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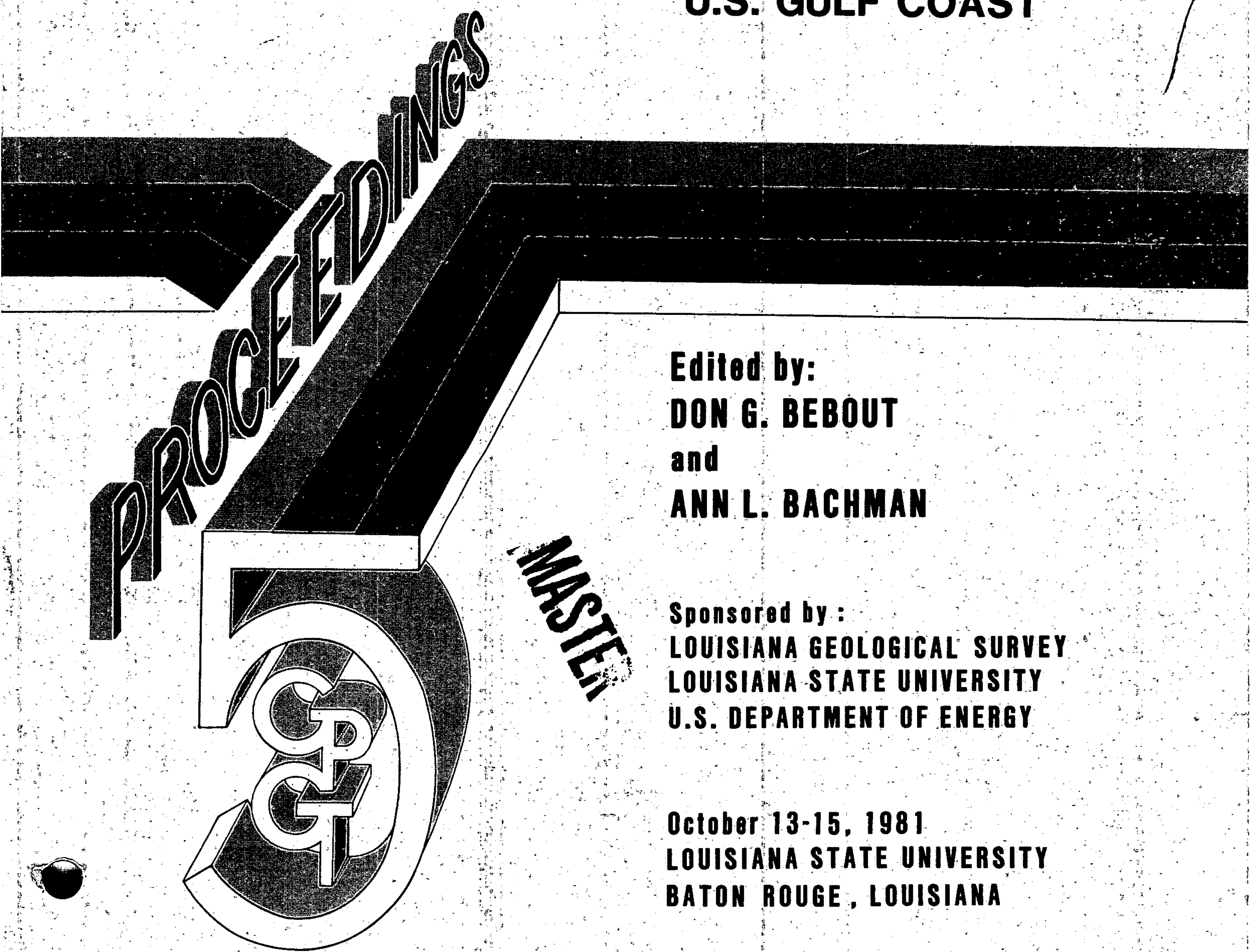

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LABORATORY DETERMINATION OF MECHANICAL PROPERTIES OF ROCKS FROM THE PARCPERDUE GEOPRESSURED/GEOTHERMAL SITE

