UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

FINAL REPORT ON THE PERMEABILITY OF GEOPRESSURED GULF COAST SHALE CORES

by

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Introduction

The purpose of this work has been to determine the permeability of geopressured-geothermal sediments from the DOW Chemical Well Sweezy #1 at simulated in-situ conditions of pressure and water chemistry.

Sample Preparation and Procedure

The samples used in this study were machined into right circular cylinders, 1 inch in diameter and .5 inches long. Porous spacers were placed on either side of the shale to ensure uniform flow of water into or out of the sample. This rock/spacer sandwich was then jacketed in a polyurethane tube, and sealed at the ends to steel plugs, thus isolating the specimen and pore fluid from the confining medium. Figure 1 shows details of this assembly. Hydrostatic confining pressure was held constant by a computer controlled servo-mechanism. Fluid pressure was maintained in the system with a large accumulator connected to the sample outlet. This accumulator could be disconnected to run atmospheric pressure experiments. The pore pressure system was designed to run steady-state flow experiments. On the inlet side of the sample, a small piston intensifier maintained the inlet pore pressure at 10 bars higher than that of the accumulator. As water flowed through the shale in response to this pressure gradient, the intensifier piston advanced to continually force water into the sample and maintain the 10 bar differential.

The flow rate of water was determined by measuring the change in volume of the intensifier reservoir over time. This reservoir has a total volume of 0.25 ml, and can be read to .001 ml. Temperature was held at $27^{\circ} \pm .5^{\circ}C$

throughout the system to ensure accurate pore volume measurements. Pore volume and pressure readings were recorded every 2 seconds on computer tape. Permeability of the samples was calculated using Darcy's Law:

$$k = \frac{q\mu}{A} \left(\frac{dP}{dx}\right)^{-1}$$

where q is the volumetric flow rate, μ is the dynamic viscosity of water, A is the cross sectional area normal to the direction of flow, dP is the pore pressure differential across the sample, and dx is the length of the sample.

Permeability was studied under a variety of conditions. Anisotropy between vertical and horizontal cores was investigated with sample 1, at a number of different confining pressures. The response to changing effective stress was studied with sample 2. Other experiments simulated the in situ conditions of pressure and fluid chemistry at the depth from which these samples were extracted.

Results:

Table 1 lists the experimental conditions and permeability of each sample. In general, the permeabilities of all samples were on the order of a microdarcy. Anisotropy is clearly demonstrated in the results of the horizontal and vertical cores of sample 1, during loading to 1 kilobar and unloading to low pressure (Figure 2). In these experiments, the pore pressure at the inlet was 10 bars, and the samples were vented to the atmosphere at the outlet. The horizontal core, where water flowed along the direction of bedding, was nearly two orders of magnitude more permeable than the vertical core, where water flowed against the bedding. There was a small amount of unrecoverable compaction in the samples after loading to 1 kilobar, thus the unloading permeabilities were consistently lower.

The permeability of sample 2 as a function of pore pressure and effective stress is shown in Figure 3. A confining pressure of 950 bars was chosen to match the in situ overburden pressure at a depth of 13,450 feet. Pore pressure was increased to 850 bars, the hydrostat at that depth. As can be seen in the figure, values ranged between .5 and 3 microdarcies. The sample became more permeable at higher pore pressures or equivalently, with decreasing effective stress.

Samples 6, 9 and 10 were each studied at in situ pressures, with a 1 M NaCl brine pore fluid solution used for 9 and 10. The brine solution approximates the chemistry of the water at the depth of burial. Permeability was again around a microdarcy in all cases and did not seem to depend on the presence of the brine. This may indicate that the fluids were flowing through cracks. If fluids flowed through the bulk of the shale, we might expect some variation in permeability due to the interaction of the brine and the expandable layers of the clay minerals. Where cracks are predominant, the brine would have less contact with the expandable clays, and hence little effect on permeability. These shale samples are not strictly homogeneous but composed of tiny thin lenses along the bedding that may provide easier flow along their interfaces. The flake-like layers become more apparent when the rocks are moistened or machined. There may also be some natural cracks present along shale/silty interfaces that cause higher permeabilities than expected.

