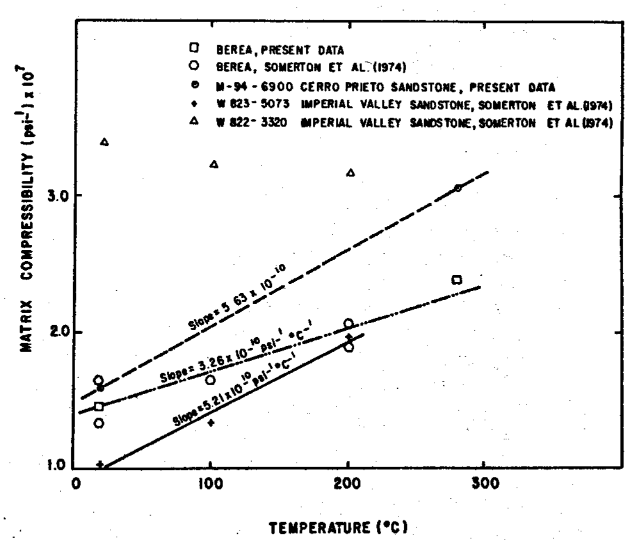

FIGURE 1. Effect of temperature on matrix compressibility

rate which is significantly greater than that of Berea. This temperature dependence lends credibility to the data corresponding to sample W823-5073, which were deemed doubtful by Somerton et al (1974) due to the large change of matrix compressibility with temperature. Compared with the evidence accumulated for Berea, Cerro Prieto and Imperial Valley W823-5073 sandstones, the trend of matrix compressibility decreasing with increasing temperature depicted by Somerton et al's data (Fig.1) on Imperial Valley sample W822-3320 seems anomalous.

Bulk compressibilities

These were computed assuming isotropy from uniaxial compression measurements on dry jacketed samples at constant temperature. The confining hydrostatic pressure was assumed to equal the effective (confining minus pore) stress. Our results for Berea sandstone at 20°C and 280°C are shown in Fig. 2. Observe that bulk compressibilities increase with increasing temperature. At 20°C these data agree well with the corresponding data from Somerton et al (1974); our 280°C data are consistent with Somerton et al's high temperature (≤ 200°C) data.

Our results for M-94-6900 Cerro Prieto sandstone at 20°C and 280°C are shown in Fig. 3. These compressibilities are significantly higher (about +90% at 2000 psi, 20°C and 280°C) than our results for Berea sandstone. They are also significantly higher than the bulk compressibilities reported for Imperial Valley sandstones by Somerton et al (1974): about + 50% at 20°C, 2000 psi for W823-5073, and about +120% at 20°C, 2000 psi for W822-3320. Subsidence computations should reflect these differences in bulk compressibilities.

Matrix thermal expansivities

We measured uniaxial thermal expansions to 280°C on unjacketed samples at constant hydrostatic pressure. The corresponding strain-temperature plots for Berea and Cerro Prieto sandstones are shown in Figs. 4 and 5 respectively. From the slopes of these curves it is seen that the linear thermal expansion coefficients of both rocks are functions of temperature. The thermal expansion coefficients increase with increasing temperature until a nearly constant value is achieved. Furthermore, for temperatures exceeding about 150°C for Berea sandstone, and greater than about 100°C for Cerro Prieto sandstone, linear thermal expansivities depend on stress. Note that for Berea sandstone thermal expansivity increases with decreasing confining pressure. For the Cerro Prieto sample the effect is more complex: at lower temperatures (100-150°C) the thermal expansivity increases with increasing confining pressure, and at higher temperatures (>200°C) the thermal expansivity decreases with increasing confining pressure. Representative values of linear thermal expansion coefficients are presented in Table 2.