Krishna P. Sinha, Thomas F. Borschel, Michael T. Holland, and John F. Schatz

Terra Tek, Inc., Salt Lake City, Utah

ABSTRACT

The deformational behavior and fluid flow characteristics of rock samples obtained from DOW-DOE L.R. SWEEZY NO. 1 TEST WELL at the Parcperdue Geopressured/Geothermal Site have been investigated in the laboratory. Elastic moduli, compressibility, uniaxial compaction coefficient strength, creep parameters, permeability, electrical resistivity, acoustic velocities (all at reservoir conditions) and changes in these quantities induced by reservoir production have been obtained from tests on several sandstone and shale samples from different depths. Tests consisting of several hydrostatic triaxial and uniaxial loading and unloading cycles, and pore pressure reduction were designed to provide measurements for calculating several of the above mentioned parameters in a single test. Pore volume changes were measured during some phases of the tests. Elastic moduli obtained from sonic velocities are also determined for comparison with static measurements and for one sample, the electrical resistivity was measured for log correlation.

Typically the full reservoir conditions simulated in the tests were: total overburden stress ≅14,000 psi, pore pressure ≅12,000 psi, confining pressure ≅13,000 psi and temperature ≅225°F. Triaxial tests were conducted up to failure to obtain a failure envelope. Preliminary interpretation of results suggests significant nonlinearity in the initial phase of loading, leading to the reservoir conditions and a compressibility value ranging between $2\text{x}10^{-6}$ and $4\text{x}10^{-6}$ psi^{-1} at the reservoir conditions.

The full paper describing experimental details and results is appended to these proceedings. This work has been funded by DOW Chemical, Oil and Gas Division as a subcontract under U.S. DOE Contract No. DE-AC08-79ET-27255.

DISCLAIMER

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The deformational behavior and fluid flow characteristics of rock samples obtained from DOW-DOE L.R. SWEEZY NO. 1 TEST WELL at the Parcperdue Geopressured/Geothermal Site have been investigated in the laboratory. Elastic moduli, compressibility, uniaxial compaction coefficient, strength, creep parameters, permeability, acoustic velocities (all at reservoir conditions) and changes in these quantities induced by simulated reservoir production have been obtained from tests on several sandstone and shale samples from different depths. Tests consisting of several hydrostatic and triaxial loading phases and pore pressure reduction were designed to provide measurements to be used for calculating several of the above mentioned parameters in a single test. Pore volume changes were measured during some phases of the tests.

INTRODUCTION

The Division of Geothermal Energy of the U.S. Department of Energy (DOE/DGE) is evaluating the technological and commercial feasibility of exploiting the geopressured/geothermal resource in the U.S. Gulf Coast area. An extensive program to design, drill and test wells in this area is being conducted to aid the evaluation process. It is recognized that physical and mechanical properties such as porosity, permeability, compressibility, etc., and changes in these properties during production play an important role in evaluating the production potential of a subsurface reservoir. The program therefore includes a systematic investigation of rock properties in the laboratory. This paper describes laboratory tests on core samples obtained from DOW-DOE L.R. SWEEZY NO. 1 TEST WELL at the Parcperdue Site (near Lafayette, Louisiana) in the Gulf Coast Area.

The test conditions and the procedures are designed to produce results that are useful for:

- identifying and anticipating problems associated with changes in porosity, strength, and deformation and fluid flow characteristics that are related to fluid production;
- providing correlation with the reservoir properties assessed from well testing

and geophysical logging such as sonic velocity and electrical resistivity logs;

- providing values or ranges of values for the input parameters such as compaction and permeability coefficients, bulk and shear moduli, etc., to the computer based models for predicting long-term production performance and subsidence profiles.

GENERAL LITHOLOGY AND CORE DESCRIPTION

The SWEEZY NO. 1 WELL is to be drilled to a final depth of 13,600 feet. The target interval is a geopressured water sand layer, named the Cib Jeff Sand, which was deposited as an ancient shoreline deposit (Oligocene Upper Trio Sand) that trends along the northeast Gulf of Mexico coast. It is felt that the Cib Jeff Sand layer at the well site contains a well confined isolated reservoir of an areal extent of approximately 940 acres (Wilson, 1980).

