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THE EFFECT OF PORE PRESSURE ON THE ELASTIC MODULI,
POROSITY AND PERMEABILITY OF BEREA SANDSTONE
AND LEUDERS LIMESTONE

by

T.W. Thompson
S.M. Kelkar
K.E. Gray

MASTER

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TABLE OF CONTENTS

	<u>Page</u>
Acknowledgements	
List of Tables	
List of Figures	
Introduction	1
1.0 Introduction to the problem.	1
1.1 Scope of the Investigation	4
Chapter 1: Theoretical and Experimental Background.	6
1.0 Theoretical Background	6
1.1 Effective Stress	7
1.2 Nonlinear Constitutive Relations	8
1.3 Uniaxial Compaction	11
1.4 Static Elastic Moduli.	14
1.5 Dynamic Elastic Moduli	15
1.6 Porosity	16
1.7 Permeability	18
2.0 Previous Experimental Work	20
Chapter 2: Equipment and procedures	22
1.0 Description of the Equipment	22
2.0 Experimental Procedure	26
2.1 Sample Preparation	26
2.2 Testing Procedure.	28
Chapter 3: Error Analysis and Data Processing	34
1.0 Data Acquisition and Analysis.	35
2.0 Sources of Errors.	37
2.1 Stresses	37
2.2 Strains.	38
2.3 Accoustic Travel Times	39

2.4 Displaced Pore Water Volume.	40
2.5 Flow Measurements.	41
3.0 Error Propagation.	41
Chapter 4: Results	45
1.0 General discussion	46
2.0 Discussion of the Computed Rock Properties	48
2.1 Young's Modulus.	48
2.2 Poisson's Ratio.	49
2.3 Bulk Modulus	49
2.4 Uniaxial Compaction.	50
2.5 Porosity	51
2.6 Permeability	51
3.0 Inferences	52
Chapter 5: Conclusions	54
Appendix: Tables and Figures.	56
1. Tables.	57
2. Figures	107
References:	150

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	A Summary of Tests.	58
2	Sample Data, Berea Sandstone, Jacketed Hydrostatic Test, PO=ATM.	59
3	Sample Data, Berea Sandstone, Jacketed Hydrostatic Test, PO=ATM.	60
4	Sample Data, Berea Sandstone, Uniaxial Compaction Test, PO=ATM.	61
5	Sample Data, Berea Sandstone, Uniaxial Compaction Text, PO=ATM.	62
6	Sample Data, Berea Sandstone, Uniaxial Compaction Test, PO=2KPSI.	63
7	Sample Data, Berea Sandstone, Uniaxial Compaction Test, PO=2KPSI.	64
8	Sample Data, Berea Sandstone, Jacketed Hydrostatic Test, PO=2KPSI.	65
9	Sample Data, Berea Sandstone, Jacketed Hydrostatic Test, PO=2KPSI.	66
10	Sample Data, Leuders Limestone, Jacketed Hydrostatic Test, PO=ATM.	67
11	Sample Data, Leuders Limestone, Jacketed Hydrostatic Test, PO=ATM.	68
12	Sample Data, Leuders Limestone, Uniaxial Compaction Test, PO=ATM.	69
13	Sample Data, Leuders Limestone, Uniaxial Compaction Test, PO=ATM.	70

14	Sample Data, Leuders Limestone, Jacketed Hydrostatic Test, PO=2KPSI.	71
15	Sample Data, Leuders Limestone, Jacketed Hydrostatic Test, PO=2KPSI.	72
16	Sample Data, Leuders Limestone, Uniaxial Compaction Test, PO=2KPSI.	73
17	Sample Data, Leuders Limestone, Uniaxial Compaction Test, PO=2KPSI.	74
18	Young's Modulus, Berea Sandstone, PO=ATM	75
19	Young's Modulus, Berea Sandstone, PO=2KPSI. . . .	76
20	Young's Modulus, Leuders Limestone, PO=ATM. . . .	77
21	Young's Modulus, Leuders Limestone, PO=2KPSI. . .	78
22	Poisson's Ratio, Berea Sandstone, PO=ATM.	79
23	Poisson's Ratio, Berea Sandstone, PO=2KPSI. . . .	80
24	Poisson's Ratio, Leuders Limestone, PO=ATM. . . .	81
25	Poisson's Ratio, Leuders Limestone, PO=2KPSI. . .	82
26	Bulk Modulus, Berea Sandstone, PO=ATM	83
27	Bulk Modulus, Berea Sandstone, PO=2KPSI	84
28	Bulk Modulus, Leuders Limestone, PO=ATM	85
29	Bulk Modulus, Leuders Limestone, PO=2KPSI	86
30	Uniaxial Compaction Coefficient, Berea Sandstone, PO=ATM	87
31	Uniaxial Compaction Coefficient, Berea Sandstone, PO=2KPSI	88
32	Uniaxial Compaction Coefficient, Leuders Limestone, PO=ATM	89
33	Uniaxial Compaction Coefficient, Leuders Limestone, PO=2KPSI	90

34	Porosity, Berea Sandstone, Hydrostatic Tests, PO=ATM	91
35	Porosity, Berea Sandstone, Hydrostatic Tests, PO=2KPSI	92
36	Porosity, Berea Sandstone, Uniaxial Compaction Tests, PO=ATM	93
37	Porosity, Berea Sandstone, Uniaxial Compaction Tests, PO=2KPSI	94
38	Porosity, Leuders Limestone, Hydrostatic Tests, PO=ATM	95
39	Porosity, Leuders Limestone, Hydrostatic Tests, PO=2KPSI	96
40	Porosity, Leuders Limestone, Uniaxial Compaction Tests, PO=ATM	97
41	Porosity, Leuders Limestone, Uniaxial Compaction Tests, PO=2KPSI	98
42	Permeability, Berea Sandstone, Hydrostatic Tests, PO=ATM	99
43	Permeability, Berea Sandstone, Hydrostatic Tests, PO=2KPSI	100
44	Permeability, Berea Sandstone, Uniaxial Compaction Tests, PO=ATM	101
45	Permeability, Berea Sandstone, Uniaxial Compaction Tests, PO=2KPSI	102
46	Permeability, Leuders Limestone, Hydrostatic Tests, PO=ATM	103
47	Permeability, Leuders Limestone, Hydrostatic Tests, PO=2KPSI	104
48	Permeability, Leuders Limestone, Uniaxial Compaction Tests, PO=ATM	105
49	Permeability, Leuders Limestone, Uniaxial Compaction Tests, PO=2KPSI	106

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1.	Block diagram of the system	108
2.	A view of the SPS and the pressure vessel . .	109
3.	Schematic drawing of the SPS	110
4.	Drawing of the jacket	111
5.	Cycled uniaxial test on Berea sandstone - stress relief and hysteresis	112
6.	Cycled uniaxial compaction test on Leuders limestone - stress relief and hysteresis. . .	113
7.	Sample to sample variation for Berea sandstone and Leuders limestone in hydro- static tests - volumetric strain vs. confining stress	114
8.	Sample to sample variation for Berea sandstone and Leuders limestone in uniaxial compaction tests - P_c vs. P_z	115
9.	E_v vs. P_c^e , $P_o=atm$, Berea sandstone, jacketed hydrostatic test, sample no. 03	116
10.	E_v vs P_c^e , $P_o=atm$, Berea sandstone, jacketed hydrostatic test, sample no. 21	117
11.	E_v vs P_z^e , $p_o=atm$, Berea sandstone, uniaxial compaction test, sample no. 18 . . .	118
12.	E_v vs P_z^e , $p_o=atm$, Berea sandstone, uniaxial compaction test, sample no. 15 . . .	119
13.	E_v vs P_c , Berea sandstone, matrix compressibility test, sample no. 23.	120
14.	E_v vs P_c , Berea sandstone, matrix compressibility test, sample no. 44	121

15.	Ev vs P_c^e , $P_o=2Kpsi$, Berea sandstone, jacketed hydrostatic test, sample no. 44. . .	122
16.	Ev vs P_c^e , $P_o=2Kpsi$, Berea sandstone, jacketed hydrostatic test, sample no. 47. . .	123
17.	Ev vs P_z^e , $p_o=2Kpsi$, Berea sandstone, uniaxial compaction test, sample no. 52 . . .	124
18.	Ev vs P_z^e , $p_o=2Kpsi$, Berea sandstone, uniaxial compaction test, sample no. 42 . . .	125
19.	Ev vs P_c^e , $P_o=atm$, Leuders limestone, jacketed hydrostatic test, sample no. 30. . .	126
20.	Ev vs P_c^e , $P_o=atm$, Leuders limestone, jacketed hydrostatic test, sample no. 10. . .	127
21.	Ev vs P_z^e , $P_o=atm$, Leuders limestone, uniaxial compaction test, sample no. 18 . . .	128
22.	Ev vs P_z^e , $P_o=atm$, Leuders limestone, uniaxial compaction test, sample no. 19 . . .	129
23.	Ev vs P_c , matrix compressibility test, Leuders limestone, sample no. 22.	130
24.	Ev vs P_c , matrix compressibility test, Leuders limestone, sample no. 23.	131
25.	Ev vs P_c^e , $P_o=2Kpsi$, Leuders limestone, jacketed hydrostatic test, sample no. 50. . .	132
26.	Ev vs P_c^e , $P_o=2Kpsi$, Leuders limestone, jacketed hydrostatic test, sample no. 52. . .	133
27.	Ev vs P_z^e , $P_o=2Kpsi$, Leuders limestone, uniaxial compaction test, sample no. 53 . . .	134
28.	Ev vs P_z^e , $P_o=2Kpsi$, Leuders limestone, uniaxial compaction test, sample no. 58 . . .	135
29.	E vs P_z^e , Berea sandstone	136
30.	E vs P_z^e , Leuders limestone	137

31.	C_m vs P_z^e , Berea sandstone.	138
32.	C_m vs P_z^e , Leuders limestone.	139
33.	K_b vs P_c^e , Berea sandstone	140
34.	K_b vs P_c^e , Leuders limestone	141
35.	$\emptyset$ vs P_{mean}^e , Berea sandstone, hydrostatic test	142
36.	$\emptyset$ vs P_{mean}^e , Berea sandstone, uniaxial compaction test	143
37.	$\emptyset$ vs P_{mean}^e , Leuders limestone, hydrostatic test	144
38.	$\emptyset$ vs P_{mean}^e , Leuders limestone, uniaxial compaction test	145
39	K vs P_c^e , Berea sandstone, hydrostatic test	146
40	K vs P_z^e , Berea sandstone, uniaxial compaction test	147
41.	K vs P_c^e , Leuders limestone, hydrostatic test	148
42.	K vs. P_z^e , Leuders limestone, uniaxial compaction test	149

INTRODUCTION

1.0 INTRODUCTION TO THE PROBLEM

In recent years there has developed a considerable interest in geopressured geothermal reservoirs as an alternative source of energy. The hot brine from these reservoirs and the associated methane could not only provide a clean form of energy but may also prove to be economically feasible in view of the energy crisis. It has been estimated that these resources could provide a substantial fraction of the U.S. energy requirements [1]. However, before this potential can be realized, many questions need to be answered. Reservoir compaction and the associated subsidence due to fluid withdrawal in large volumes are some of the outcomes which could lead to significant economic and environmental impact. A project is currently in progress at the University of Texas at Austin to obtain realistic estimates of reservoir behavior, a part of which constitutes the subject matter of this study. The results reported in this study are at present being used as a basis for designing test programs for the cores from the geothermal test wells situated in Texas.

The bulk of underground fluid reservoirs is usually composed of some type of sedimentary rocks. These rocks generally possess intergranular pore space which is occupied by one or more fluid types such as oil, gas and water. The reservoir can be envisaged as being made up of two components- the rock matrix and the interstitial fluids. The state of the reservoir is determined by the stress-strain equilibrium between the rock matrix, the pore fluids and the boundaries. The stresses in the reservoir fall into two categories, namely, the external stress created by the overburden and surrounding geological formations, and the internal stress created by the hydrostatic pressure in the pore fluids. Changes in any of these stresses create corresponding changes in the reservoir properties of interest such as porosity, permeability, elastic moduli and acoustic velocities.

Pore fluid production and the associated pressure drawdown can lead to reservoir compaction and a decrease in the bulk volume. The compaction of rocks can play an important role in the development of fluid reservoirs as a mechanism for pore pressure maintenance. This is the well known compaction drive mechanism [1]. The reservoir compaction can also lead to some hazardous effects such as surface subsidence [1]. These effects are expected to be of particular importance when the production

volumes are large and the constituent rocks comparatively soft. Early results indicate that this may be the case in the geothermal geopressured reservoirs of the Gulf coast of Texas and Louisiana.

In the light of these facts it becomes important to understand the behavior of reservoir rocks under changing external and internal pressures. This study reports the behavior of Berea sandstone and Leuders limestone under atmospheric and elevated pore pressures. The porosity and the permeability changes, along with the static and dynamic moduli for these rocks have been determined under various conditions. The existing theoretical background pertinent to the study is reviewed in chapter 1 along with the previous experimental work. The detailed descriptions and the discussions on the experimental procedure involved and the equipment utilized are presented in chapter 2. Chapter 3 includes a discussion on the sources of experimental errors. It also includes the error propagation equations and relevant discussions on the data acquisition and analysis. The findings are summarized in chapter 4 together with a discussion of the results. The fifth chapter contains the conclusions drawn from these results. The bulk of the data acquired and the results computed from it are presented in the appendix.

1.1 Scope of the Investigation

The object of this study is to experimentally investigate the properties of some well known rocks within the elastic range under elevated external and internal stresses. Berea sandstone and Leuders limestone were chosen for this purpose because they are relatively homogeneous, isotropic, continuous, elastic and well behaved rocks. Also their porosities and permeabilities lie in a range which is of interest to the geothermal geopressured reservoir analysis. This investigation consisted of determining the elastic moduli, acoustic velocities, porosity and permeability for each of these rocks under various stress conditions. Tests were conducted on jacketed, water saturated samples at atmospheric and elevated pore pressures. Unjacketed tests with oil saturated samples were also conducted to measure matrix compressibility. The jacketed tests fall into two categories which are discussed below. During each test the pore pressure was held constant at the atmospheric pressure for the low pore pressure tests and at 2000 psi for the elevated pore pressure tests.

1. Hydrostatic tests: the samples were subjected to hydrostatic external loading while the pore pressure was held constant at the level of interest. The range of the effective hydrostatic load was from 0 to 8000 psi.

2. Uniaxial compaction tests: the radial strain was controlled at a constant value using the confining pressure while the samples were subjected to axial loading, the pore pressure being maintained at the level of interest. The range of effective axial stress was from 0 to 8000 psi.
3. Matrix compressibility tests: these tests were conducted onunjacketed, oil saturated samples under hydrostatic loading. The range of the hydrostatic load was from 0 to 8000 psi.

These tests are summarized in table 1.

Chapter 1

THEORETICAL AND EXPERIMENTAL BACKGROUND

This chapter is divided into two sections. Section 1 deals with the theoretical background and the second section covers previous experimental work.

1.0 THEORETICAL BACKGROUND

Fluid withdrawal from underground reservoirs leads to an increase in the effective overburden stress with subsequent decrease in the reservoir volumes. This compaction tends to compensate for the decrease in the pore pressure. This is the so called compaction drive mechanism, which can play a significant role in the reservoir development. The compaction may also lead to some unwanted effects such as surface subsidence. For these reasons it is important to understand the reservoir rock behavior under external as well as internal stresses.