TABLE 2. Matrix linear thermal expansion coefficients

Temp. Int. (°C)	Rock	Conf. Press (psi)	Coeff. (°C^{-1})
20-100	Berea	435 and 3000	12.5×10^{-6}
150-280	"	435	21.2×10^{-6}
150-280	"	3000	19.4×10^{-6}
20-100	Cerro Prieto	435	11.5×10^{-6}
20-100	" "	3000	12.5×10^{-6}
200-280	" "	435	22.0×10^{-6}
200-280	" "	3000	20.0×10^{-6}

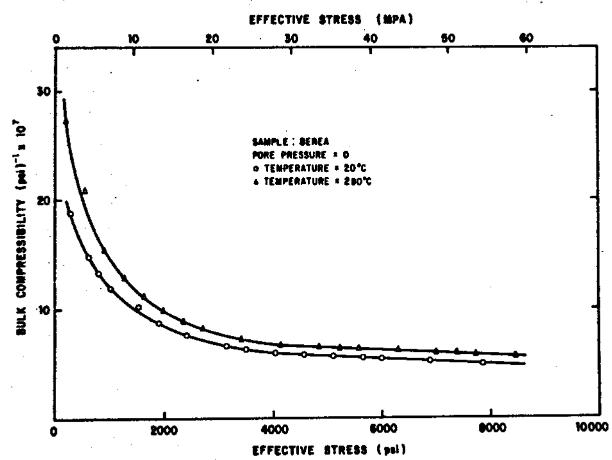

FIGURE 2. Effect of stress at constant temperature on the bulk compressibility of Berea sandstone.

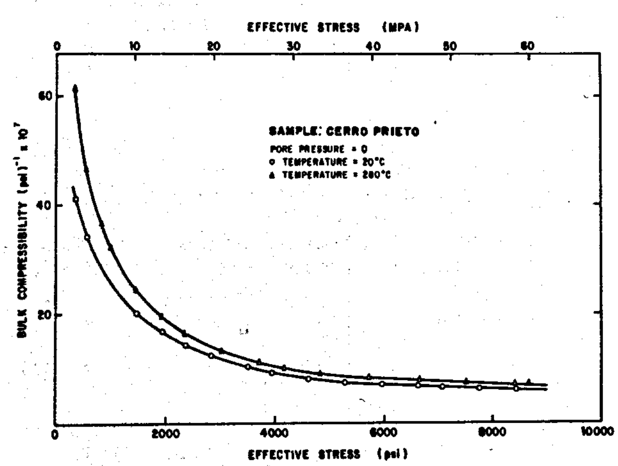

FIGURE 3. Effect of stress at constant temperature on the bulk compressibility of the Cerro Prieto sandstone.

Bulk thermal expansivities

We measured uniaxial thermal expansions on dry jacketed samples at constant hydrostatic confining pressure to 280°C. The corresponding strain-temperature plots for the rocks studied are shown in Figs. 4 and 5. It will be noticed that linear bulk thermal expansion coefficients depend both on temperature and pressure, as is the case for matrix thermal expansivities. Representative values of linear bulk thermal expansion coefficients computed from Figs. 4 and 5 are given in Table 3. Our values for Berea sandstone closely bracket the value of 13.0×10^{-6} °C^{-1} for 100-200°C found by Somerton et al (1981).

TABLE 3. Linear bulk thermal expansion coefficients

Temp. Int. (°C)	Rock	Conf. Press. (psi)	Coeff. (°C^{-1})
20-100	Berea	435 and 3000	10.0×10^{-6}
150-280	"	435	14.7×10^{-6}
150-280	"	3000	14.0×10^{-6}
20-100	Cerro Prieto	435 and 3000	8.3×10^{-6}
120-180	"	435	13.8×10^{-6}
120-200	"	3000	11.8×10^{-6}
200-280	"	435	13.8×10^{-6}
200-280	"	3000	13.8×10^{-6}

For Berea sandstone our results indicate that for T >150°C the linear bulk thermal expansion coefficient decreases with increasing effective stress. This is consistent with the results of Somerton et al (1981), and with theoretical estimates by Sweet (1978). Our results for the Cerro Prieto sandstone studied indicate however that increasing the effective stress does not necessarily result in a decrease of the bulk thermal expansion coefficient.