Two cores of 60 feet length and 4 inch diameter each were obtained from the interval between 13,340 feet and 13,460 feet levels. The cores were carefully cleaned, labelled, described and preserved in polyurethane plastic wrap, aluminum foil and bees wax. Extreme care was taken to minimize the amount of damage to the cores caused by handling and exposure to the atmosphere.

Figure 1 shows a vertical profile of the cored interval. A total of 70 feet of the core length recovered is sand approximately half of which represents potential reservoir sand. The sandstone interval exhibits an upward coarsening trend with the greatest permeability (~1 darcy) occurring in the upper interval between 13,343 feet and 13,391 feet. The lower sand interval exhibits many sedimentary structures such as cross bedding, burrowing, sand flow, etc. Permeability is low within this interval due to high clay content produced by burrowing during initial compaction.

TEST EQUIPMENT AND EXPERIMENTAL TECHNIQUE

All tests have been performed using a system designed and built at Terra Tek for high-temperature creep measurements. The system uses gas-backed, thermally stabilized hydraulic accumulators for applying the axial, confining and pore pressures. The gas-backed accumulators are designed to maintain constant confining pressure and axial load over long periods if desired. Figure 2 shows a schematic of the axial load, confining pressure and pore pressure units. The pore pressure unit is also used for flow (permeability) and ejected fluid volume (pore volume changes) measurements. The axial and transverse strain measurements are made using, respectively, linear

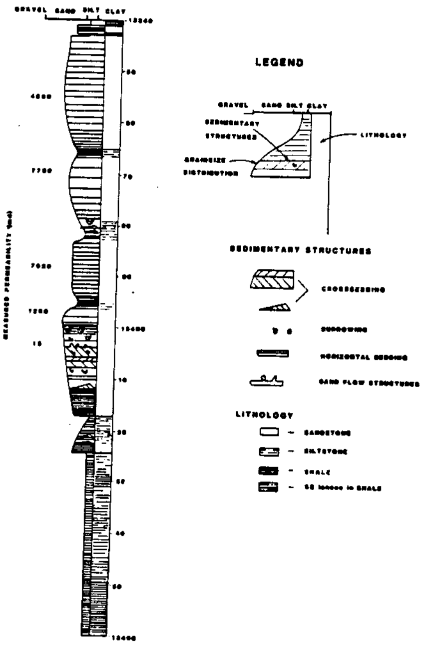
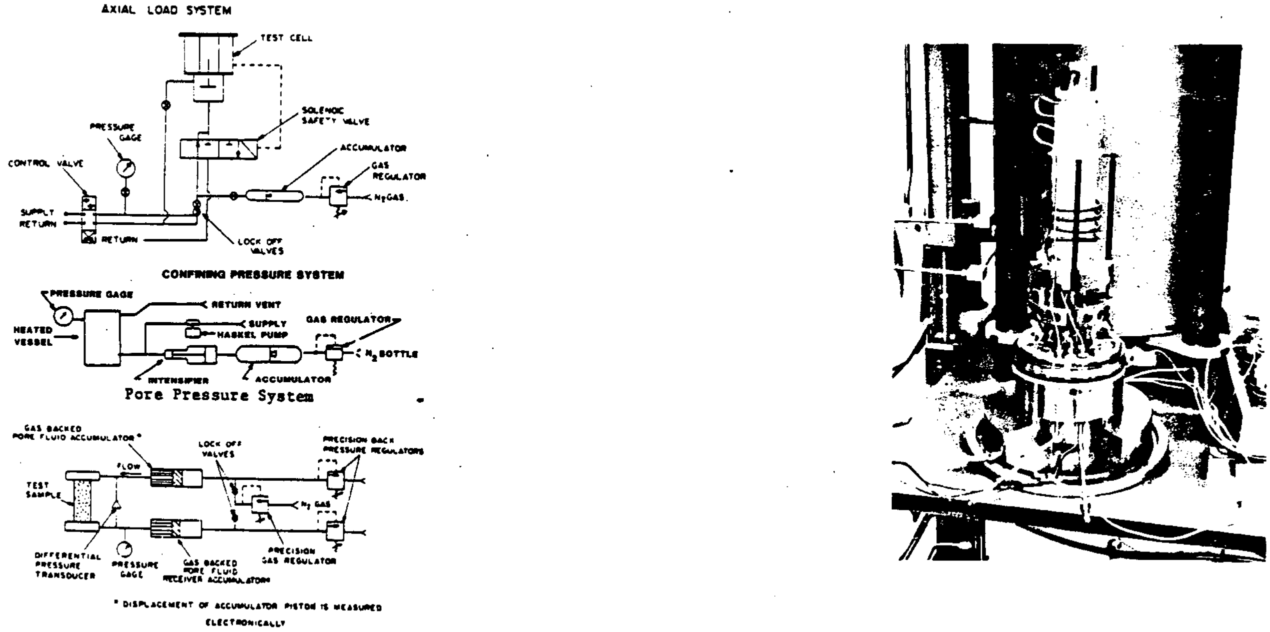