1.1 Effective Stress

In theoretically modeling the pore and bulk volume changes the interplay between the external and internal stress is important. A particularly attractive approach to this problem is the concept of effective stress. Terzaghi [2] stated this concept for soils as

$$\sigma^e = \sigma + P \quad (1)$$

where σ^e is the effective vertical stress, σ is the total vertical overburden and P is the pore pressure.

Biot [3] generalized this concept to 3-dimensional loading as

$$\sigma_i^e = \sigma_i + P \quad (2)$$

where σ_i^e is the i -th principal component of effective stress, σ_i is the i -th principal component of external stress and P is pore pressure.

Although quantitatively inexact for porous rocks, this law is conceptually valuable because of its simplicity. In the rest of this study, unless otherwise specified, the term effective stress is used in this sense.

Many investigators have modified this law for linear elastic, continuous and homogeneous rocks. A general definition of effective stress may be given as follows:

Let F be the rock property of interest. In general it is a function of the external as well as the internal stress

$$F = F(\sigma_{ij}, P) \quad (3)$$

where σ_{ij} is the external stress tensor and P is the pore pressure. If a function σ_{ij}^e can be found such that

$$\sigma_{ij}^e = \sigma_{ij}^e(\sigma_{ij}, P) \quad (4)$$

and

$$F(\sigma_{ij}, P) = G(\sigma_{ij}^e) \quad (5)$$

then σ_{ij}^e is defined as the effective stress corresponding to the stresses σ_{ij} and P .

For this definition to be useful, the function G must meet two criteria, namely, that it be independent of the property F under consideration and its functional form be simple. Robin [4] has pointed out that in general neither of these requirements is met for real rocks.

For homogeneous, linear elastic materials the law has been stated as

$$\sigma_{ij}^e = \sigma_{ij} + \alpha P \delta_{ij} \quad (6)$$

where α is a constant for the given material.

Skempton [4] and Geertsma [5] have suggested the form

$$\alpha = 1 - K_b/K_m \quad (7)$$

where K_m is the matrix modulus and K_b is the bulk modulus. In the limit of a rigid rock matrix, $K_m \gg K_b$ and the law reduces to the form suggested by Terzaghi.

In 1935 and 1941 Biot [3], [7] presented his widely used theory of three dimensional consolidation for a homogeneous linear elastic material. He stated the constitutive equations as

$$\epsilon_{ij} = \frac{1}{2\mu} \sigma_{ij} - \frac{\nu}{E} \sigma_{kk} \delta_{ij} + \frac{P}{3H} \delta_{ij} \quad (8)$$

$$\theta = \frac{1}{3H_1} \sigma_{kk} + \frac{P}{R} \quad (9)$$

where ϵ_{ij} , σ_{ij} are the strain and stress tensors,

P is the pore pressure and θ is the pore volume change.

E , ν , μ are Young's modulus, Poisson's ratio and Lamé's constant respectively.

H , H_1 , R are the three new constants introduced by Biot. These equations can be shown to give

$$\sigma_{ij}^e = \sigma_{ij} + \alpha P \delta_{ij} \quad (10)$$

which has the form suggested by Skempton.

Lubinski [8] studied this problem using the analogy between thermal gradients and pore pressures. For homogeneous, linear elastic rocks with stiff pores he derived

$$\epsilon_{ij} = \frac{1}{2\mu} \sigma_{ij} - \frac{\nu}{E} \sigma_{kk} \delta_{ij} + \frac{1-2\nu}{E} (1-\beta-\phi) P \delta_{ij} \quad (11)$$

where β is the ratio of the bulk modulus to the matrix modulus and ϕ is the porosity. It should be noted that this equation can also be transformed to the form suggested by Skempton.

Geertsma [6] generalized these theories to include viscoelastic pore deformations. He gave expressions relating Biot's constants to matrix and bulk moduli.

Except for Geertsma's theory, all these developments assume the rocks to be linear elastic. While such an assumption simplifies the treatment, it may not always be valid. One of the objectives of these investigations is to quantify the variation of various elastic moduli with respect to stresses.

1.2 Nonlinear Constitutive Relations

Stress dependent elastic moduli can be treated using nonlinear constitutive relations. For the purpose of this study, this can be accomplished by assuming that the standard linear relations are applicable to the nonlinear case in their differential forms. This is equivalent to assuming that a small change in stress will produce only a small change in strain and that this change will be locally linear. At constant pore pressure, the constitutive relations for a homogeneous, isotropic rock may now be written as

$$d\varepsilon_i = \frac{1}{E} (d\sigma_i^e - \nu d\sigma_j^e - \nu d\sigma_k^e) \quad (12)$$

where i, j, k are x, y, z cyclically and x, y, z indicate the three principal components of stress and strain.

The symbol d before a variable denotes a differential change and the symbol Δ before a variable denotes a change in the variable. This notation is used throughout the rest of this report.

Consider a cylindrical rock with cylindrically symmetric boundary conditions and the major principal axis along the axis of the cylinder. Let the axis of the cylinder be the z axis.

The constitutive relations now become

$$d\varepsilon_z = \frac{1}{E} (d\sigma_z^e - 2\nu d\sigma_r^e) \quad (13)$$

$$d\varepsilon_r = \frac{1}{E} ((1-\nu)d\sigma_r^e - d\sigma_z^e) \quad (14)$$

where ε_r, σ_r are the radial components of the strain and the effective stress respectively. The differential volumetric strain may be expressed as

$$d\varepsilon_v = \frac{1-\nu}{E} (d\sigma_z^e + 2d\sigma_r^e) \quad (15)$$

1.3 Uniaxial Compaction

Most reservoir models incorporate the assumption of uniaxial deformation in studying compaction, introduced by Geertsma [6], [9]. It is assumed that during the development of a fluid reservoir no lateral deformation takes place. The vertical deformation is described in terms of the Uniaxial Compaction Coefficient, given by

$$\varepsilon_z = C_m \sigma_z^e \quad (16)$$

where ε_z is the vertical strain, σ_z^e is the vertical effective stress and C_m is the uniaxial compaction coefficient. C_m may be related to other elastic moduli

for a linear material with a vertical principal axis.

$$\varepsilon_z = \frac{1}{E} (\sigma_z^e - 2\nu\sigma_r^e) \quad (17)$$

$$\varepsilon_r = \frac{1}{E} ((1-\nu)\sigma_r^e - \nu\sigma_z^e) \quad (18)$$

where ε_z , σ_z and ε_r , σ_r are the vertical and radial components of the strain and the effective stress respectively.

with $\varepsilon_r = 0$,

this leads to

$$\varepsilon_z = \frac{(1-2\nu)(1+\nu)}{E(1-\nu)} \sigma_z^e \quad (19)$$

from which follows

$$C_m = \frac{(1-2\nu)(1+\nu)}{1-\nu} \cdot \frac{1}{E} \quad (20)$$

The concept of uniaxial compaction simplifies the treatment of the problem considerably. Being a concept of economical and environmental significance, it needs to be verified under in situ as well as under laboratory conditions.

1.4 Static Elastic Moduli

Two types of situations will be considered

1. Hydrostatic loading

2. Uniaxial compaction

1. Hydrostatic loading

$$\sigma_z^e = \sigma_r^e = p_c^e \quad (21)$$

$$\therefore d\varepsilon_v = \frac{3(1-\nu)}{E} dp_c^e \quad (22)$$

The bulk modulus is defined by the relation

$$d\varepsilon_v = K_b dp_c^e \quad (23)$$

$$\therefore K_b = 1 / (d\varepsilon_v / dp_c^e) \quad (24)$$

2. Uniaxial compaction

$$\begin{aligned} d\varepsilon_r &= 0 \\ \therefore \nu &= \frac{(d\sigma_r^e / d\sigma_z^e)}{1 + (d\sigma_r^e / d\sigma_z^e)} \quad \text{and} \end{aligned} \quad (25)$$

$$E = \left(1 - \frac{2\nu^2}{1-\nu}\right) / (d\varepsilon_z / d\sigma_z^e) \quad (26)$$

The uniaxial compaction coefficient is given by

$$d\varepsilon_z = C_m d\sigma_z^e \quad (27)$$

$$\therefore C_m = 1 / (d\varepsilon_z / d\sigma_z^e) \quad (28)$$

In order to compute the elastic moduli, the experimental data were fitted to nonlinear functions of stress. The elastic moduli were computed from the derivatives of the fitted functions. No theoretical significance is attached to the functional forms of the strains at this time.

1.5 Dynamic Elastic Moduli

The following equations were used to determine the dynamic elastic moduli from acoustic data

$$E = \frac{V_s^2 \rho}{9} \frac{[3(V_p/V_s)^2 - 4]}{[(V_p/V_s)^2 - 1]} \quad (29)$$

$$\nu = \frac{1}{2} \frac{[(V_p/V_s)^2 - 2]}{[(V_p/V_s)^2 - 1]} \quad (30)$$

$$C_m = \frac{(1+\nu)(1-2\nu)}{E(1-\nu)} \quad (31)$$

where V_p is the P-wave velocity, V_s is the S-wave velocity,

ρ is the bulk density and g is the gravitational constant.

1.6 Porosity

Porosity is defined by

$$\phi_o = V_{pp} / V_b \quad (32)$$

where ϕ_o is the initial porosity, V_{pp} is the initial pore volume and V_b is the initial bulk volume.

Three different methods were used for computing the porosity

1. Volume strain method:

$$\Delta V = \epsilon_v \cdot V \quad (33)$$

where ΔV is the change in volume, ϵ_v is the volumetric strain and V is the initial volume. After the sample undergoes a volumetric strain ϵ_v , its porosity becomes

$$\phi = \frac{V_{pp} - \Delta V_{pp}}{V_b - \Delta V_b} \quad (34)$$

$$\therefore \phi = \frac{\phi_o - \Delta V_{pp} / V_b}{1 - \epsilon_v} \quad (35)$$

it is assumed, for the purpose of this calculation, that

$$\Delta V_{pp} \cong \Delta V_b$$

$$\therefore \phi = \frac{\phi_o - \epsilon_v}{1 - \epsilon_v} \quad (36)$$

2. Displaced pore fluid method

When a saturated sample undergoes deformation, it displaces an amount of pore fluid equal to the change in its pore volume and

$$\phi = \frac{V_{pp} - \Delta V_{pp}}{V_b - \Delta V_b} \quad (37)$$

again, at constant pore pressure, it is assumed

$$\Delta V_{pp} \cong \Delta V_b$$

$$\therefore \phi = \frac{V_{pp} - \Delta V_{pp}}{V_b - \Delta V_{pp}} \quad (38)$$

The displaced pore fluid volume is measured directly and the system is calibrated for the fluid compressibility.

3. Porosity from acoustic measurements

The time average formula [10] was used for this purpose

$$\phi = \frac{V_L (V_M - V_P)}{V_P (V_M - V_L)} \quad (39)$$

where V_L is the P-wave velocity through the pore fluid, V_M is

the p-wave velocity through the rock matrix and V_p is the P-wave velocity through the saturated rock bulk.

1.7 Permeability

Darcy's law states, for nonturbulent flow,

$$q = - \frac{\kappa}{\mu} \nabla \Phi \quad (40)$$

where, q is the flow rate,

Φ is the flow potential,

$\nabla \Phi$ is the flow potential gradient,

μ is the fluid viscosity,

κ is the permeability. Morita [12] has used this law to describe flow across a cylindrical sample where the inlets and outlets are in the form of cylindrical shoes, as described in chapter 2.

$$\kappa = \frac{q\mu}{L(\Delta P)} \cdot \frac{K_e}{K'_e} \quad (41)$$

where L is the sample length, ΔP is the pressure drop across the core and K_e / K'_e is a geometrical correction factor to account for the shoes.

Tellinghuisen [12] suggested another modification of this formula to account for the length difference between the sample and the shoes

$$k = \frac{q\mu}{L\Delta P} \cdot \frac{1}{R} \cdot \frac{K_e}{K'_e} \quad (42)$$

He showed that for the particular geometry used

$$R = 0.94 \quad \text{and} \quad K_e/K'_e = 1.$$

This was the equation used for permeability calculations in this study.

2.0 PREVIOUS EXPERIMENTAL WORK

There is a wealth of experimental data available on the strength of various rocks at elevated pore pressures. Some work has been done to evaluate the various laws of effective stress. However, little work was found in the literature that studied Berea sandstone and Leuders limestone in the elastic range with reference to the properties of interest in reservoir engineering. In 1960 Mann and Fatt [13] published their work in which they compared the elastic properties of dry and wet sandstones. They concluded that the bulk modulus and Young's modulus were less for the wet sandstone as compared to the dry stone. They also found a marked nonlinearity in Berea sandstone.

Handin and coworkers [14] published an extensive work on the strength of various rocks under elevated pore pressures. They concluded that the effective stress is a valid law as applied to the strength of sandlike permeable rocks such as Berea sandstone and Marianna limestone. They also observed an increase in the porosity when pore pressure became comparable to the confining pressure.

In 1964 Aldrich [15] reported results from drained and undrained tests on Berea sandstone. He concluded that the strength of this sandstone depends only on the effective stress.

Garg and Nur [16] studied various effective stress laws from both theoretical and experimental point of view. They compared fracture as well as elastic data on Weber sandstone. They concluded that the various laws of effective stress do not correctly estimate the pore pressure effects. They emphasized the role of linearity in various theoretical developments.

In 1975 Zoback and Byrlee [17] made an experimental study of the permeability of Berea sandstone at elevated pore pressures. They found that permeability is not a simple function of effective stress and proposed a composite model for the pore structure of Berea sandstone.

Chapter 2

Equipment and Procedure

The experimental system and the test procedures utilized in the present investigation are described in this chapter. Section 1 outlines the experimental apparatus. Section 2 contains the details of the test procedures with the first subsection being devoted to core preparation, jacket preparation and core mounting and the following section being devoted to the discussion of various tests procedures.

1.0 DESCRIPTION OF THE EQUIPMENT

The experimental apparatus is designed to measure simultaneously the elastic properties, acoustic properties, porosity and permeability of a cylindrical rock specimen under elevated axial, confining and pore pressures. Details of the Simultaneous Property System may be found in Evan's dissertation [18], and of the dual mode ultrasonic technique for wave velocity measurements in a paper by Gregory and Podio [19]. Only a brief description of the equipment will be given here.

The schematics of the system are sketched in Fig. 1. It consists of three major components, the Simultaneous Property System (SPS), the Material Testing and Pressurization Control System (MTS) and the Data Acquisition System (DAS).

Simultaneous Property System (SPS)

The SPS is shown in Fig. 2 and the Fig. 3 presents a schematic drawing of the the subsystem. The essential components of this subsystem are the pressure vessel, the confining pressure system, the axial load system, the pore pressure system, the acoustic system, the control valves and the electronic monitoring and amplifying devices.

1. Pressure Vessel :

This vessel is constructed out of steel and is capable of withholding 50,000 psi axial load, 25,000 psi confining pressure and 25,000 psi pore pressure. The vessel head houses the acoustic receiver crystals and also contains passthroughs for various purposes.

2. Confining Pressure System .

The confining pressure is applied by pumping drake oil into the pressure vessel by means of a Sprague air pump. An 11 cc capacity screw pump is used for fine control. The pressure is monitored using a BLH 20,000 psi transducer.

3. Axial Load System :

The axial load is applied through a piston at the bottom of the pressure vessel. A Sprague air pump is used for loading and a 30 cc capacity screw pump gives fine control. The stress is monitored by a transducer housed in the piston.