Table 1

Sample Number	Depth (ft.)	Sample Orientation	Confining Pressure (bars)	Pore Pressure (bars)	Pore Fluid	Permeability (microdarcy)
1	13412-13412.3	horizontal core	100	10	distilled water	81.1
			300	10	"	41.8
			500	10	"	26.0
			1000	10	"	8.8
			500	10	"	22.2
			300	10	"	24.5
			100	10	"	35.2
1	13412-13412.3	vertical core	100	10	distilled water	1.39
			300	10	"	.83
			500	10	"	.54
			1000	10	"	.18
			500	10	"	.41
			300	10	"	.50
			100	10	"	.82
2	13432-13433	horizontal core	950	50	distilled water	.48
			950	150	"	.53
			950	250	"	.61
			950	350	"	.75
			950	450	"	.85
			950	550	"	1.02
			950	650	"	1.43
			950	750	"	1.89
			950	850	"	3.0
6	13459.6-13460.2	horizontal core	950	856	distilled water	1.65
			950	20	"	.334
			950	805	"	1.073
9	13436.9-13437.6	vertical core	950	850	1 M NaCl	.89
10	13455-13455.8	vertical core	950	850	1 M NaCl	2.0

Figure Captions

Figure 1. Sample assembly.

Figure 2. Permeability of sample 1 as a function of confining pressure. The higher permeability core was cut along the direction of bedding, the lower permeability sample was cut perpendicular to the direction of bedding. Pore pressure was low in these experiments.

Figure 3. Permeability of sample 2 (horizontal core) as a function of pore pressure (bottom axis) and effective stress (top axis). The effective stress is the confining pressure (held constant at 950 bars) minus the pore pressure. Each data point was taken over one day of fluid flow.

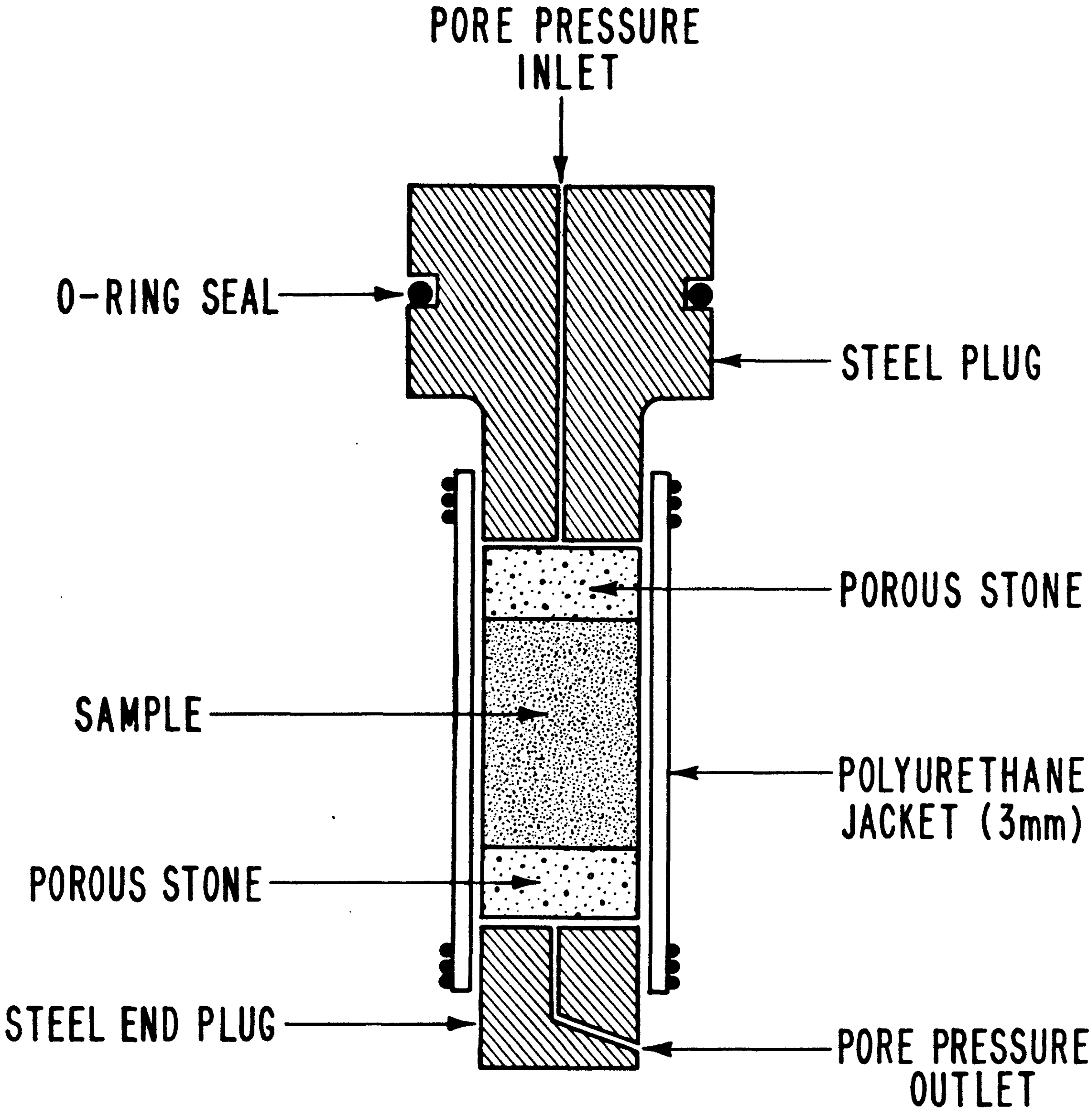
PORE PRESSURE
INLET
O-RING SEAL
STEEL PLUG
POROUS STONE
SAMPLE
POLYURETHANE
JACKET (3mm)
POROUS STONE
STEEL END PLUG
PORE PRESSURE
OUTLET

Figure 1.