Fig. 1 Vertical profile for cored interval for SWEEZY NO. 1 TEST WELL.



a) Schematics of loading systems

b) Test stack assembly

Fig. 2 Terra Tek high temperature creep testing system details.

variable differential transformers (LVDTs) and strain-gaged cantilever fixtures. The strain gages indicate some drift over prolonged measurement durations, especially at elevated temperature. The LVDTs, on the other hand, are extremely stable and have high sensitivity for prolonged measurements on most rocks. The specimen is heated internally within the cell by convection of the hot cell fluid within a ceramic shroud. Temperatures are measured by thermocouples attached to the test specimen and placed in the cell fluid at several positions.

The system is electronically linked with a PDP-11 computer system with the pressure, temperature, stress and strain transducer outputs being acquired in real time.

The test procedure consists of the following steps:

A test stack, consisting of a 2 inch diameter and 4 inch long cylindrical rock specimen, ceramic spacers and titanium end caps, is jacketed in an elastomer material (silicone rubber), over which a thin teflon tubing is heat shrunk. After approximately 24 hours of curing period allowing the rubber silicone to dry, strain transducer fixtures are attached to the stack and the entire assembly is placed in the pressure cell.

The test specimen is heated and loaded to simulate the estimated reservoir conditions at the depth from which the specimen originated. The approximate reservoir conditions simulated in each case are: temperature 107°C, confining pressure 13,000 psi, total overburden stress 13,500 psi and pore pressure 12,000 psi. The confining pressure and the pore pressure are increased simultaneously (maintaining a constant differential of approximately 50 psi to prevent a jacket failure). After the pore pressure reaches its maximum value the confining pressure is increased to the reservoir level followed by deviatoric stress application. Once reservoir conditions have been attained, the test procedure varies for different test types.

In the compaction tests, the pore pressure is lowered to approximately 60% of its maximum value while constantly adjusting the confining pressure and the deviatoric stress values to obtain a uniaxial compaction (no lateral strain change) and maintain a constant total axial stress (representing the overburden).

In the triaxial tests to failure, conducted over three sand samples from generally the same level, the pore pressure is reduced to approximately 20%, 40% and 60%, respectively, of their maximum values (representing the reservoir condition). The deviatoric stress is then increased until the specimen fails while maintaining the pore pressure and the confining pressure constant.

In the creep tests, the pore pressure is lowered to approximately 7000 psi while maintaining a constant total axial stress and uniaxial compaction. The specimen is allowed to creep for several days under constant stress conditions.

EXPERIMENTAL RESULTS

The deformational behavior of a test specimen under complex triaxial loading sequence perhaps can best be represented by a mean effective pressure (σ_m) versus volumetric strain (ε_v) relationship. Figure 3 shows a plot of this nature for a sandstone and a shale specimen. Initial nonlinearity in the stress-strain relationships is significant and can be attributed to the closure of pre-existing cracks and pore collapse. In addition to nonlinearity, inelasticity is clearly exhibited resulting in hysteresis. In one sandstone sample (DOW #6, depth 13,344 ft.) only about 33% of the strain at the maximum effective stress of 6000 psi was recovered during unloading to 200 psi.