4. Pore Pressure System :

A Sprague air pump is used for loading and an 11 cc capacity screw pump is used for fine control. The pore lines are coupled to the jacketed sample by passthroughs. There are three transducers in the pore line- a 20,000 psi BLH transducer upstream of the sample, a 20,000 psi BLH transducer downstream of the sample and a 10,000 psi line pressure Validyne differential transducer across the sample which was introduced into the system at a later date. The downstream pore line has a filter and a microvalve to control the flow rate. The downstream pore line leads into a system of three burettes of capacities 1 cc, 10 cc and 50 cc respectively.

The pore pressure system is coupled to the MTS intensifier through a piston type oil-water separator with the capacity of 400 cc

5. The Acoustic System :

Acoustic P and S waves are generated by Barium Titanate crystals driven by a tone burst amplifier-oscillator combination. The waves are transmitted to the sample through Aluminium wedges. The receiver assembly is also a pair of Barium Titanate crystals. The output of the receiver crystals is amplified and fed to a gate-control oscilloscope and a digital timer that monitors both the P and S waves.

Material Testing and Pressurizing Control System :

This system is capable of delivering 206 cc of fluid at a constant pressure psi. The maximum output pressure is 25,000.

1. Data Acquisition System :

A Data General Supernova computer with a real time disk operating system is used for automatic data acquisition. The output from the monitoring device amplifiers is fed to the computer through an analog to digital (A/D) converter. The system can transfer and input/output a maximum of 10 numbers per second. The same system is used for displaying a corrected radial strain output on a center-zero voltmeter during uniaxial compaction tests.

2.0 EXPERIMENTAL PROCEDURE

This section is divided into two subsections. Part 1 describes the core and jacket preparation as well as mounting. The second part contains a detailed description of the test procedures according to the loading pattern.

2.1 Sample Preparation

Cores from Berea sandstone were cut perpendicular to the bedding plane. No noticeable bedding plane was observed in Leuders limestone, hence any special attention to the core orientation was not considered necessary.

Cores were cut with diameter 2 inches and length close to 2.75 inches. The ends were machined parallel to within 0.001 of an inch. This L/D ratio was chosen as a compromise between the higher values which would be preferred to minimize the end effects and smaller values needed to obtain good shear wave propagation. Previous work has shown this L/D ratio to be a minimum if end effects are to be negligible in the center [18], [20].

Two strain gauges were mounted on the center of the cylindrical surface diagonally opposite to each other. Each

strain gauge had a radial and vertical component. After soldering the conducting wires on the gauge terminals, a thin coat of epoxy was applied over the gauges to prevent short circuiting.

According to the test requirements each sample was saturated with either deionized water or oil under vacuum before testing.

Jacket Preparation :

The jacket, shown in Fig. 4, had two components, a polyurethane sleeve and metal passthroughs for pore fluid. The metal passthroughs were made of steel cut into cylindrical surface sections. Each was 90 degrees wide and had grooves cut on the inner surface to ensure proper circulation of the pore water. Each had an outlet in the center which could be coupled to the external pore lines. The polyurethane jacket was moulded into a cylinder around the passthroughs, which were embedded diagonally opposite to each other. The Fig. 4 shows a drawing of a jacket. The inner surface of the jacket and the passthroughs was continuous. The pore outlets were positioned diagonally across from each other. The jacket was 0.25 inch thick.

Core Mounting :

The core was pushed into the jacket so that the strain gauges were at right angles to the passthroughs. Thin lead sheets, $\frac{1}{32}$ inches thick, were put on the sample ends to prevent the acoustic coupling between the cell heads and the sample from being affected by the pore water.

A thin layer of dow resin was applied to the seating surface to ensure a good acoustic coupling. The sample was seated with the jacket fitting over the end pieces. The jacket was then filled with water and the bottom end piece raised till the sample was in contact with both the end pieces. Water was circulated through the pore system to remove any air trapped inside. The jacket was clamped tightly over the end pieces.

2.2 Testing Procedure

It was found necessary to exercise the samples to remove stress relief effects and give consistent readings. This was achieved by cycling each specimen three times over the stress range of 0 to 8000 psi before taking data. Examples of the stress relief and hysteresis effects are presented in figure (5) for Berea sandstone and in figure (6) for Leuders limestone.

During each test, measurements were made at 2000 psi intervals. Each time a stress level of interest was reached, the

load was held constant while the measurements were made. The procedure took about 5 to 10 minutes at each stress level. No time dependant deformation was observed during the tests. Also at the end of each test, strain was recovered to within .01 millistrains.

The tests conducted fall into three general categories,

1. Tests at atmospheric pore pressure on jacketed, water saturated samples.
2. Tests at elevated pore pressure on jacketed, water saturated samples.
3. Matrix compressibility tests onunjacketed, oil saturated samples.

The tests on water saturated samples were further divided into two categories according to the loading pattern.

1. Hydrostatic loading
2. Uniaxial compaction tests

Table (1) gives a summary of the tests conducted. The test procedures are discussed below in detail.

1. Atmospheric pore pressure tests on jacketed samples

A : Hydrostatic loading

During these tests, the confining pressure was raised from 0 to 8000 psi in steps of 2000 psi. The axial pressure was equal to the confining pressure. On the upcycle the pore

water squeezed out of the sample into a small burette at atmospheric pressure where it could be measured. During the down cycle the pore water was allowed to get back in to the sample out of the same burette at atmospheric pressure. At intervals of 2000 psi the load was held constant to facilitate measurements. The amount of displaced pore water was recorded. Axial, confining and pore pressures along with axial and radial strains were recorded on the computer. Travel time for P and S waves were read from the ultrasonic equipment. To determine the permeability the valves to the MTS intensifier were opened and a horizontal water flow at a constant pressure differential was established. Using a large burette and a stopwatch, the flow rate was determined. The large burette valve and the MTS valve were then closed and the loading resumed.

B : Uniaxial compaction tests

The range of axial stress during these tests was from 0 to 8000 psi. The radial strain was continuously monitored by the computer and the output fed to a null galvanometer. The confining pressure was controlled in such a way as to give a null deflection on the galvanometer. Thus the radial strain was held zero throughout the test. The rest of the data acquisition was similar to the hydrostatic tests.

2. Matrix Compressibility Tests

These tests were conducted usingunjacketed, oil saturated samples. Pore fluid displacement was not monitored. Permeability readings were not taken. The rest of the procedure was similar to the jacketed tests.

3. Elevated Pore Pressure Tests

Jacketed, water saturated samples were used for these tests.

A : Hydrostatic tests

Confining and axial stresses were raised from 0 to 2000 psi hydrostatically keeping the pore pressure atmospheric which was then raised to 2000 psi using a screw pump. This screw pump was graduated to read the displaced water volumes. The external hydrostatic stress was then raised to 10,000 psi in steps of 2000 psi. During loading the pore pressure was maintained at 2000 psi. Stress-strain data were gathered in a manner similar to the previous tests but the procedure for measuring permeability differed from that at atmospheric pore pressure. Initially, the upstream and downstream pressures were measured on two different transducers. At a later date, a differential transducer was included across the sample to improve the accuracy. During the permeability measurements the

MTS was used to maintain a constant flowing upstream pressure. The flow rate and the pressure differential were controlled by a fine tune microvalve on the downstream side.

B : Uniaxial compaction tests

The following loading pattern was used in these tests. First the confining, axial and pore pressure were elevated to 2000 psi in a manner similar to the hydrostatic tests. During the rest of the test, the radial strain was maintained at the value it had achieved at this point. To accomplish this, the computer and the confining screw pump were used as before to control the radial strain.

The axial load was raised from 2000 to 10,000 psi in steps of 2000 psi. The confining pressure was controlled so as to give a constant value of radial strain. The pore pressure was maintained at 2000 psi using the screw pump. All measurements were carried out in the manner described before.

CHAPTER 3

ERROR ANALYSIS AND DATA PROCESSING

This chapter presents a discussion of various sources of errors along with error propagation equations and the manner of data processing. During the experiments the following variables were measured as the primary data

1. Stress:

Confining pressure P_c

Axial stress P_z

Upstream pore pressure P_o

Downstream pore pressure P_d

Differential pore pressure ΔP_o

2. Strains

Axial strain ϵ_z

Radial strain ϵ_r

3. Acoustic travel time

P-wave travel time T_p

S-wave travel time T_s

4. Displaced pore water volume V_w

5. Permeability variables

Volume flow of water V_F

Time of water flow T_F

Section 1 of this chapter deals with the manner of collecting and handling these data. Section 2 covers the sources of errors during these measurements and section 3 presents the equations for error propagation.

1.0 DATA ACQUISITION AND ANALYSIS

1.1 Stress:

The stresses were measured with pressure transducers. The output of each transducer was amplified and read by a Data General Supernova computer through an analog/digital converter.

1.2 Strains

The strains were measured using resistance type strain gauges. The output of these gauges were amplified and fed to the computer.

1.3 Acoustic Travel Times

The time difference between the onset and the first arrival of each wave was measured using a time-based oscilloscope and a digital timer.

1.4 Displaced Pore Volume

In atmospheric pore pressure tests, the displaced pore fluid volume was measured directly using a system of burettes (figure 2). During elevated pore pressure tests, the volume was measured using a calibrated screw pump.

1.5 Permeability Variables

The volume of water flow was measured using a burette and the time was measured with an electric timer.

Data Analysis :

The stress-strain data gathered on the computer were transferred to a CDC-6600 computer. The strains were then fitted to suitable functions of stresses and these functional forms were in computing the elastic moduli.

The rest of the data were processed using programmable Hewlett Packard calculators.

Table (1) shows a summary of the types of tests run on each rock and the number of samples processed in each case. Within each test group, the data from the individual samples were averaged to give the final results. The sample to sample variation is represented by the standard deviation around the mean.

2.0 SOURCES OF ERRORS

2.1 Stresses

Confining Pressure :

The confining pressure transducer had an accuracy of .1 % of the full range. The range used was from 0 to 25,000 psi.

Axial Stress :

The axial transducer had an accuracy of .1 % of the full range.

The range used was 50,000 psi. There was an added error in the axial readings due to the friction between the load cell piston and the sealing rings.

Pore Pressures :

The upstream and downstream pore line pressure transducers had an accuracy of .1 % of the full range. The range used was from 0 to 12,500 psi. This accuracy was sufficient for line pressure measurements , however, it introduced a large error in the differential pressure calculations whenever used for this purpose. This was particularly true for Berea sandstone where the pressure difference across the core ranged from 5 to 20 psi. For this reason, the permeabilities computed for Berea sandstone indicate only an order of magnitude trend.

The differential pressure transducer, introduced into the system at a later date, had three interchangeable diaphragms with full scale readings of 50, 250 and 500 psi respectively. The accuracy of this transducer was .1 % of the full range.

2.2 Strains

Strains were measured with strain gauges cemented onto the rock. This method of measuring strains poses many problems. The cement which holds the gauges onto the rock tends to harden

the rock locally thus changing the strain distribution in the neighborhood. Secondly, there may exist some slippage between the rock and the gauge due to imperfect bonding. This problem becomes significant in high porosity, large grain rocks. Thirdly, the gauges get flattened against the rock at higher confining pressures. Despite these problems, the presence of jacketing material and passthroughs combined with the limited volume of the SPS precluded the use of other deformation monitoring systems. In cementing the gauges, care was taken to make the mounting cement layer as thin as possible. The flattening of the gauges under confining pressure was corrected for by calibrating the system with an Aluminium sample. Reference [20] discusses the use of strain gauges in detail.

The strain gauges had an error of 0.1 millistrains. It was not possible to quantify the errors discussed before due to their nature. It was found that the sample to sample variation in the strain readings was about 5 to 40%. It is assumed that this represents a realistic upper bound on the individual strain readings. In computing the elastic moduli, the strains were obtained from a least square fit to the raw data.

2.3 Acoustic Travel Times

Travel times were measured using a counter-timer triggered by the transmitted pulse and by the received pulse. Times were measured with a precision of 0.1 microseconds, giving a precision of the order of 0.5% for P wave travel times and 1% for

shear wave travel times. It is assumed that the accuracy of the system is less than these precisions.

A potentially more significant source of error lies in the correction for end effects. The calibration for these effects is run with no rock in place, and thus with one metal/metal interface. Two rock/metal interfaces exist during actual measurements. Despite the use of an acoustic coupling compound on the ends of the specimen it seems likely that some additional delay will exist, particularly at low axial stresses. This error cannot be quantified.

2.4 Displaced Pore Water Volume

Volumes were measured using positive displacement pumps calibrated in 0.01 cm^3 divisions. Due to the small volumes involved this could lead to a precision of as high as 5%.

A more troublesome source of error occurred at low confining pressures and, to some effect, at high confining pressure and low effective stress. This is related to the volume of saturating fluid contained in the jacket/specimen interface. Due to the requirement of ensuring perfect saturation of the specimens the existence of this fluid is unavoidable. On initial loading much of this fluid is squeezed out into the pore pressure lines and gives an anomalously high pore water displacement volume. At low effective stresses fluid could also be trapped in this interface leading to the same result on increase of effective stress. This error is not thought to be significant at higher values of effective stress.

2.5 Flow Measurements:

About two minutes had to be allowed for the water flow to be static before measurements could be made. Even after the flow stabilized, the pore pressure fluctuated by about 5% of the differential pore pressure.

The volume flow of water was measured to within .5 cc The time of flow was measured to within .1 sec.

3.0 ERROR PROPAGATION

This section presents a discussion of the propagation of the experimental errors. The standard differential formulas are used in these computations [24]. The symbol δ before a variable denotes the error in the variable. the d symbol before a variable denotes a differential change in the variable.

1. Static Bulk Modulus

$$\text{since } k = 1 / (d\varepsilon_v / dP_c^e)$$

$$\frac{\delta k}{k} = \frac{\delta (d\varepsilon_v)}{d\varepsilon_v} + \frac{\delta (dP_c^e)}{dP_c^e}$$

2. Static Poisson's Ratio

$$\nu = \frac{S}{S+1} \quad ; \quad S = \frac{dP_c^e}{dP_z^e}$$

$$\therefore \delta \nu = \nu \frac{\delta S}{S} \cdot \frac{1}{S+1}$$

$$\text{and} \quad \frac{\delta S}{S} = \frac{\delta (dP_c^e)}{dP_c^e} + \frac{\delta (dP_z^e)}{dP_z^e}$$

3. Static Young's Modulus

$$E = \frac{1}{S} \left(1 - \frac{2\nu^2}{1-\nu} \right) \quad ; \quad S = \frac{d\varepsilon_z}{d\sigma_z^e}$$

$$\therefore \delta E = E \frac{\delta S}{S} + \frac{1}{S} \cdot \frac{\delta \nu}{\nu} \cdot \frac{2\nu^2(2-\nu)}{(1-\nu)^2}$$

4. Static Uniaxial Compaction Coefficient

$$\frac{\delta C_m}{C_m} = \frac{\delta (d\varepsilon_z)}{d\varepsilon_z} + \frac{\delta (d\sigma_z^e)}{d\sigma_z^e}$$

5. Dynamic Poisson's Ratio

$$\nu = \frac{1}{2} \frac{S-2}{S-1} ; S = (V_P/V_S)^2$$

$$\therefore \frac{\delta \nu}{\nu} = \frac{\delta S}{(S-2)(S-1)}$$

$$\text{and } \frac{\delta S}{S} = 2 \frac{\delta V_P}{V_P} + 2 \frac{\delta V_S}{V_S}$$

where δV_P and δV_S are given by

$$\frac{\delta V_P}{V_P} = \frac{\delta T_P}{T_P} + \frac{\delta L}{L} \quad \text{and}$$

$$\frac{\delta V_S}{V_S} = \frac{\delta T_S}{T_S} + \frac{\delta L}{L}$$

with L as the sample length.