Porosity vs. stress

Combining our uniaxial compression measurements on jacketed and unjacketed samples, we computed the effects of stress at constant temperature on the porosities of the samples studied. From the definitions of porosity and of matrix and bulk linear compressibilities, and assuming isotropy, it is easy to show that

$$\phi/\phi_o = \{1-(1-\phi_o)\ (1+3\ \frac{\Delta L'}{L'_o})/(1+3\ \frac{\Delta L}{L_o})\}/\phi_o \quad (1)$$

were ϕ is the porosity at a given effective stress; ϕ_o, L'_o and L_o the porosity and the lengths of the unjacketed and jacketed samples respectively at the initial stress of the test; $\Delta L'$ and ΔL the uniaxial compressions for the unjacketed and jacketed samples respectively; and all these quantities correspond to the (constant) temperature of the test. The validity of expression (1) hinges on the usual

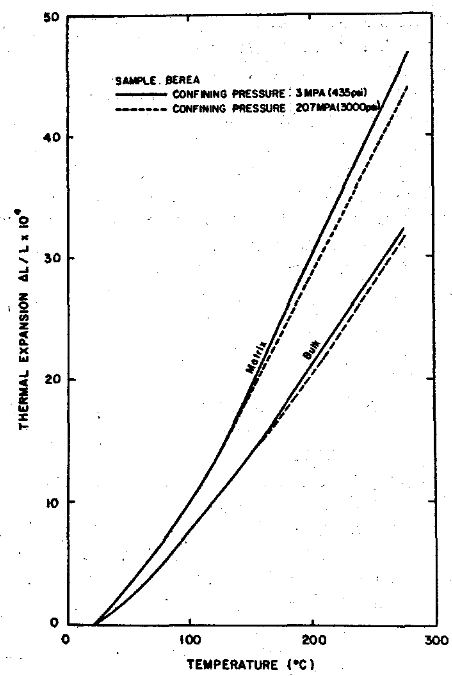

FIGURE 4. Linear matrix and bulk thermal expansion at constant effective stress for Berea sandstone.

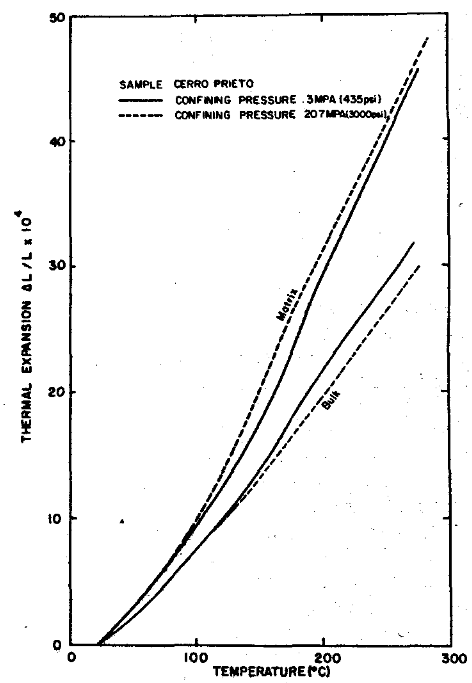

FIGURE 5. Linear matrix and bulk thermal expansion at constant effective stress for the Cerro Prieto sandstone.

assumption that the deformation of the matrix is the same for both unjacketed and jacketed samples. In actual computations with expression (1) we used the values of ϕ_o corresponding to 20°C and 14.7 psi. This is strictly correct for the data at 20°C, and introduces a small error in the data corresponding to 280°C: about 0.1 percent for a 3 percent error in ϕ_o.

Expression (1) was used to compute the results shown in Fig. 6. Clearly, increasing the effective stress reduces the porosity. This effect is more pronounced for the Cerro Prieto sandstone than for the Berea sandstone, due to the higher compressibilities of the former.