Figure 4 shows the compressibility variation with the mean effective stress for the same sandstone and shale specimens. Compressibility is obtained for all phases of loading by the slope of the tangent to the ($\sigma_m \sim \varepsilon_v$) curve. These curves are typical of all the samples tested.

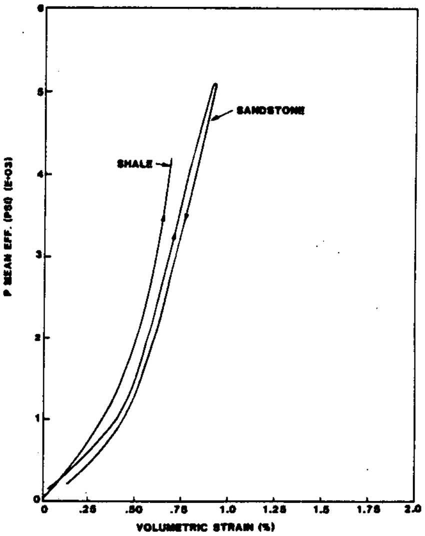


Fig. 3 Mean effective pressure - volumetric strain relationships for sandstone (#68) and shale (#129) specimens.

The Young's and shear moduli are calculated from the deviatoric stress-strain ($\sigma_1 - \sigma_3 \sim \varepsilon_1$) and shear stress-strain ($\sigma_1 - \sigma_3/2 \sim \varepsilon_1 - \varepsilon_3$) curves. The Young's modulus remained very much constant throughout the deviatoric stress loading phase although the shear modulus decreased considerably near the maximum shear stress. The flattening of shear stress-strain curves near the maximum shear stress is typical of many other rock types (Isenberg, 1972).

Figure 5 shows the Mohr's circles and the failure envelopes obtained from the triaxial tests on three sandstone samples. The failure envelope at lower normal stresses is very linear and if extrapolated backwards, gives a low cohesion of approximately 300 psi and a friction angle of 28° (a lower cohesion and a friction angle value slightly higher than 28° may be a more realistic approximation if nonlinearity is assumed at the beginning). A reduction in the friction angle at the higher stresses probably is due to the associated higher strains causing a breakdown of the

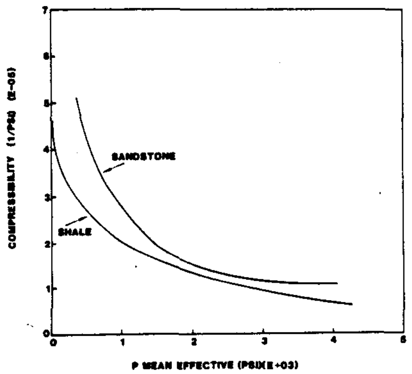


Fig. 4 Compressibility variation with mean effective stress for sandstone (#68) and shale (#129) specimens.

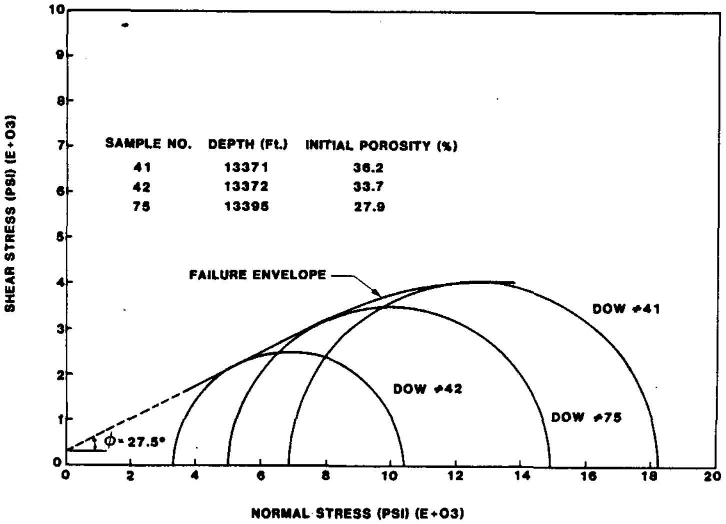


Fig. 5 Mohr's circles and failure envelope for sandstone samples.

original structure of the grains and the pores within the sample.