6. Dynamic Young's Modulus

$$E = \frac{V_S^2 \rho}{g} \cdot \frac{3S-4}{S-1}$$

where S is given as before.

$$\therefore \delta E = \frac{2\delta V_S}{V_S} E + \frac{\delta \rho}{\rho} E + \frac{V_S^2 \rho}{g} \cdot \frac{\delta S}{(S-1)^2}$$

δS is given as before.

7. Dynamic Uniaxial Compaction Coefficient

$$\delta C_m = C_m \delta E/E + \frac{1}{E} \frac{2\nu^2(2-\nu)}{(1-\nu)^2} \delta \nu/\nu$$

8. Porosity

$$\phi = V_{PP}/V_b$$

$$\therefore \frac{\delta \phi}{\phi} = \frac{\delta V_{PP}}{V_{PP}} + \frac{\delta V_b}{V_b}$$

9. Permeability

$$K = \frac{q\mu}{L\Delta P} \cdot \frac{1}{R} \cdot \frac{K_e}{K_e'}$$

$$\therefore \frac{\delta K}{K} = \frac{\delta q}{q} + \frac{\delta(\Delta P)}{\Delta P} + \frac{\delta L}{L} + \frac{\delta \mu}{\mu}$$

and

$$\frac{\delta q}{q} = \frac{\delta V_F}{V_F} + \frac{\delta T_F}{T_F}$$

Magnitudes of Errors:

Berea sandstone data was found to have errors of about 3% for elastic moduli, about 5% for porosity and about 50% for permeability. Leuders limestone data was found to have errors of about 3% for elastic moduli, about 5% for porosity and about 5% for permeability. Except for permeability of Berea sandstone, these errors are less than the sample to sample variations observed in these tests.

CHAPTER 4

RESULTS

In the first part of this chapter the experimental results are discussed in general terms along with the pertinent material. The second section goes into the specific discussion of each of the rock properties studied in this investigation. Section three presents the inferences that can be drawn from these results. The data and the derived numerical results are presented in the appendix.

The entire sample data could not be presented due to its bulk , however, two typical sets of data have been included as examples for each test conducted on both rocks investigated. These data clearly show the trends observed in all samples. These are followed by the average results from all samples presented according to the type of test for each rock along with the standard deviations arising from sample to sample variation.

1.0 GENERAL DISCUSSION

During these tests it was found necessary to exercise each sample three times over the stress range of interest to obtain consistent results. Figures (5) and (6) show this effect for Berea sandstone and Leuders limestone. The stress-strain curves were found to exhibit hysteresis behavior even after the residual stress was removed. This is also demonstrated in these figures.

There was observed to be considerable sample to sample variation in all the properties studied for each type of test. Figure (7) shows volumetric strain as a function of confining stress. The dotted lines represent jacketed, water saturated samples and the solid lines represent the data for unjacketed, oil saturated samples. The variation of confining pressure as a function of axial stress is shown in figure (8). As far as the sample to sample variation is concerned, these figures are representative of other parameters as well.

Tables (2) to (17) contain the individual sample data for each rock from various tests. Two samples are presented for each type. These data are observed to follow the trends discussed below. The stress-strain data for these samples are shown in figures (9) to (28). The down cycle data are omitted for the

sake of clarity. The curves through the data points represent the least squares functional fit to the raw data. Volumetric strain is plotted as a function of effective confining stress for hydrostatic tests and as a function of effective axial stress for uniaxial compaction tests.

The data from Berea sandstone were found to best fit the function

$$\epsilon_v = a_0 + a_1 \sigma + a_2 \sqrt{\sigma}$$

where ϵ_v is the volumetric strain, σ is the relevant stress and

a_0, a_1, a_2
are empirical constants.

The function

$$\epsilon_v = a_0 + a_1 \sigma + a_2 \sigma^2$$

was found to best fit the data for Leuders limestone.

These are the functions used in computing the static elastic moduli, although at this time no theoretical significance is attached to the actual functional forms.

2.0 DISCUSSION OF THE COMPUTED ROCK PROPERTIES

As indicated in previous sections, values for Young's modulus, Poisson's ratio, Bulk modulus and uniaxial compaction coefficient were computed from both static and dynamic data. Porosities were calculated from strain gauge, acoustic travel time and displaced pore water volume data. Permeabilities were computed from flow data. The results for those properties are discussed in this section.

2.1 Young's modulus

Values for the Young's modulus are given in Tables 4-7 for Berea sandstone and Tables 12, 13, 16, 17 for Leuders limestone. Mean values for Berea sandstone are shown in Tables 18 and 19 and for Leuders limestone in Tables 20 and 21. The data is plotted in Fig. 29 for Berea sandstone and Figure 30 for Leuders limestone.

The non-linearity of Berea sandstone is shown by the increase of Young's modulus with increased stress, the effect being most pronounced at higher stresses for the elevated pore pressure test. However over much of the effective stress range the atmospheric pore pressure and elevated pore pressure curves are not

well separated, indicating that the simple form of the effective stress law is a fair approximation for this property. The Young's modulus decreases with the axial stress in case of Leuders limestone under elevated pore pressure tests, indicating that the rock becomes softer with increasing pore pressure. This is contradictory to the results found for Berea sandstone.

The dynamic values of Young's modulus are significantly larger than the static values. They do not correlate with the static values.

2.2 Poisson's Ratio

Poisson's ratio was found to be independent of the external load, as shown in tables (22) through (25).

2.3 Bulk Modulus

The dependance of the bulk modulus on stress is qualitatively similar to the dependance of Young's modulus on stress. Figures 31) and (32) show its variation with effective confining stress. The data are summarized in tables 26 through 29.

The modulus increases with the confining pressure, indicating that the rocks become stiffer at higher stresses, as is to be expected. The curves for elevated pore pressure lie close to those at atmospheric pore pressure, indicating again that the simple form of effective stress is a good approximation for the bulk modulus.

The dynamic values of this modulus are larger than the static values and bear no correlation with them.

2.4 Uniaxial Compaction Coefficient

This coefficient varies in a markedly nonlinear fashion with the effective axial stress. In the case of Berea sandstone it decreases with increasing stress for both elevated and atmospheric pore pressures. For Leuders limestone, the coefficient at atmospheric pore pressure decreases with increasing stress but this trend is reversed at elevated pore pressures. For both the rocks, the values for elevated and atmospheric pore pressures lie close to each other. These data are summarized in tables 30 through 33 and Figs. 33 and 34.

The dynamic values are lower than the static values and do not correlate with them.

2.5 Porosity

In figures 35 to 38 porosity computed by three different methods is plotted as a function of effective mean stress. These data are presented in tables 34 through 41. The values obtained from the volumetric strains and from the pore fluid displacements lie quite close to each other but the values obtained from the time average formula seem to bear little relation to them. The overall change in porosity with external as well as internal stress is small, less than 2%. The effect of the pore pressure increase is to increment the porosity, which is shown quite clearly by these curves. This is as expected.

2.6 Permeability

Permeability data from various tests is shown in figures 39 through 42 and tables 42 to 49. For both Leuders limestone and Berea sandstone the permeability varies markedly with stress.

The permeability of Berea sandstone increases with increasing pore pressure and decreases with increasing external stress as it is to be expected. This is true as well of Leuders limestone under hydrostatic loading but the trend with respect to pore pressure is reversed in uniaxial compaction tests.

3.0 INFERENCES

1. There is a substantial specimen to specimen variation for both Berea sandstone and Leuders limestone.
2. Both rocks show a nonlinear stress-strain behavior. This is more pronounced in the case of Berea sandstone.
3. Both rocks are reasonably elastic but exhibit hysteresis effects.
4. For both rocks the static bulk modulus and Young's modulus increase with increasing external stress at atmospheric pore pressure, showing that the rocks become stiffer at higher external pressures.
5. The overall change in the static bulk modulus and Young's modulus with increasing pore pressure is small, indicating that the simple form of the effective stress law is a reasonably good approximation for these rocks with respect to these parameters.
6. The ratio of matrix modulus to the bulk modulus is not small, indicating a significant matrix volume change under stress. This implies that an effective stress constant less than one is appropriate for these rocks.

7. The uniaxial compaction coefficient for Berea sandstone is a nonlinear function of stress, decreasing sharply at low axial stresses and approaching a constant value at higher loads. For Leuders limestone the nonlinearity is less marked.
8. Poisson's ratio can be treated as a constant for these rocks.
9. The elastic moduli computed from the dynamic measurements are larger than the static moduli. Also the dynamic moduli do not reflect the strong nonlinearities observed in the static data.
10. The porosity changes under external loading are small. The porosities at elevated pore pressure are higher, indicating the influence of the matrix compression.
11. The permeability reduction with increasing external stress is quite significant.
12. The fractional change in permeability is large compared to the fractional change in porosity, suggesting that much of the compaction takes place in smaller pores.
13. The dynamic values of porosity obtained from the time average formula do not correlate with the static values.

CHAPTER 5

CONCLUSIONS

The conclusions based on the data obtained in this investigation are presented in this chapter. When drawing conclusions from this data it must be remembered that the subjects of the present study, Berea sandstone and Leuders limestone, are relatively well behaved rocks that have been studied by many investigators. The complexities observed in these well known rocks can only be expected to multiply for real reservoirs.

Although elastic within the studied range, both the rocks displayed strong nonlinearity and hysteresis. The elastic moduli were found to vary with stress quite markedly. The effective stress concept seems to be a good approximation with respect to the elastic moduli, but there is a significant amount of matrix compression present in both Leuders limestone and Berea sandstone. An effective stress constant less than one is indicated by the data. The porosity and permeability are not simple functions of the stress. The acoustic data does not

compare very well with the static data. Even in these relatively homogeneous, isotropic and continuous rocks the sample to sample variation is quite large.

Cores from geothermal, geopressured reservoirs are much more inhomogeneous, and have a complex structure which is a mixture of clays, sand and shale. The law of effective stress has to be studied carefully on these rocks before it can be used in reservoir modeling. The extent of nonlinearity along with a possible time dependent behavior needs to be evaluated in the laboratory. A statistically significant comparison of dynamic and static data needs to be made before the sonic log data can be used in reservoir simulation.

Appendix

Tables and Figures

In this appendix the data are presented in form of tables and figures. Section one contains the tables and the second section contains the figures.

1. TABLES

TABLE 1
SUMMARY OF TESTS

Berea Sandstone
Number of Samples

	Jacketed Hydrostatic Tests	Uniaxial Compaction Tests	Matrix Compressibility Tests
Atmospheric Pore Pressure	9	9	8
Pore Pressure Equals 2KPSI	5	5	-

Leuders Limestone
Number of Samples

	Jacketed Hydrostatic Tests	Uniaxial Compaction Tests	Matrix Compressibility Tests
Atmospheric Pore Pressure	8	8	9
Pore Pressure Equals 2KPSI	5	5	-

TABLE 2.

INDIVIDUAL SAMPLE DATA

BEREA SANDSTONE

JACKETED HYDROSTATIC TEST

SAMPLE NUMBER: 3

PRESSURES			STRAINS		ACOUSTIC VELOCITIES		BULK MODULUS		POROSITIES			PERMEABILITY
CONF	AXIAL	PORE	RADIAL	AXIAL	P	S	STAT	DYNA	VOLUME	PORE	TIME	
KPSI	KPSI	KPSI	(10.E-3)XME		FT/SEC	FT/SEC	(10.E6)XPSI		STRAIN	FLUID	AVRG	MD
									PERCENT			
.99	.97	0.00	341.	691.	11643.		.78		19.50	19.39		71.
1.94	1.90	0.00	638.	1202.	12228.	7506.	1.06	2.34	19.40	19.27	20.31	71.
4.04	3.89	0.00	1113.	1877.	12788.	7716.	1.41	2.64	19.30	19.16	17.95	70.
6.06	5.72	0.00	1501.	2300.	13008.	7902.	1.65	2.70	19.20	19.07	17.07	70.
7.88	7.33	0.00	1821.	2622.	13130.	7979.	1.84	2.75	19.10	18.99	16.60	70.
6.03	5.78	0.00	1486.	2371.	13044.	7929.	1.87	2.71	19.20	19.04	16.93	67.
4.05	3.92	0.00	1117.	2004.	12865.	7797.	1.54	2.65	19.30	19.10	17.64	68.
2.00	2.00	0.00	677.	1468.	12472.	7489.	1.10	2.54	19.40	19.19	19.25	68.
1.06	1.10	0.00	415.	1013.	11994.		.78		19.50	19.27		70.

TABLE 3.

INDIVIDUAL SAMPLE DATA

BEREA SANDSTONE

JACKETED HYDROSTATIC TEST

SAMPLE NUMBER: 21

PRESSURES			STRAINS		ACOUSTIC VELOCITIES		BULK MODULUS		POROSITIES			PERMEABILITY
CONF	AXIAL	PORE	RADIAL	AXIAL	P	S	STAT	DYNA	VOLUME	PORE	TIME	
KPSI	KPSI	KPSI	(10.E-3)XME		FT/SEC	FT/SEC	(10.E6)XPSI		STRAIN	FLUID	AVRG	MD
									PERCENT			
1.04	1.00	0.00	480.	813.	11737.		.72		19.40	19.27		68.
1.98	1.93	0.00	789.	1294.	12479.	7631.	1.01	2.47	19.30	19.17	19.22	60.
3.88	3.69	0.00	1231.	1806.	13011.	7849.	1.43	2.76	19.20	19.08	17.06	58.
6.04	5.65	0.00	1666.	2210.	13201.	8002.	1.75	2.81	19.10	19.01	16.33	57.
7.99	7.41	0.00	2042.	2540.	13350.	8082.	2.02	2.88	19.00	18.95	15.77	57.
6.07	5.82	0.00	1670.	2284.	13253.	8019.	1.86	2.84	19.10	19.99	16.13	57.
4.05	3.92	0.00	1255.	1939.	13099.	7900.	1.51	2.79	19.20	19.05	16.72	57.
1.93	1.94	0.00	777.	1437.	12734.	7574.	1.06	2.71	19.30	19.14	18.16	57.
1.01	1.02	0.00	497.	978.	12171.		.75		19.40	19.25		57.

TABLE 4.