Increasing the temperature results in increased porosity reductions, which is consistent with bulk compressibilities being greater at higher temperatures. Again, this effect is more pronounced for the Cerro Prieto sandstone than for Berea.

The relative porosity reductions $\Delta\phi/\phi_o$ computed by Somerton (1978) for Berea sandstone at 20°C are much higher (about 134 percent at 9000 psi) than our results for the same rock. These calculations by Somerton were based on heterogeneous data: bulk compressibilities from Somerton et al. (1974), and pore compressibilities from Von Gonteu and Choudhary (1969). Using expression (1) and matrix and bulk compressibilities from Somerton et al. (1974) we computed values of $\Delta\phi/\phi_o$ much closer to our own results: at 9000 psi about 18 percent higher than the results of Fig. 6 using one set (El-Shaarani, 1973) of data, and about 10 percent lower than our results for the set of data corresponding to Lobree (1968). This close agreement lends credibility to the computed porosities shown in Fig. 6.

These results indicate that in sandstone-dominated geothermal reservoirs, such as most found in the Mexicali/Imperial area, changes of porosity due to pressure drawdown are probably small. For example our data shows that the Cerro Prieto sandstone from well M-94 at a depth of 7000 feet, with an initial pore fluid pressure equal to 3000 psi, and a temperature of 280°C would undergo a reduction in porosity of only about 0.4% upon a pore pressure reduction of 1000 psi.

Porosity vs. temperature

Combining our uniaxial thermal expansion measurements on jacketed and unjacketed samples, and using an expression analogous to (1), where the uniaxial compressions were replaced by uniaxial thermal expansions, we computed the effects of temperature, at constant stress, on porosity. The validity of this method of computation hinges on the usual assumption that the matrix thermal expansion is independent of the samples being jacketed or unjacketed. As before, in actual computations of relative porosities ϕ/ϕ_o versus temperature we used the values of ϕ_o corresponding to 20°C and 14.7 psi, because the errors introduced in this way are small.

Porosities vs. temperature for Berea and Cerro Prieto sandstones are shown in Fig. 7. It will be noticed that porosities decrease with increasing temperature. We interpret this effect as demonstrating that in confined rocks the thermal expansion of the grains is partly at the expense of the pore volume, because the measured bulk thermal expansion coefficients are smaller than the matrix thermal expansion coefficients (Tables 2 and 3).

The effects of the (constant) confining stress seem to depend on the type of rock. For temperatures exceeding about 120°C the porosity of the Cerro Prieto sandstone studied decreases faster for greater confining pressure. However the effect of the confining pressure on Berea sandstone seems to be opposite: for T > 160°C its porosity decreases more rapidly for smaller confining pressures. This opposite dependence of the porosities of Cerro Prieto and Berea sandstones is traceable to the behavior of the corresponding matrix strain-temperature curves (Figs. 4 and 5), which show opposite dependences with stress.

The curves in Fig. 7 show that at the lower temperatures porosities decrease relatively slowly; then at intermediate temperatures the absolute value of the rate of change increases; and finally, at higher temperatures, the absolute value of the rate of change decreases again and becomes nearly constant. From pore volume thermal contraction measurements Somerton et al (1981) made similar observations. These authors concluded that both the temperature at which the nearly constant rates of

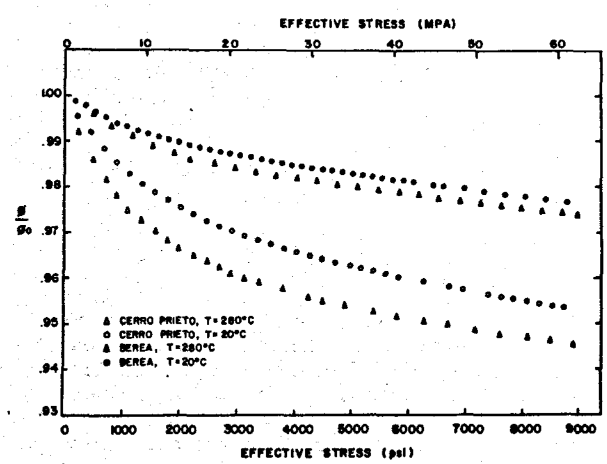

FIGURE 6. Effect of stress at constant temperature on the porosities of Berea and Cerro Prieto sandstones.