Compaction coefficient (C_m) is obtained from the pore pressure ~ axial strain ($P_p \sim \varepsilon_1$) relationship during uniaxial compaction phase (change in lateral strain, $\delta\varepsilon_3 = 0$) simply as the slope $\partial\varepsilon_1/\partial P_p$. Compaction coefficients are fairly constant throughout the uniaxial compaction phase for most of the samples tested.

Table 1 gives a summary of all the results and the ranges of values obtained for different parameters. The elastic constants obtained from the sonic velocity measurements on three sandstone samples are much higher than the corresponding values obtained from static measurements. This is expected due to the low stress and short duration pulses used in sonic velocity measurements.

Figure 6 shows the creep curves obtained for a sandstone specimen allowed to creep under constant stress conditions for approximately five days. It appears that a steady-state creep mode had been attained in this case. Although it is difficult to say from these results how long the steady-state creep would have taken place, it is felt that over extended production periods creep compaction would be significant.

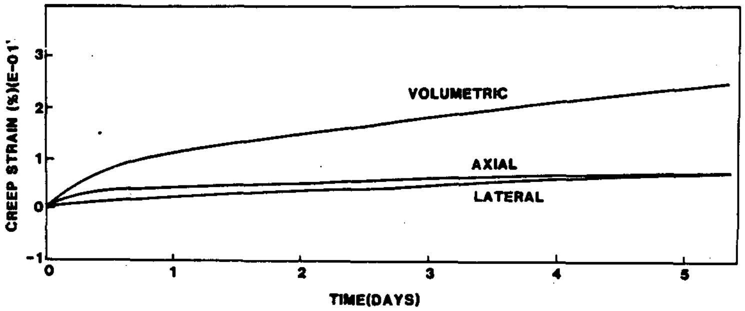


Fig. 6 Creep curves for a sandstone specimen (#67B).

CONCLUSION

These results provide some information on the mechanical properties and the deformational characteristics of the rocks from the Parcperdue Geothermal/Geopressured site. Generally, the compressibility values are slightly higher than those obtained for reservoir rocks from the Pleasant Bayou Wells (Gray, 1980). Elastic moduli and the compaction coefficients in the two cases are of the same order. Higher initial compressibility of Parcperdue samples can be attributed to higher temperatures during tests (Pleasant Bayou samples were tested at room temperature).

Table 1 Summary of Test Results

Test and Rock Type	Sample No.	Depth (feet)	Porosity (%)	Young's Modulus (psi) x10^6	Shear Modulus (psi) x10^6†	Compressibility $\left(\frac{1}{psi}\right)$ x10^{-6}††	Compaction Coefficient $\left(\frac{1}{psi}\right)$ x10^{-6}
Compaction							
Sandstone	6	13,344	28.6	1.26 3.24*	0.58 1.31*	3.30~1.38	0.35
	33	13,364	25.8	0.84 1.27*	0.36 0.49*	10.30~1.95	0.35
	35	13,366	28.0	1.69	0.61	6.66~2.26	0.46
	67A	13,389	30.1	0.60	0.25	5.12~3.54	0.72
	68	13,390	26.7	1.55 2.16*	0.35~1.0 0.85*	5.08~3.19	0.65
Shale	129	13,369	20.2	0.54	--	3.15	--
Triaxial (to failure)							
Sandstone	41	13,371	36.2	1.18	0.75~0.45	3.52~2.58	--
	42	13,372	33.7	0.97	0.45~0.44	4.87~2.95	--
	75	13,395	27.9	0.96	0.51~0.37	5.59~3.85	--
Creep							
Sandstone	71A	13,393	29.6	1.58	1.06~0.52	4.06~2.83	0.70
	67B	13,389	30.1	0.68	0.30	4.42~3.69	0.66

*These values were obtained from sonic velocity measurements

†The range of values correspond to initial and final stages of triaxial loading phase.

††The range of values correspond to stress range between zero effective stress and reservoir conditions.

Time and stress-dependent inelasticity exist and may be significant. These factors should be considered in evaluation and modification of field test procedures to obtain reservoir properties as well as mathematical modeling for long-term reservoir performance and subsidence prediction.

ACKNOWLEDGEMENTS

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