INDIVIDUAL SAMPLE DATA

BEREA SANDSTONE

UNIAXIAL COMPACTION TEST

SAMPLE NUMBER: 15

PRESSURES			STRAINS		ACOUSTIC		YOUNGS		POISSONS		UNIAXIAL COMPACTION		POROSITIES		PERMEABILITY
CONF	AXIAL	PORE	RADIAL	AXIAL	VELOCITIES		MODULUS		RATIO		COEFFICIENT		VOLUME	PORE	TIME
KPSI	KPSI	KPSI	(10.E-3)XME		P	S	STAT	DYNA	STAT	DYNA	STAT	DYNA	STRAIN	FLUID	AVRG
					FT/SEC	FT/SEC	(10.E6)XPSI				(10.E 6)XPSI		PERCENT		MD
.22	1.10	0.00		434.			1.74		.176		.531		19.50	19.44	
.41	2.09	0.00	8.	902.	12363.	7080.	2.16	3.97	.176	.256	.429	.208	19.40	19.41	19.72
.78	3.98	0.00	16.	1669.	12774.	7286.	2.59	4.21	.176	.259	.357	.194	19.40	19.33	18.00
1.21	5.92	0.00	14.	2334.	12961.	7521.	2.85	4.44	.176	.246	.325	.189	19.30	19.24	17.26
1.71	8.01	0.00	2.	2936.	13079.	7631.	3.03	4.56	.176	.242	.306	.186	19.30	19.17	16.80
1.35	6.07	0.00	12.	2555.	13024.	7574.	3.44	4.50	.172	.244	.270	.187	19.30	19.21	17.01
.90	4.00	0.00	14.	1942.	12835.	7399.	2.84	4.32	.172	.251	.327	.193	19.30	19.30	17.76
.46	1.90	0.00	12.	1072.	12489.	7201.	2.04	4.09	.172	.251	.456	.203	19.40	19.38	19.18
.28	.97	0.00	15.	579.			1.46		.172		.637		19.50	19.42	

TABLE 5.

INDIVIDUAL SAMPLE DATA

BEREA SANDSTONE

UNIAXIAL COMPACTION TEST

SAMPLE NUMBER: 18

PRESSURES			STRAINS		ACOUSTIC		YOUNGS		POISSONS		UNIAXIAL COMPACTION COEFFICIENT		POROSITIES			PERMEABILITY MP
CONF KPSI	AXIAL KPSI	PORE KPSI	RADIAL (10.E-3)XME	AXIAL	VELOCITIES P FT/SEC	S FT/SEC	MODULUS STAT DYNA (10.E6)XPSI		RATIO STAT DYNA		STAT DYNA (10.E 6)XPSI		VOLUME STRAIN	PORE FLUID PERCENT	TIME AVRG	
.24	1.09	0.00	9.	502.			1.44		.187		.636		19.50	19.49		72.
.47	2.07	0.00	2.	1046.	12297.	7068.	1.96	3.96	.187	.253	.467	.209	19.40	19.45	20.01	72.
.94	4.09	0.00	3.	1872.	12747.	7356.	2.63	4.28	.187	.250	.348	.195	19.40	19.36	18.11	69.
1.35	5.99	0.00	6.	2454.	12992.	7566.	3.10	4.50	.187	.243	.295	.187	19.30	19.32	17.13	68.
1.78	7.91	0.00	7.	2969.	13165.	7702.	3.47	4.65	.187	.240	.263	.182	19.30	19.29	16.47	68.
1.46	6.01	0.00	1.	2595.	13020.	7615.	3.79	4.55	.187	.240	.241	.187	19.30	19.31	17.03	68.
1.02	4.10	0.00	5.	2082.	12880.	7458.	2.93	4.39	.187	.248	.312	.191	19.40	19.35	17.58	68.
.49	1.92	0.00	0.	1235.	12441.	7391.	1.94	4.24	.187	.227	.471	.204	19.40	19.42	19.39	69.
.28	1.08	0.00	7.	728.			1.31		.187		.697		19.50	19.50		70.

TABLE 6.

INDIVIDUAL SAMPLE DATA

BEREA SANDSTONE

UNIAXIAL COMPACTION TEST

SAMPLE NUMBER: 42

PRESSURES			POISSON STRAINS		ACOUSTIC		YOUNGS		POISSONS		UNIAXIAL COMPACTION		POROSITIES		PERMEABILITY
CONF	AXIAL	PORE	RADIAL	AXIAL	VELOCITIES		MODULUS		RATIO		COEFFICIENT		VOLUME	PORE	TIME
KPSI	KPSI	KPSI	(10.E-3)XME		P	S	STAT	DYNA	STAT	DYNA	STAT	DYNA	STRAIN	FLUID	AVRG
					FT/SEC	FT/SEC	(10.E6)XPSI				(10.E 6)XPSI		PERCENT		MD
2.34	3.05	2.01	191.	685.	11984.		2.76		.169		.338		19.90	19.96	84.
2.48	4.04	2.01	193.	911.	12403.		2.99		.169		.311		19.80	19.89	82.
2.92	6.04	2.01	191.	1576.	12804.		3.33		.169		.280		19.60	19.81	81.
3.33	8.02	2.02	194.	2116.	13030.	7570.	3.56	4.60	.169	.245	.261	.183	19.60	19.75	16.99
3.73	10.02	2.01	196.	2585.	13158.	7744.	3.74	4.77	.169	.235	.249	.179	19.50	19.70	16.49
3.35	8.05	2.01	194.	2183.	13021.	7593.	3.87	4.62	.165	.242	.242	.183	19.60	19.74	17.02
3.00	6.07	2.01	194.	1683.	12867.	7426.	3.28	4.44	.165	.250	.205	.187	19.70	19.78	17.63
2.59	4.05	2.01	194.	993.	12510.		2.61		.165		.358		19.80	19.85	77.
2.37	3.04	2.01	193.	560.	12112.		2.23		.165		.419		19.90	19.92	78.

TABLE 7.

INDIVIDUAL SAMPLE DATA

BEREA SANDSTONE

UNIAXIAL COMPACTION TEST

SAMPLE NUMBER: 52

PRESSURES			STRAINS		ACOUSTIC		YOUNGS		POISSONS		UNIAXIAL COMPACTION		POROSITIES		PERMEABILITY
CONF	AXIAL	PORE	RADIAL	AXIAL	VELOCITIES		MODULUS		RATIO		COEFFICIENT		VOLUME	PORE	TIME
KPSI	KPSI	KPSI	(10.E-3)XME		P	S	STAT	DYNA	STAT	DYNA	STAT	DYNA	STRAIN	FLUID	AVRG
					FT/SEC	FT/SEC	(10.E6)XPSI				(10.E+6)XPSI		PERCENT		MD
2.22	3.05	2.03	194.	1104.	11679.		1.32		.151		.718		19.80	20.27	89.
2.38	4.03	2.03	192.	1712.	12221.		1.66		.151		.568		19.80	20.13	83.
2.72	6.03	2.03	192.	2550.	12657.		2.42		.151		.391		20.00	20.00	77.
3.09	8.02	2.02	201.	3216.	12877.		3.31		.151		.286		20.40	19.92	74.
3.46	10.00	2.02	200.	3795.	12957.	7545.	4.43	4.45	.151	.243	.214	.189	21.10	19.86	17.27
3.12	8.02	2.02	197.	3354.	12875.	7375.	4.43	4.30	.145	.256	.215	.192	21.10	19.90	17.60
2.74	6.03	2.03	196.	2783.	12668.		2.72		.145		.349		20.30	19.96	78.
2.42	4.02	2.02	192.	2006.	12303.		1.66		.145		.574		19.80	20.05	77.
2.28	3.04	2.03	198.	1438.	11888.		1.24		.145		.764		19.80	20.13	78.

TABLE 8.

INDIVIDUAL SAMPLE DATA

BEREA SANDSTONE

JACKETED HYDROSTATIC TEST

SAMPLE NUMBER: 47

PRESSURES			STRAINS		ACOUSTIC VELOCITIES		BULK MODULUS		POROSITIES			PERMEABILITY
CONF	AXIAL	PORE	RADIAL	AXIAL	P	S	STAT	DYNA	VOLUME	PORE	TIME	
KPSI	KPSI	KPSI	(10.E-3)XME		FT/SEC	FT/SEC	(10.E6)XPSI		STRAIN	FLUID	AVRG	MD
.....												
3.04	3.01	2.02	790.	982.	11708.		.76		19.90	19.87		91.
4.04	3.95	2.02	1094.	1491.	12405.	7489.	.95	2.49	19.80	19.84	19.54	88.
6.05	5.78	2.01	1543.	2088.	12885.	7748.	1.38	2.70	19.70	19.75	17.56	82.
8.06	7.57	2.01	1959.	2493.	13064.	7905.	1.87	2.75	19.60	19.67	16.85	78.
10.02	9.38	2.02	2363.	2849.	13187.	7988.	2.47	2.79	19.50	19.61	16.38	75.
8.06	7.83	2.01	1941.	2604.	13107.	7901.	2.03	2.78	19.60	19.66	16.69	77.
6.07	5.91	2.01	1520.	2242.	12847.	7757.	1.42	2.67	19.70	19.73	17.71	79.
4.05	4.00	2.01	1074.	1715.	12600.	7714.	.95	2.50	19.80	19.83	18.72	80.
3.05	3.10	2.01	794.	1237.	12100.		.74		19.90	19.92		82.

TABLE 9.

INDIVIDUAL SAMPLE DATA

BEREA SANDSTONE

JACKETED HYDROSTATIC TEST

SAMPLE NUMBER: 44

PRESSURES			STRAINS		ACOUSTIC VELOCITIES		BULK MODULUS		POROSITIES			PERMEABILITY
CONF	AXIAL	PORE	RADIAL	AXIAL	P	S	STAT	DYNA	VOLUME	PORE	TIME	
KPSI	KPSI	KPSI	(10.E-3)XME		FT/SEC	FT/SEC	(10.E6)XPSI		STRAIN	FLUID	AVRG	MD
									PERCENT			
3.01	2.99	2.01	588.	721.	11293.		.96		20.10	20.01		87.
4.00	3.90	2.00	870.	1115.	12060.		1.16		20.00	19.93		84.
6.02	5.79	2.00	1289.	1660.	12059.	7352.	1.52	2.30	19.90	19.83	21.07	80.
8.02	7.57	2.00	1691.	2079.	12313.	7559.	1.87	2.37	19.80	19.76	19.94	79.
10.01	9.25	2.00	2046.	2404.	12456.	7655.	2.22	2.42	19.70	19.71	19.32	80.
8.03	7.74	1.99	1677.	2144.	12332.	7564.	2.07	2.38	19.80	19.76	19.85	90.
6.03	5.82	1.99	1282.	1821.	12160.	7451.	1.58	2.32	19.90	19.82	20.61	89.
4.00	3.93	1.99	851.	1355.	11742.		1.13		20.00	19.91		90.
3.02	3.01	1.99	568.	939.	11711.		.91		20.10	19.99		92.

TABLE 10.

INDIVIDUAL SAMPLE DATA

LEUDERS LIMESTONE

JACKETED HYDROSTATIC TEST

SAMPLE NUMBER: 10

PRESSURES			STRAINS		ACOUSTIC VELOCITIES		BULK MODULUS		POROSITIES			PERMEABILITY
CONF	AXIAL	PORE	RADIAL	AXIAL	P	S	STAT	DYNA	VOLUME	PORE	TIME	
KPSI	KPSI	KPSI	(10.E-3)XME		FT/SEC	FT/SEC	(10.E6)XPSI		STRAIN	FLUID	AVRG	MD
									PERCENT			
1.02	.98	0.00	328.	85.	13517.	7160.	1.53	3.78	15.90	15.91	18.50	.29
2.01	1.94	0.00	569.	226.	13627.	7300.	1.59	3.79	15.90	15.86	18.12	.29
4.02	3.80	0.00	982.	468.	13821.	7419.	1.73	3.88	15.80	15.80	17.46	.28
6.01	5.59	0.00	1374.	677.	13952.	7488.	1.90	3.96	15.70	15.76	17.03	.28
8.00	7.37	0.00	1771.	912.	14008.	7503.	2.11	4.00	15.60	15.72	16.85	.27
6.03	5.70	0.00	1455.	752.	13917.	7441.	2.24	3.96	15.70	15.74	17.15	.28
4.03	3.81	0.00	1074.	546.	13795.	7382.	1.81	3.89	15.70	15.77	17.55	.28
2.01	1.94	0.00	657.	304.	13602.	7256.	1.52	3.79	15.80	15.80	18.20	.28
1.03	.98	0.00	402.	133.	13445.	7178.	1.41	3.70	15.90	15.81	18.75	.28

TABLE 11.

INDIVIDUAL SAMPLE DATA

LEUDERS LIMESTONE

JACKETED HYDROSTATIC TEST

SAMPLE NUMBER: 30

PRESSURES			STRAINS		ACOUSTIC VELOCITIES		BULK MODULUS		POROSITIES			PERMEABILITY
CONF	AXIAL	PORE	RADIAL	AXIAL	P	S	STAT	DYNA	VOLUME	PORE	TIME	
KPSI	KPSI	KPSI	(10.E-3)XME		FT/SEC	FT/SEC	(10.E6)XPSI		STRAIN	FLUID	AVRG	MD
									PERCENT			
.94	.95	0.00	119.	133.	13571.	7365.	2.17	3.66	16.10	16.06	18.31	.27
2.04	2.00	0.00	257.	284.	13748.	7433.	2.21	3.78	16.10	16.03	17.71	.26
3.95	3.79	0.00	538.	570.	13902.	7522.	2.30	3.86	16.00	15.99	17.20	.26
5.93	5.59	0.00	784.	820.	14007.	7588.	2.41	3.91	15.90	15.96	16.86	.25
7.98	7.43	0.00	1045.	1075.	14072.	7623.	2.52	3.95	15.80	15.93	16.65	.25
6.03	5.78	0.00	836.	922.	13981.	7565.	2.57	3.90	15.90	15.95	16.94	.25
4.05	3.92	0.00	574.	677.	13858.	7500.	2.32	3.83	16.00	15.97	17.34	.25
2.01	1.98	0.00	277.	373.	13705.	7439.	2.11	3.74	16.00	16.00	17.85	.25
1.05	1.09	0.00	152.	202.	13603.	7353.	2.02	3.70	16.10	16.02	18.20	.26

TABLE 12.

INDIVIDUAL SAMPLE DATA

LEUDERS LIMESTONE

UNIAXIAL COMPACTION TEST

SAMPLE NUMBER: 19

PRESSURES			STRAINS		ACOUSTIC		YOUNGS		POISSONS		UNIAXIAL COMPACTION		POROSITIES			PERMEABILITY
CONF	AXIAL	PORE	RADIAL	AXIAL	VELOCITIES		MODULUS		RATIO		COEFFICIENT		VOLUME	PORE	TIME	
KPSI	KPSI	KPSI	(10.E-3)XME		P	S	STAT	DYNA	STAT	DYNA	STAT	DYNA	STRAIN	FLUID	AVRG	MD
					FT/SEC	FT/SEC	(10.E6)XPSI				(10.E 6)XPSI		PERCENT			
.42	1.01	0.00	0.	221.	12351.	6890.	2.56	3.96	.262	.274	.318	.200	17.40	17.37	22.93	.38
.76	1.98	0.00	1.	500.	12595.	6955.	2.59	4.06	.262	.281	.314	.193	17.40	17.28	21.93	.37
1.41	3.99	0.00	1.	1165.	12966.	7058.	2.65	4.20	.262	.289	.308	.182	17.30	17.24	20.49	.36
2.17	6.07	0.00	2.	1808.	13215.	7125.	2.71	4.30	.262	.295	.301	.175	17.30	17.20	19.57	.36
2.86	7.96	0.00	2.	2333.	13378.	7175.	2.77	4.37	.262	.298	.294	.171	17.20	17.17	18.98	.35
2.26	5.91	0.00	2.	1972.	13212.	7139.	3.33	4.32	.252	.294	.249	.175	17.30	17.19	19.58	.36
1.66	4.10	0.00	11.	1474.	12962.	7069.	2.71	4.21	.252	.288	.307	.182	17.30	17.22	20.51	.36
.95	2.09	0.00	0.	797.	12605.	6960.	2.28	4.06	.252	.281	.364	.192	17.40	17.27	21.89	.36
.62	1.11	0.00	5.	433.	12323.	6899.	2.11	3.96	.252	.272	.393	.201	17.40	17.30	23.04	.37

TABLE 13.