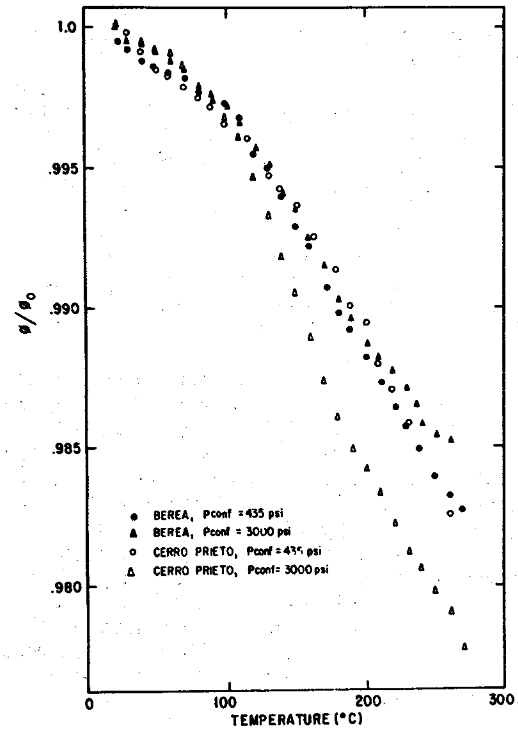

FIGURE 7. Effect of temperature at constant effective stress on the porosities of Berea and Cerro Prieto sandstones.

change begin, and the corresponding slopes are related to the porosity of the sandstone: (a) for lower porosity sandstone the absolute value of $(\partial\phi/\partial T)_p$ is greater; and (b) for lower porosity sandstone the onset of the constant slope takes place at lower temperature. Conclusions (a) and (b) are consistent with the data presented in Fig. 7. To understand the physical reasons underlying observations (a) and (b) it is helpful to consider the thermal expansion analogue of expression (1). Noting that $\varepsilon' = 3\Delta L'/L'_o << 1$ and that $\varepsilon = 3\Delta L/L_o << 1$, equation (1) can be approximated by

$$\varepsilon = 1 - (1 - \phi_o)(1 + \varepsilon' - \varepsilon), \quad (2)$$

and

$$\left(\frac{\partial\phi}{\partial T}\right)_p = -(1 - \phi_o)\left(\frac{\partial\varepsilon'}{\partial T} - \frac{\partial\varepsilon}{\partial T}\right)_p \quad (3)$$

Thus it is seen that the absolute value of $(\partial\phi/\partial T)_p$ increases with decreasing values of ϕ_o, as observed. This can also ve verified pluging the values of ϕ_o for Berea and Cerro Prieto sandstones (0.185 and 0.178 respectively) and the high temperature thermal expansion coefficients from Tables 2 and 3 in expression (3).

Regarding point (b), we approximated each of the bulk and matrix strain-temperature curves (Figs. 4 and 5) by two straight lines: One with the slope corresponding to the lower temperature intervals in Tables 2 and 3, and the other with the slope corresponding to the high temperature intervals of those tables. With these approximations and equation (2) it is easy to show that (i) the curves (ϕ/ϕ_o) vs. T should show three different slopes, as observed; and (ii) the temperatures at which these slopes change values are given by

$$T_* = \frac{(\Delta L'/L')_i}{\alpha_{i-1} - \alpha_i} \quad (4)$$

where $(\Delta L'/L')_i$ is the intercept of the straight line representing the matrix strain-temperature curve to the high temperature side of T_*, α_i the matrix linear thermal expansion coefficient for $T > T_*$, and α_{i-1} the coefficient corresponding to the low temperature side of T_*. The important point here is that T_* does not depend explicitly on ϕ. Therefore Somerton et al's conclusion (b) seems to be either fortuituos or arising from some correlation between porosity and the matrix thermal expansion coefficient. Such correlation is not apparent from our data (see Figs. 5 and 6 and Table 2), perhaps because the porosity contrast between the Berea and Cerro Prieto sandstones studied is small.