INDIVIDUAL SAMPLE DATA

LEUDERS LIMESTONE

UNIAXIAL COMPACTION TEST

SAMPLE NUMBER: 18

PRESSURES			STRAINS		ACOUSTIC		YOUNGS		POISSONS		UNIAXIAL COMPACTION COEFFICIENT		POROSITIES			PERMEABILITY
CONF	AXIAL	PORE	RADIAL	AXIAL	VELOCITIES		MODULUS		RATIO		STAT DYNA		VOLUME	PORE	TIME	
KPSI	KPSI	KPSI	(10.E-3)XME		P	S	STAT	DYNA	STAT	DYNA	(10.E 6)XPSI	STRAIN	FLUID	AVRG		MD
					FT/SEC	FT/SEC	(10.E6)XPSI						PERCENT			
.....																
.30	1.01	0.00	16.	259.	12900.	6939.	2.65	4.09	.255	.296	.311	.183	17.20	17.13	20.74	.35
.54	1.95	0.00	5.	557.	13095.	6989.	2.74	4.17	.255	.301	.301	.178	17.20	17.05	20.01	.34
1.30	4.10	0.00	11.	1186.	13301.	7100.	2.94	4.30	.255	.301	.281	.172	17.10	17.01	19.26	.32
1.91	5.97	0.00	1.	1677.	13457.	7172.	3.17	4.39	.255	.302	.260	.168	17.10	16.97	18.71	.32
2.72	8.04	0.00	7.	2209.	13586.	7220.	3.45	4.45	.255	.303	.239	.165	17.00	16.96	18.26	.31
2.06	6.04	0.00	2.	1865.	13471.	7186.	3.88	4.40	.253	.301	.214	.168	17.10	16.97	18.66	.31
1.36	3.98	0.00	6.	1364.	13305.	7105.	3.08	4.30	.253	.301	.269	.172	17.10	16.98	19.24	.31
.70	2.04	0.00	7.	802.	13092.	6987.	2.56	4.16	.253	.301	.324	.178	17.10	17.02	20.02	.32
.33	1.00	0.00	1.	447.	12912.	6941.	2.36	4.10	.253	.297	.352	.183	17.20	17.04	20.70	.34

TABLE 14.

INDIVIDUAL SAMPLE DATA

LEUDERS LIMESTONE

JACKETED HYDROSTATIC TEST

SAMPLE NUMBER: 52

CONF	PRESSURES		STRAINS		ACOUSTIC VELOCITIES		BULK MODULUS		POROSITIES			PERMEABILITY MD
	AXIAL	PORE	RADIAL	AXIAL	P	S	STAT	DYNA	VOLUME	PORE	TIME	
	KPSI	KPSI	(10.E-3)XME		FT/SEC	FT/SEC	(10.E6)XPSI		STRAIN	FLUID	AVRG	
										PERCENT		
3.04	2.99	2.01	299.	212.	13005.	7618.	2.05	3.03	15.70	15.72	20.34	.25
4.04	3.92	2.02	471.	341.	13137.	7712.	2.11	3.08	15.70	15.69	19.85	.24
6.06	5.79	2.02	803.	568.	13278.	7810.	2.25	3.14	15.60	15.64	19.34	.24
8.05	7.58	2.01	1122.	780.	13376.	7878.	2.42	3.17	15.50	15.59	18.99	.23
10.04	9.29	2.01	1430.	982.	13507.	7931.	2.61	3.25	15.40	15.55	18.53	.22
8.05	7.74	2.01	1153.	817.	13368.	7872.	2.62	3.17	15.50	15.59	19.02	.23
6.05	5.83	2.01	840.	617.	13262.	7799.	2.25	3.13	15.60	15.63	19.40	.23
4.03	3.93	2.00	496.	382.	13084.	7688.	1.98	3.05	15.70	15.68	20.05	.23
3.04	3.02	2.00	314.	239.	13004.	7603.	1.86	3.04	15.70	15.72	20.35	.24

TABLE 15.

INDIVIDUAL SAMPLE DATA

LEUDERS LIMESTONE

JACKETED HYDROSTATIC TEST

SAMPLE NUMBER: 50

PRESSURES			STRAINS		ACOUSTIC VELOCITIES		BULK MODULUS		POROSITIES			PERMEABILITY
CONF	AXIAL	PORE	RADIAL	AXIAL	P	S	STAT	DYNA	VOLUME	PORE	TIME	
KPSI	KPSI	KPSI	(10.E-3)XME		FT/SEC	FT/SEC	(10.E6)XPSI		STRAIN	FLUID	AVRG	MD
									PERCENT			
3.04	2.99	2.01	347.	321.	13453.	7123.	1.68	3.70	17.20	17.28	18.72	.43
4.04	3.92	2.01	532.	508.	13700.	7259.	1.76	3.84	17.20	17.24	17.87	.42
6.03	5.77	2.01	892.	814.	13903.	7355.	1.94	3.96	17.10	17.18	17.19	.41
8.03	7.55	2.01	1244.	1082.	14027.	7434.	2.15	4.02	17.00	17.12	16.79	.40
10.05	9.26	2.00	1580.	1339.	14118.	7495.	2.43	4.07	16.90	17.08	16.50	.40
8.05	7.76	2.01	1274.	1149.	14009.	7426.	2.38	4.01	17.00	17.12	16.85	.40
6.04	5.82	2.00	931.	899.	13860.	7340.	1.95	3.93	17.10	17.17	17.34	.40
4.02	3.92	2.01	569.	589.	13666.	7213.	1.65	3.84	17.20	17.23	17.99	.41
3.04	3.00	2.01	374.	381.	13500.	7085.	1.53	3.77	17.20	17.27	18.56	.41

TABLE 16.

INDIVIDUAL SAMPLE DATA

LEUDERS LIMESTONE

UNIAXIAL COMPACTION TEST

SAMPLE NUMBER: 58

PRESSURES			STRAINS		ACOUSTIC		YOUNGS		POISSONS		UNIAXIAL COMPACTION		POROSITIES			PERMEABILITY
CONF	AXIAL	PORE	RADIAL	AXIAL	VELOCITIES		MODULUS		RATIO		COEFFICIENT		VOLUME	PORE	TIME	
KPSI	KPSI	KPSI	(10.E-3)XME		P	S	STAT	DYNA	STAT	DYNA	STAT	DYNA	STRAIN	FLUID	AVRG	MD
					FT/SEC	FT/SEC	(10.E6)XPSI				(10.E 6)XPSI		PERCENT			
2.26	3.07	2.03	104.	313.	13978.	7576.	3.75	4.87	.253	.292	.221	.156	15.50	15.76	16.95	.23
2.54	4.09	2.02	105.	519.	14069.	7597.	3.67	4.91	.253	.294	.226	.154	15.40	15.70	16.66	.21
3.20	6.06	2.02	108.	959.	14133.	7632.	3.53	4.95	.253	.294	.235	.152	15.30	15.64	16.45	.21
3.93	8.06	2.02	108.	1423.	14135.	7633.	3.39	4.95	.253	.294	.245	.152	15.30	15.60	16.45	.21
4.71	10.07	2.03	112.	1958.	14153.	7634.	3.26	4.96	.253	.295	.254	.152	15.20	15.55	16.39	.20
4.10	8.01	2.02	109.	1709.	14087.	7606.	5.35	4.92	.243	.294	.158	.153	15.50	15.59	16.60	.20
3.43	6.05	2.02	110.	1310.	13981.	7541.	3.76	4.84	.243	.295	.224	.156	15.40	15.62	16.94	.20
2.69	4.06	2.02	108.	829.	13777.	7468.	2.90	4.73	.243	.292	.291	.160	15.40	15.67	17.61	.20
2.44	3.06	2.01	105.	541.	13625.	7441.	2.61	4.68	.243	.287	.324	.164	15.50	15.70	18.12	.20

TABLE 17.

INDIVIDUAL SAMPLE DATA

LEUDERS LIMESTONE

UNIAXIAL COMPACTION TEST

SAMPLE NUMBER: 53

PRESSURES			STRAINS		ACOUSTIC		YOUNGS		POISSONS		UNIAXIAL COMPACTION		POROSITIES			PERMEABILITY
CONF	AXIAL	PORE	RADIAL	AXIAL	VELOCITIES		MODULUS		RATIO		COEFFICIENT		VOLUME	PORE	TIME	
KPSI	KPSI	KPSI	(10.E-3)XME		P	S	STAT	DYNA	STAT	DYNA	STAT	DYNA	STRAIN	FLUID	AVRG	MD
					FT/SEC	FT/SEC	(10.E6)XPSI				(10.E 6)XPSI		PERCENT	PERCENT		
2.18	2.97	2.02	122.	291.	13845.	7230.	3.38	4.49	.226	.313	.257	.159	16.90	17.26	17.38	.31
2.39	3.99	2.01	123.	560.	13874.	7313.	3.38	4.58	.226	.308	.257	.159	16.90	17.20	17.29	.31
2.95	5.95	2.01	123.	1080.	14011.	7401.	3.38	4.69	.226	.306	.256	.156	16.80	17.14	16.84	.30
3.62	7.98	2.00	128.	1582.	14116.	7393.	3.39	4.69	.226	.311	.256	.153	16.80	17.10	16.51	.29
4.31	9.94	2.01	128.	2090.	14136.	7409.	3.39	4.71	.226	.311	.256	.153	16.90	17.06	16.44	.29
3.79	7.96	2.01	130.	1836.	14001.	7328.	4.85	4.61	.219	.311	.181	.156	17.10	17.10	16.87	.29
3.12	5.97	2.01	126.	1364.	13821.	7241.	3.51	4.50	.219	.311	.250	.160	16.90	17.13	17.46	.29
2.63	3.97	2.00	125.	802.	13551.	7080.	2.75	4.31	.219	.312	.319	.166	16.80	17.19	18.38	.29
2.31	2.97	2.01	123.	460.	13382.	7032.	2.48	4.24	.219	.309	.354	.171	16.90	17.23	18.97	.29

TABLE 18.

BEREA SANDSTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	YOUNGS MODULUS STATIC	STANDARD DEVIATION	YOUNGS MODULUS DYNAMIC	STANDARD DEVIATION
KPSI	KPSI	KPSI	(10.E6)PSI	(10.E6)PSI	(10.E6)PSI	(10.E6)PSI
.....						
.19	1.00	0.00	1.38	.42	3.47	.03
.38	2.00	0.00	1.88	.62	3.86	.19
.75	4.00	0.00	2.53	.90	3.04	2.58
1.13	6.00	0.00	2.99	1.12	4.37	.18
1.51	8.00	0.00	3.35	1.32	4.51	.27
1.48	8.00	0.00	4.23	1.34	4.38	.33
1.11	6.00	0.00	3.56	1.02	4.18	.40
.74	4.00	0.00	2.81	.72	3.97	.45
.37	2.00	0.00	1.91	.41	3.97	.45
.18	1.00	0.00	1.31	.25	3.97	.45

TABLE 19.

BEREA SANDSTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	YOUNGS MODULUS STATIC	STANDARD DEVIATION	YOUNGS MODULUS DYNAMIC	STANDARD DEVIATION
KPSI	KPSI	KPSI	(10.E6)PSI	(10.E6)PSI	(10.E6)PSI	(10.E6)PSI
2.18	3.00	2.00	1.33	.07		
2.36	4.00	2.00	1.68	.06		
2.71	6.00	2.00	2.46	.05	4.41	.01
3.07	8.00	2.00	3.39	.06	4.43	.28
3.42	10.00	2.00	4.56	.07	4.40	.16
3.44	10.00	2.00	8.00	.17	4.30	.07
3.08	8.00	2.00	4.58	.11	4.30	.07
2.72	6.00	2.00	2.81	.08	4.30	.07
2.36	4.00	2.00	1.71	.07	4.30	.07
2.18	3.00	2.00	1.28	.07	4.30	.07

TABLE 20.

LEUDERS LIMESTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	YOUNGS MODULUS STATIC	STANDARD DEVIATION	YOUNGS MODULUS DYNAMIC	STANDARD DEVIATION
KPSI	KPSI	KPSI	(10.E6)PSI	(10.E6)PSI	(10.E6)PSI	(10.E6)PSI
.....						
.32	1.00	0.00	3.07	.39	4.38	.60
.64	2.00	0.00	3.14	.45	4.36	.54
1.28	4.00	0.00	3.30	.58	4.55	.51
1.92	6.00	0.00	3.47	.73	4.66	.50
2.55	8.00	0.00	3.66	.92	4.72	.53
2.49	8.00	0.00	5.76	2.43	4.63	.55
1.87	6.00	0.00	4.22	1.17	4.53	.53
1.24	4.00	0.00	3.33	.65	4.34	.55
.62	2.00	0.00	2.75	.39	4.73	1.25
.31	1.00	0.00	2.53	.31	4.73	1.25

TABLE 21.

LEUDERS LIMESTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	YOUNGS MODULUS STATIC	STANDARD DEVIATION	YOUNGS MODULUS DYNAMIC	STANDARD DEVIATION
KPSI	KPSI	KPSI	(10.E6)PSI	(10.E6)PSI	(10.E6)PSI	(10.E6)PSI
2.29	3.00	2.00	3.52	.28	4.68	.28
2.58	4.00	2.00	3.44	.15	4.69	.27
3.16	6.00	2.00	3.30	.07	4.80	.15
3.74	8.00	2.00	3.17	.05	4.81	.16
4.32	10.00	2.00	3.05	.03	4.81	.16
4.45	10.00	2.00	6.63	.01	4.75	.18
3.84	8.00	2.00	4.48	.01	4.66	.18
3.23	6.00	2.00	3.38	.01	4.53	.22
2.61	4.00	2.00	2.72	.01	4.45	.24
2.31	3.00	2.00	2.48	.01	4.45	.24

TABLE 22.

BEREA SANDSTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	POISSONS RATIO STATIC	STANDARD DEVIATION	POISSONS RATIO DYNAMIC	STANDARD DEVIATION
KPSI	KPSI	KPSI				
.....						
.19	1.00	0.00	.16	.02	.26	.02
.38	2.00	0.00	.16	.02	.26	.04
.75	4.00	0.00	.16	.02	.36	.28
1.13	6.00	0.00	.16	.02	.25	.03
1.51	8.00	0.00	.16	.02	.25	.05
1.48	8.00	0.00	.16	.02	.25	.05
1.11	6.00	0.00	.16	.02	.26	.07
.74	4.00	0.00	.16	.02	.25	.08
.37	2.00	0.00	.16	.02	.25	.08
.18	1.00	0.00	.16	.02	.25	.08

TABLE 23.

BEREA SANDSTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	POISSONS RATIO STATIC	STANDARD DEVIATION	POISSONS RATIO DYNAMIC	STANDARD DEVIATION
KPSI	KPSI	KPSI				
2.18	3.00	2.00	.15	.00		
2.36	4.00	2.00	.15	.00		
2.71	6.00	2.00	.15	.00	.23	.01
3.07	8.00	2.00	.15	.00	.24	.04
3.42	10.00	2.00	.15	.00	.25	.03
3.44	10.00	2.00	.15	.00	.25	.02
3.08	8.00	2.00	.15	.00	.25	.02
2.72	6.00	2.00	.15	.00	.25	.02
2.36	4.00	2.00	.15	.00	.25	.02
2.18	3.00	2.00	.15	.00	.25	.02

TABLE 24.

LEUDERS LIMESTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	POISSONS RATIO STATIC	STANDARD DEVIATION	POISSONS RATIO DYNAMIC	STANDARD DEVIATION
KPSI	KPSI	KPSI				
.....						
.32	1.00	0.00	.24	.01	.28	.10
.64	2.00	0.00	.24	.01	.29	.09
1.28	4.00	0.00	.24	.01	.29	.08
1.92	6.00	0.00	.24	.01	.29	.07
2.55	8.00	0.00	.24	.01	.29	.07
2.49	8.00	0.00	.24	.01	.29	.08
1.87	6.00	0.00	.24	.01	.29	.09
1.24	4.00	0.00	.24	.01	.29	.09
.62	2.00	0.00	.24	.01	.24	.20
.31	1.00	0.00	.24	.01	.24	.20

TABLE 25.

LEUDERS LIMESTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE KPSI	AXIAL STRESS KPSI	PORE PRESSURE KPSI	POISSONS RATIO STATIC	STANDARD DEVIATION	POISSONS RATIO DYNAMIC	STANDARD DEVIATION
2.29	3.00	2.00	.22	.02	.30	.03
2.58	4.00	2.00	.22	.02	.31	.03
3.16	6.00	2.00	.22	.02	.31	.02
3.74	8.00	2.00	.22	.02	.31	.02
4.32	10.00	2.00	.22	.02	.31	.02
4.45	10.00	2.00	.23	.00	.31	.03
3.84	8.00	2.00	.23	.00	.31	.03
3.23	6.00	2.00	.23	.00	.30	.03
2.61	4.00	2.00	.23	.00	.30	.04
2.31	3.00	2.00	.23	.00	.30	.04

TABLE 26.

BEREA SANDSTONE
JACKETED HYDROSTATIC TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	BULK MODULUS STATIC	STANDARD DEVIATION	BULK MODULUS DYNAMIC	STANDARD DEVIATION
KPSI	KPSI	KPSI	(10.E6)PSI	(10.E6)PSI	(10.E6)PSI	(10.E6)PSI
1.00	1.00	0.00	.81	.13	1.94	.33
2.00	2.00	0.00	1.13	.20	2.32	.38
4.00	4.00	0.00	1.54	.31	2.64	.30
6.00	6.00	0.00	1.85	.40	2.73	.31
8.00	8.00	0.00	2.10	.48	2.79	.38
8.00	8.00	0.00	2.24	.77	2.75	.29
6.00	6.00	0.00	1.97	.63	2.70	.36
4.00	4.00	0.00	1.64	.48	2.52	.57
2.00	2.00	0.00	1.18	.30	2.17	.80
1.00	1.00	0.00	.85	.19	2.17	.80

TABLE 27.

BEREA SANDSTONE
JACKETED HYDROSTATIC TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	BULK MODULUS STATIC	STANDARD DEVIATION	BULK MODULUS DYNAMIC	STANDARD DEVIATION
KPSI	KPSI	KPSI	(10.E6)PSI	(10.E6)PSI	(10.E6)PSI	(10.E6)PSI
3.00	3.00	2.00	.82	.04		
4.00	4.00	2.00	1.02	.03	2.15	.72
6.00	6.00	2.00	1.44	.03	2.46	1.26
8.00	8.00	2.00	1.92	.03	2.52	1.20
10.00	10.00	2.00	2.48	.03	2.57	1.20
10.00	10.00	2.00	3.16	.07	2.47	1.03
8.00	8.00	2.00	2.20	.05	2.41	.89
6.00	6.00	2.00	1.52	.05		
4.00	4.00	2.00	1.00	.04		
3.00	3.00	2.00	.78	.05		

TABLE 28.

LEUDERS LIMESTONE
JACKETED HYDROSTATIC TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	BULK MODULUS STATIC	STANDARD DEVIATION	BULK MODULUS DYNAMIC	STANDARD DEVIATION
KPSI	KPSI	KPSI	(10.E6)PSI	(10.E6)PSI	(10.E6)PSI	(10.E6)PSI
1.00	1.00	0.00	1.81	.27	3.64	.63
2.00	2.00	0.00	1.88	.31	3.64	.58
4.00	4.00	0.00	2.01	.42	3.73	.54
6.00	6.00	0.00	2.18	.56	3.81	.55
8.00	8.00	0.00	2.37	.73	3.84	.54
8.00	8.00	0.00	3.01	1.57	3.79	.58
6.00	6.00	0.00	2.40	.87	3.76	.55
4.00	4.00	0.00	1.99	.52	3.64	.60
2.00	2.00	0.00	1.71	.32	3.55	.62
1.00	1.00	0.00	1.59	.25	3.55	.62

TABLE 29.

LEUDERS LIMESTONE
JACKETED HYDROSTATIC TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	BULK MODULUS STATIC	STANDARD DEVIATION	BULK MODULUS DYNAMIC	STANDARD DEVIATION
KPSI	KPSI	KPSI	(10.E6)PSI	(10.E6)PSI	(10.E6)PSI	(10.E6)PSI
3.00	3.00	2.00	1.87	.02	3.47	1.09
4.00	4.00	2.00	1.94	.02	3.56	1.01
6.00	6.00	2.00	2.08	.01	3.64	1.03
8.00	8.00	2.00	2.25	.01	3.71	1.06
10.00	10.00	2.00	2.45	.01	3.76	1.06
10.00	10.00	2.00	3.32	.04	3.71	.98
8.00	8.00	2.00	2.56	.04	3.63	1.07
6.00	6.00	2.00	2.08	.04	3.55	1.03
4.00	4.00	2.00	1.76	.06	3.46	1.03
3.00	3.00	2.00	1.63	.09	3.46	1.03

TABLE 30.

BEREA SANDSTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	UNIAXIAL COMPACTION COEFFECIENT STATIC (10E-6)/PSI	STANDARD DEVIATION (10E-6)/PSI	UNIAXIAL COMPACTION COEFFECIENT DYNAMIC (10E-6)/PSI	STANDARD DEVIATION (10E-6)/PSI
KPSI	KPSI	KPSI				
.....						
.19	1.00	0.00	.68	.20	.23	.03
.38	2.00	0.00	.50	.16	.21	.06
.75	4.00	0.00	.37	.13	.20	.68
1.13	6.00	0.00	.31	.12	.19	.05
1.51	8.00	0.00	.28	.11	.19	.06
1.48	8.00	0.00	.22	.07	.19	.08
1.11	6.00	0.00	.26	.08	.20	.10
.74	4.00	0.00	.34	.08	.21	.12
.37	2.00	0.00	.49	.10	.21	.12
.18	1.00	0.00	.72	.13	.21	.12

TABLE 31.

BEREA SANDSTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	UNIAXIAL COMPACTION COEFFECIENT STATIC (10E-6)/PSI	STANDARD DEVIATION (10E-6)/PSI	UNIAXIAL COMPACTION COEFFECIENT DYNAMIC (10E-6)/PSI	STANDARD DEVIATION (10E-6)/PSI
KPSI	KPSI	KPSI				
2.18	3.00	2.00	.71	.04		
2.36	4.00	2.00	.56	.02		
2.71	6.00	2.00	.38	.01	.20	.01
3.07	8.00	2.00	.28	.00	.19	.06
3.42	10.00	2.00	.21	.00	.19	.05
3.44	10.00	2.00	.12	.00	.19	.03
3.08	8.00	2.00	.21	.00	.19	.03
2.72	6.00	2.00	.34	.01	.19	.03
2.36	4.00	2.00	.55	.02	.19	.03
2.18	3.00	2.00	.74	.04	.19	.03

TABLE 32.

LEUDERS LIMESTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	UNIAXIAL COMPACTION COEFFECIENT STATIC	STANDARD DEVIATION	UNIAXIAL COMPACTION COEFFECIENT DYNAMIC	STANDARD DEVIATION
KPSI	KPSI	KPSI	(10E-6)/PSI	(10E-6)/PSI	(10E-6)/PSI	(10E-6)/PSI
.....						
.32	1.00	0.00	.28	.03	.18	.16
.64	2.00	0.00	.27	.04	.17	.14
1.28	4.00	0.00	.26	.04	.17	.13
1.92	6.00	0.00	.24	.05	.16	.12
2.55	8.00	0.00	.23	.06	.16	.12
2.49	8.00	0.00	.15	.06	.17	.13
1.87	6.00	0.00	.20	.06	.17	.14
1.24	4.00	0.00	.26	.05	.18	.15
.62	2.00	0.00	.31	.04	.18	.26
.31	1.00	0.00	.34	.04	.18	.26

TABLE 33.

LEUDERS LIMESTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	UNIAXIAL COMPACTION COEFFECIENT STATIC	STANDARD DEVIATION	UNIAXIAL COMPACTION COEFFECIENT DYNAMIC	STANDARD DEVIATION
KPSI	KPSI	KPSI	(10E-6)/PSI	(10E-6)/PSI	(10E-6)/PSI	(10E-6)/PSI
2.29	3.00	2.00	.25	.02	.16	.06
2.58	4.00	2.00	.25	.01	.15	.06
3.16	6.00	2.00	.26	.01	.15	.04
3.74	8.00	2.00	.27	.00	.15	.04
4.32	10.00	2.00	.29	.00	.15	.04
4.45	10.00	2.00	.13	.00	.15	.04
3.84	8.00	2.00	.19	.00	.16	.05
3.23	6.00	2.00	.25	.00	.16	.06
2.61	4.00	2.00	.31	.00	.17	.06
2.31	3.00	2.00	.35	.00	.17	.06

TABLE 34.

BEREA SANDSTONE
JACKETED HYDROSTATIC TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	POROSITY DISPLACED VOLUME	STANDARD DEVIATION	VOLUME STRAIN	POROSITY STANDARD DEVIATION PERCENT	TIME AVERAG	POROSITY STANDARD DEVIATION
KPSI	KPSI	KPSI						
1.00	1.00	0.00	19.40	.24	19.86	.97	23.20	.41
2.00	2.00	0.00	19.18	.36	19.67	.68	20.12	.35
4.00	4.00	0.00	19.21	.25	19.29	.58	17.72	.22
6.00	6.00	0.00	19.13	.25	18.91	.54	16.77	.21
8.00	8.00	0.00	19.06	.25	18.53	.52	16.24	.29
8.00	8.00	0.00	19.11	.25	18.54	.85	16.62	.22
6.00	6.00	0.00	19.17	.25	18.92	.88	17.26	.30
4.00	4.00	0.00	19.25	.25	19.29	.92	18.98	.30
2.00	2.00	0.00	19.35	.24	19.65	1.03	21.39	.41
1.00	1.00	0.00			19.83	1.27		

TABLE 35.

BEREA SANDSTONE
JACKETED HYDROSTATIC TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	POROSITY		POROSITY		POROSITY	
			DISPLACED	STANDARD	VOLUME	STANDARD	TIME	STANDARD
KPSI	KPSI	KPSI	VOLUME	DEVIATION	STRAIN	DEVIATION PERCENT	AVERAG	DEVIATION
3.00	3.00	2.00	19.87	.18	19.80	1.89	23.70	.57
4.00	4.00	2.00	19.80	.19	19.71	1.22	21.49	1.12
6.00	6.00	2.00	19.70	.19	19.58	.79	19.42	1.06
8.00	8.00	2.00	19.62	.19	19.48	.63	18.48	.93
10.00	10.00	2.00	19.59	.21	19.41	.54	17.90	.90
10.00	10.00	2.00	19.65	.22	19.41	.84	18.86	.84
8.00	8.00	2.00	19.71	.22	19.48	.95	19.66	.77
6.00	6.00	2.00	19.74	.20	19.57	1.17	32.38	26.23
4.00	4.00	2.00	19.81	.20	19.70	1.76	23.00	1.02
3.00	3.00	2.00			19.79	2.70		

TABLE 36.

BEREA SANDSTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	POROSITY		POROSITY		POROSITY	
			DISPLACED	STANDARD	VOLUME	STANDARD	TIME	STANDARD
KPSI	KPSI	KPSI	VOLUME	DEVIATION	STRAIN	DEVIATION	AVERAG	DEVIATION
						PERCENT		
.....								
.19	1.00	0.00	19.58	.19	19.92	2.16	22.90	.63
.38	2.00	0.00	19.53	.15	19.82	1.23	20.39	.51
.75	4.00	0.00	19.41	.14	19.62	1.00	18.39	.38
1.13	6.00	0.00	19.34	.13	19.42	.94	17.46	.31
1.51	8.00	0.00	19.27	.16	19.21	.90	16.85	.29
1.48	8.00	0.00	19.30	.16	19.02	.68	17.31	.31
1.11	6.00	0.00	19.35	.16	19.27	.70	18.09	.39
.74	4.00	0.00	19.43	.16	19.52	.73	19.80	.54
.37	2.00	0.00	19.48	.11	19.77	.84	21.68	.70
.18	1.00	0.00			19.89	1.15		

TABLE 37.

BEREA SANDSTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	POROSITY		POROSITY		POROSITY	
			DISPLACED	STANDARD	VOLUME	STANDARD	TIME	STANDARD
KPSI	KPSI	KPSI	VOLUME	DEVIATION	STRAIN	DEVIATION	AVERAG	DEVIATION
						PERCENT		
2.18	3.00	2.00	20.09	.23	19.85	1.18	21.91	.66
2.36	4.00	2.00	19.99	.21	19.80	.82	19.71	.39
2.71	6.00	2.00	19.89	.21	19.72	.56	18.26	.17
3.07	8.00	2.00	19.82	.21	19.67	.46	17.49	.21
3.42	10.00	2.00	19.77	.21	19.62	.40	17.22	.36
3.44	10.00	2.00	19.81	.21	19.63	.68	17.76	.46
3.08	8.00	2.00	19.86	.22	19.65	.74	18.69	.73
2.72	6.00	2.00	19.94	.23	19.70	.87	20.28	.91
2.36	4.00	2.00	20.02	.23	19.77	1.19	21.36	.33
2.18	3.00	2.00			19.82	1.63		

TABLE 38.

LEUDERS LIMESTONE
JACKETED HYDROSTATIC TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	POROSITY		POROSITY		POROSITY	
KPSI	KPSI	KPSI	DISPLACED VOLUME	STANDARD DEVIATION	VOLUME STRAIN	STANDARD DEVIATION PERCENT	TIME AVERAG	STANDARD DEVIATION
1.00	1.00	0.00	16.66	.55	16.87	.54	18.64	.73
2.00	2.00	0.00	16.60	.49	16.87	.85	18.33	.66
4.00	4.00	0.00	16.54	.52	16.88	1.19	17.70	.58
6.00	6.00	0.00	16.49	.52	16.88	1.37	17.28	.52
8.00	8.00	0.00	16.43	.51	16.88	1.48	17.06	.48
8.00	8.00	0.00	16.45	.51	16.88	2.11	17.35	.52
6.00	6.00	0.00	16.49	.52	16.88	2.12	17.66	.53
4.00	4.00	0.00	16.53	.53	16.88	2.13	18.38	.64
2.00	2.00	0.00	16.50	.59	16.87	2.16	18.95	.73
1.00	1.00	0.00			16.87	2.24		

TABLE 39.