SUMMARY AND CONCLUSIONS

We have measured matrix and bulk compressibilities and thermal expansion coefficient of Berea sandstone and of a sandstone from Cerro Prieto well M-94 to 280°C. Furthermore, we have developed and demonstrated a novel technique for computing porosities as functions of effective stress or temperature, from uniaxial compression and thermal expansion measurements respectively. Finally, we compared our results with published data on Berea sandstone and on two Imperial Valley sandstones. The following conclusions may be reached from this work.

1. The measured matrix and bulk compressibilities of the Cerro Prieto sandstone from M-94 are significantly higher than those found for Berea sandstone and for two Imperial Valley sandstones (W822-3320 and W823-5073). If the trend indicated by the samples from Cerro Prieto and Imperial Valley is representative of these locations, our results indicate significantly greater subsidence potential for Cerro Prieto.

2. The porosities of Berea and Cerro Prieto sandstone M-94-6900 decrease slightly with increasing effective pressure at constant temperature: about 2.5% for Berea sandstone and about 4.5% for Cerro Prieto sandstone at 9000 psi. The greater sensitivity shown by the Cerro Prieto sandstone is due to its higher compressibility. These porosity changes are smaller at lower temperatures, reflecting the temperature dependence of the matrix and bulk compressibilities. Our results indicate that in sandstone dominated geothermal reservoirs, changes of porosity due to pressure drawdown are probably small.

3. The porosities of Berea sandstone and of the Cerro Prieto sandstone M94-6900 decrease with increasing temperature at constant effective stress. This effect is due to the grains expanding partly at the expense of the pore volume (because the bulk thermal expansion coefficients are smaller than the corresponding matrix thermal expansion coefficients). Our results indicate that in sandstone dominated geothermal reservoirs changes of porosity due to thermal drawdown are, very likely, small.

4. At intermediate to high temperatures (>150°C) porosity decreases with temperature more rapidly for rocks of smaller porosities because the absolute value of $(\partial\phi/\phi T)_p$ is proportional to $(1-\phi_o)$. Thus, greater increases in porosity are expected for tighter sandstones upon thermal drawdown in geothermal reservoirs.

5. Comparison of our results with others found in the literature shows that significant differences in the magnitudes and in the thermal behavior of the compressibilities, thermal expansivities, and porosities of different sandstones exist which warrant further studies at high temperatures.

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REFERENCES

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

- Lobree D.T., (1968), "Measurement of Compressibilities of Reservoir Type Rocks at Elevated Temperatures", MS thesis, University of California, Berkeley.

- Somerton W. H., El-Shaarani A.H., and Mobarak S.M., (1974), "High Temperature Behavior of Rocks Associated with Geothermal Type Reservoirs", Soc. Petrol. Engrs. preprint No. 4897.

- Somerton W. H., (1978), "Some Physical Properties of Cerro Prieto Cores", Proceedings 1st. Symp. on the Cerro Prieto Geothermal Field, pp. 333-338, Lawrence Berkeley Laboratory Report LBL-7098.

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

- Sweet J.N., (1978), "Pressure Effects on Thermal Conductivity and Expansion of Geologic Material", D.O.E. Report # SAND 78-1991.

- Von Gonten W.D., and Choudhary B.K., (1969), "Effect of Pressure and Temperature on Pore Volume Compressibility", Soc. Petrol. Engrs. preprint No. 2526.