LEUDERS LIMESTONE
JACKETED HYDROSTATIC TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	POROSITY DISPLACED VOLUME	POROSITY STANDARD DEVIATION	POROSITY VOLUME STRAIN	POROSITY STANDARD DEVIATION PERCENT	POROSITY TIME AVERAG	POROSITY STANDARD DEVIATION
KPSI	KPSI	KPSI						
3.00	3.00	2.00	16.96	.80	16.79	.43	19.05	.62
4.00	4.00	2.00	16.92	.79	16.75	.27	18.38	.68
6.00	6.00	2.00	16.86	.79	16.67	.16	17.82	.68
8.00	8.00	2.00	16.81	.79	16.59	.11	17.40	.70
10.00	10.00	2.00	16.76	.78	16.52	.09	17.09	.66
10.00	10.00	2.00	16.81	.78	16.52	.43	17.45	.62
8.00	8.00	2.00	16.86	.78	16.58	.51	17.90	.65
6.00	6.00	2.00	16.92	.78	16.65	.69	18.52	.68
4.00	4.00	2.00	17.26	.56	16.74	1.16	19.05	.62
3.00	3.00	2.00			16.79	1.87		

TABLE 40.

LEUDERS LIMESTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	POROSITY DISPLACED VOLUME	POROSITY STANDARD DEVIATION	POROSITY VOLUME STRAIN	POROSITY STANDARD DEVIATION PERCENT	POROSITY TIME AVERAG	POROSITY STANDARD DEVIATION
KPSI	KPSI	KPSI						
.32	1.00	0.00	16.71	.59	16.88	.10	20.32	1.16
.64	2.00	0.00	16.64	.59	16.88	.18	19.52	1.03
1.28	4.00	0.00	16.59	.59	16.88	.35	18.64	.87
1.92	6.00	0.00	16.55	.59	16.88	.49	18.09	.75
2.55	8.00	0.00	16.53	.59	16.88	.62	17.85	.74
2.49	8.00	0.00	16.54	.59	16.88	.51	18.28	.88
1.87	6.00	0.00	16.54	.59	16.88	.48	18.98	1.11
1.24	4.00	0.00	16.59	.60	16.88	.42	19.65	1.06
.62	2.00	0.00	16.57	.51	16.87	.31	20.36	1.23
.31	1.00	0.00			16.87	.20		

TABLE 41.

LEUDERS LIMESTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE	AXIAL STRESS	PORE PRESSURE	POROSITY		POROSITY		POROSITY	
			DISPLACED VOLUME	STANDARD DEVIATION	VOLUME STRAIN	STANDARD DEVIATION PERCENT	TIME AVERAG	STANDARD DEVIATION
KPSI	KPSI	KPSI						
2.29	3.00	2.00	16.73	.59	16.83	1.36	17.16	.24
2.58	4.00	2.00	16.67	.55	16.81	.91	16.71	.36
3.16	6.00	2.00	16.57	.58	16.76	.54	16.41	.30
3.74	8.00	2.00	16.52	.58	16.72	.38	16.31	.28
4.32	10.00	2.00	16.48	.58	16.67	.29	16.27	.28
4.45	10.00	2.00	16.60	.54	16.67	.03	16.64	.32
3.84	8.00	2.00	16.69	.55	16.70	.04	17.06	.34
3.23	6.00	2.00	16.87	.63	16.73	.05	17.78	.43
2.61	4.00	2.00	17.02	.78	16.78	.07	18.33	.45
2.31	3.00	2.00			16.81	.11		

TABLE 42.

BEREA SANDSTONE
JACKETED HYDROSTATIC TESTS

CONFINING PRESSURE KPSI	AXIAL STRESS KPSI	PORE PRESSURE KPSI	PERMEABILITY MD	STANDARD DEVIATION MD
1.00	1.00	0.00	66.	6.
2.00	2.00	0.00	62.	9.
4.00	4.00	0.00	58.	10.
6.00	6.00	0.00	56.	11.
8.00	8.00	0.00	56.	12.
8.00	8.00	0.00	55.	12.
6.00	6.00	0.00	55.	12.
4.00	4.00	0.00	55.	13.
2.00	2.00	0.00	56.	13.
1.00	1.00	0.00		

TABLE 43.

BEREA SANDSTONE
JACKETED HYDROSTATIC TESTS

CONFINING PRESSURE KPSI	AXIAL STRESS KPSI	PORE PRESSURE KPSI	PERMEABILITY MD	STANDARD DEVIATION MD
3.00	3.00	2.00	91.	5.
4.00	4.00	2.00	88.	7.
6.00	6.00	2.00	82.	4.
8.00	8.00	2.00	78.	7.
10.00	10.00	2.00	73.	5.
10.00	10.00	2.00	77.	8.
8.00	8.00	2.00	79.	6.
6.00	6.00	2.00	81.	5.
4.00	4.00	2.00	80.	2.
3.00	3.00	2.00		

TABLE 44.

BEREA SANDSTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE KPSI	AXIAL STRESS KPSI	PORE PRESSURE KPSI	PERMEABILITY MD	STANDARD DEVIATION MD
.....				
.19	1.00	0.00	64.	12.
.38	2.00	0.00	68.	12.
.75	4.00	0.00	64.	10.
1.13	6.00	0.00	63.	10.
1.51	8.00	0.00	63.	10.
1.48	8.00	0.00	62.	10.
1.11	6.00	0.00	63.	10.
.74	4.00	0.00	62.	10.
.37	2.00	0.00	59.	13.
.18	1.00	0.00		

TABLE 45.

BEREA SANDSTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE KPSI	AXIAL STRESS KPSI	PORE PRESSURE KPSI	PERMEABILITY MD	STANDARD DEVIATION MD
-------------------------------	-------------------------	--------------------------	--------------------	-----------------------------

.....

2.18	3.00	2.00	83.	7.
2.36	4.00	2.00	80.	6.
2.71	6.00	2.00	80.	2.
3.07	8.00	2.00	78.	3.
3.42	10.00	2.00	77.	3.
3.44	10.00	2.00	76.	2.
3.08	8.00	2.00	78.	0.
2.72	6.00	2.00	78.	0.
2.36	4.00	2.00	79.	1.
2.18	3.00	2.00		

TABLE 46.

LEUDERS LIMESTONE
JACKETED HYDROSTATIC TESTS

CONFINING PRESSURE KPSI	AXIAL STRESS KPSI	PORE PRESSURE KPSI	PERMEABILITY MD	STANDARD DEVIATION MD
.....				
1.00	1.00	0.00	.33	.080
2.00	2.00	0.00	.32	.083
4.00	4.00	0.00	.30	.081
6.00	6.00	0.00	.30	.084
8.00	8.00	0.00	.29	.085
8.00	8.00	0.00	.30	.083
6.00	6.00	0.00	.30	.084
4.00	4.00	0.00	.30	.080
2.00	2.00	0.00	.31	.082
1.00	1.00	0.00		

TABLE 47.

LEUDERS LIMESTONE
JACKETED HYDROSTATIC TESTS

CONFINING PRESSURE KPSI	AXIAL STRESS KPSI	PORE PRESSURE KPSI	PERMEABILITY MD	STANDARD DEVIATION MD
3.00	3.00	2.00	.44	.146
4.00	4.00	2.00	.42	.141
6.00	6.00	2.00	.41	.143
8.00	8.00	2.00	.40	.139
10.00	10.00	2.00	.39	.135
10.00	10.00	2.00	.39	.135
8.00	8.00	2.00	.39	.135
6.00	6.00	2.00	.40	.132
4.00	4.00	2.00	.41	.149
3.00	3.00	2.00		

TABLE 48.

LEUDERS LIMESTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE KPSI	AXIAL STRESS KPSI	PORE PRESSURE KPSI	PERMEABILITY MD	STANDARD DEVIATION MD
.....				
.32	1.00	0.00	.33	.034
.64	2.00	0.00	.39	.095
1.28	4.00	0.00	.38	.091
1.92	6.00	0.00	.37	.086
2.55	8.00	0.00	.35	.090
2.49	8.00	0.00	.36	.090
1.87	6.00	0.00	.36	.093
1.24	4.00	0.00	.36	.097
.62	2.00	0.00	.35	.081
.31	1.00	0.00		

TABLE 49.

LEUDERS LIMESTONE
UNIAXIAL COMPACTION TESTS

CONFINING PRESSURE KPSI	AXIAL STRESS KPSI	PORE PRESSURE KPSI	PERMEABILITY MD	STANDARD DEVIATION MD
2.29	3.00	2.00	.32	.071
2.58	4.00	2.00	.28	.079
3.16	6.00	2.00	.28	.080
3.74	8.00	2.00	.29	.068
4.32	10.00	2.00	.28	.067
4.45	10.00	2.00	.28	.065
3.84	8.00	2.00	.28	.069
3.23	6.00	2.00	.29	.066
2.61	4.00	2.00	.28	.075
2.31	3.00	2.00		

2. FIGURES

FIGURE 1

BLOCK DIAGRAM OF THE SYSTEM

Pressure Vessel

SPS

A View of the SPS and the Pressure Vessel

Figure 2.

FIGURE 4
JACKET

FIGURE 5.

FIGURE 6.

CYCLED UNIAxIAL COMPACTION TEST ON LEUDERS LIMESTONE

FIGURE 7

FIGURE 8

JACKETED HYDROSTATIC TEST

BEREA SANDSTONE

SAMPLE NO. 21

FIGURE 9

ATMOSPHERIC PORE PRESSURE

JACKETED HYDROSTATIC TEST

BEREA SANDSTONE

SAMPLE NO.03

FIGURE 10

ATMOSPHERIC PORE PRESSURE

UNIAXIAL COMPACTION TEST

BEREA SANDSTONE

SAMPLE NO. 18

FIGURE 11

ATMOSPHERIC PORE PRESSURE

UNIAXIAL COMPACTION TEST

BEREA SANDSTONE

SAMPLE NO. 15

FIGURE 12

ATMOSPHERIC PORE PRESSURE

JACKETED HYDROSTATIC TEST

BEREA SANDSTONE

SAMPLE NO. 44

FIGURE 13

PORE PRESSURE = 2 KPSI

JACKETED HYDROSTATIC TEST

BEREA SANDSTONE

SAMPLE NO. 47

FIGURE 14

PORE PRESSURE = 2 KPSI

UNIAXIAL COMPACTION TEST

BEREA SANDSTONE

SAMPLE NO. 52

FIGURE 15

PORE PRESSURE = 2 KPSI

UNIAXIAL COMPACTION TEST

BEREA SANDSTONE

SAMPLE NO. 42

FIGURE 16

PORE PRESSURE = 2 KPSI

MATRIX COMPRESSIBILITY TEST

BEREA SANDSTONE

SAMPLE NO. 19

FIGURE 17

MATRIX COMPRESSIBILITY TEST

BEREA SANDSTONE

SAMPLE NO. 23

FIGURE 18

JACKETED HYDROSTATIC TEST
LEUDERS LIMESTONE
SAMPLE NO. 10

FIGURE 19

ATMOSPHERIC PORE PRESSURE

JACKETED HYDROSTATIC TEST

LEUDERS LIMESTONE

SAMPLE NO. 30

FIGURE 20

ATMOSPHERIC PORE PRESSURE

UNIAXIAL COMPACTION TEST

LEUDERS LIMESTONE

SAMPLE NO. 18

FIGURE 21

ATMOSPHERIC PORE PRESSURE

UNIAXIAL COMPACTION TEST

LEUDERS LIMESTONE

SAMPLE NO. 19

FIGURE 22

ATMOSPHERIC PORE PRESSURE

MATRIX COMPRESSIBILITY TEST

LEUDERS LIMESTONE

SAMPLE NO. 22

FIGURE 23

MATRIX COMPRESSIBILITY TEST
LEUDERS LIMESTONE
SAMPLE NO. 23

FIGURE 24

JACKETED HYDROSTATIC TEST

LEUDERS LIMESTONE

SAMPLE NO. 52

FIGURE 25

PORE PRESSURE = 2 KPSI

JACKETED HYDROSTATIC TEST
LEUDERS LIMESTONE
SAMPLE NO. 50

FIGURE 26

PORE PRESSURE = 2 KPSI

UNIAXIAL COMPACTION TEST

LEUDERS LIMESTONE

SAMPLE NO. 53

FIGURE 27

PORE PRESSURE = 2 KPSI

UNIAXIAL COMPACTION TEST
LEUDERS LIMESTONE
SAMPLE NO. 58

FIGURE 28

PORE PRESSURE = 2 KPSI

YOUNGS MODULUS

BEREA SANDSTONE

UNIAXIAL COMPACTION TEST

FIGURE 29

LEGEND:

 Δ : $P_o = \text{ATM}$ $\diamond$: $P_o = 2 \text{ Kpsi}$

YOUNGS MODULUS
LEUDERS LIMESTONE
UNIAXIAL COMPACTION TEST

FIGURE 30

LEGEND: $\diamond$: $P_0 = \text{ATM}$
 $\triangle$: $P_0 = 2 \text{ KPSI}$

BULK MODULUS

BEREA SANDSTONE

JACKETED HYDROSTATIC TEST

FIGURE 31

LEGEND:

 Δ : $P_0 = \text{ATM}$ $\diamond$: $P_0 = 2 \text{ KPSI}$

BULK MODULUS

LEUDERS LESTONE

JACKETED HYDROSTATIC TEST

FIGURE 32

LEGEND:

 $\triangle$: $P_0 = \text{ATM}$ $\diamond$: $P_0 = 2\text{KPSI}$

UNIAXIAL COMPACTION COEFFICIENT
BEREA SANDSTONE
UNIAXIAL COMPACTION TEST

FIGURE 33

UNIAXIAL COMPACTION COEFFICIENT
LEUDERS LESTONE
UNIAXIAL COMPACTION TEST

FIGURE 34

POROSITY

BEREA SANDSTONE

JACKETED HYDROSTATIC TEST

FIGURE 35

LEGEND:

Porosity by;

◇ time average

displaced pore volume

△ po = atm

▽ po = 2kpsi

volume strain

△ po = atm

▽ po = 2kpsi

POROSITY

BEREA SANDSTONE

UNIAXIAL COMPACTION TEST

FIGURE 36

LEGEND:

Porosity by;

◇ time average

△ displaced pore volume

△ volume strain

POROSITY

LEUDERS Limestone

JACKETED HYDROSTATIC TEST

FIGURE 37

LEGEND

Porosity by;

◇ time average

△ displaced pore volume
 $P_0 = \text{atm}$
 ▽ $P_0 = 2 \text{ kpsi}$

△ volume strain
 $P_0 = \text{atm}$
 ▽ $P_0 = 2 \text{ kpsi}$

POROSITY

LEUDERS LIMESTONE

UNIAXIAL COMPACTION TEST

FIGURE 38

LEGEND:

Porosity by;

◇ time average

△ displaced pore volume

△ volume strain

PERMEABILITY

BEREA SANDSTONE

JACKETED HYDROSTATIC TEST

FIGURE 39

LEGEND: Δ : $P_o = \text{atm}$
 ∇ : $P_o = 2 \text{ Kpsi}$

PERMEABILITY

BEREA SANDSTONE

UNIAXIAL COMPACTION TEST

FIGURE 40

LEGEND:

 Δ : $P_o = \text{atm}$ ∇ : $P_o = 2\text{Kpsi}$

PERMEABILITY
LEUDERS LIMESTONE
JACKETED HYDROSTATIC TEST

FIGURE 41

PERMEABILITY

LEUDERS LESTONE

UNIAXIAL COMPACTION TEST

FIGURE 42

LEGEND:

Δ : $P_o = \text{atm}$
 ∇ : $P_o = 2 \text{ Kpsi}$

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