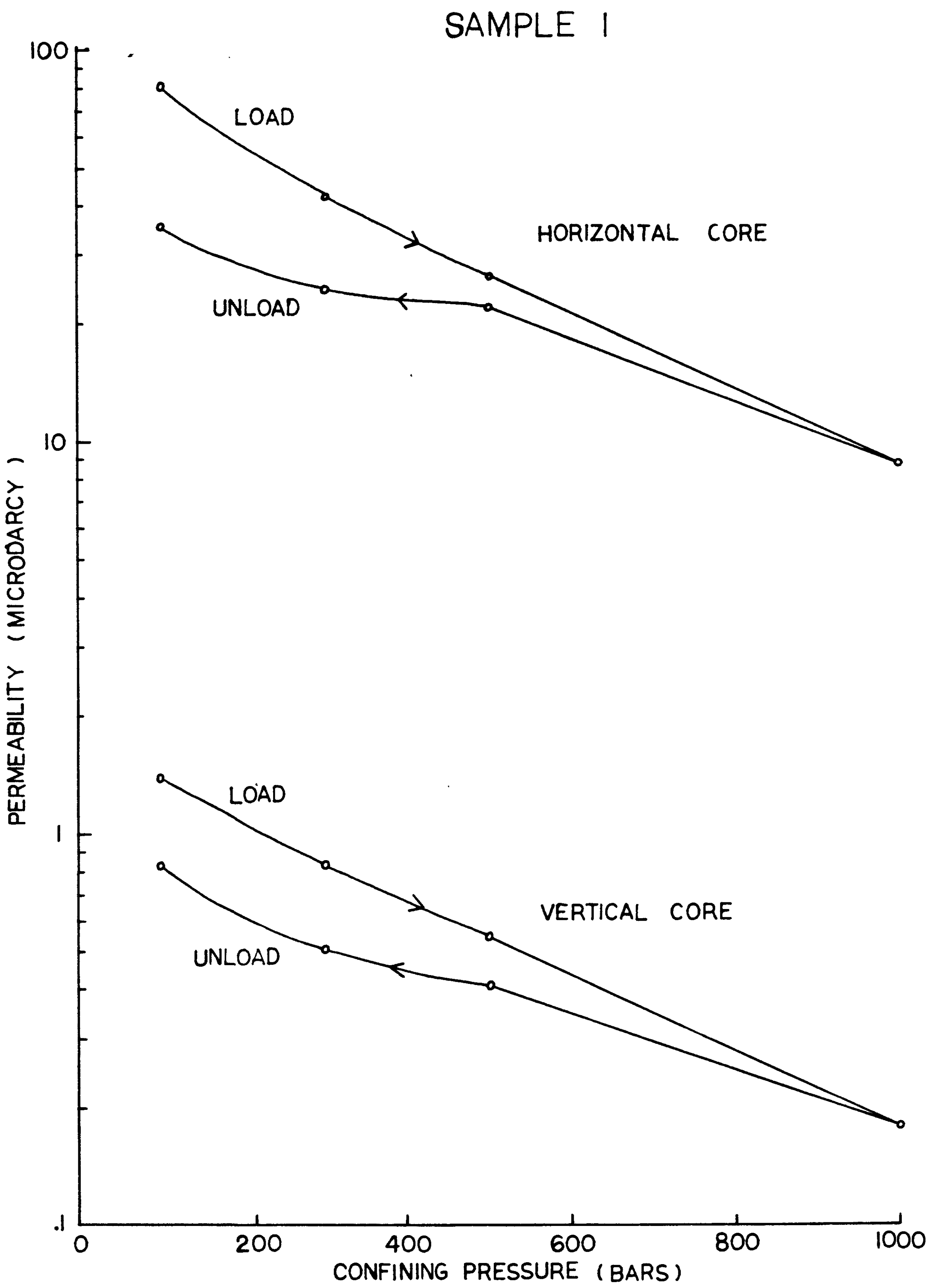
SAMPLE I
100
10
1
.1
PERMEABILITY (MICRODARCY)
LOAD
UNLOAD
HORIZONTAL CORE
LOAD
UNLOAD
VERTICAL CORE
0
200
400
600
800
1000
CONFINING PRESSURE (BARS)

Figure 2.

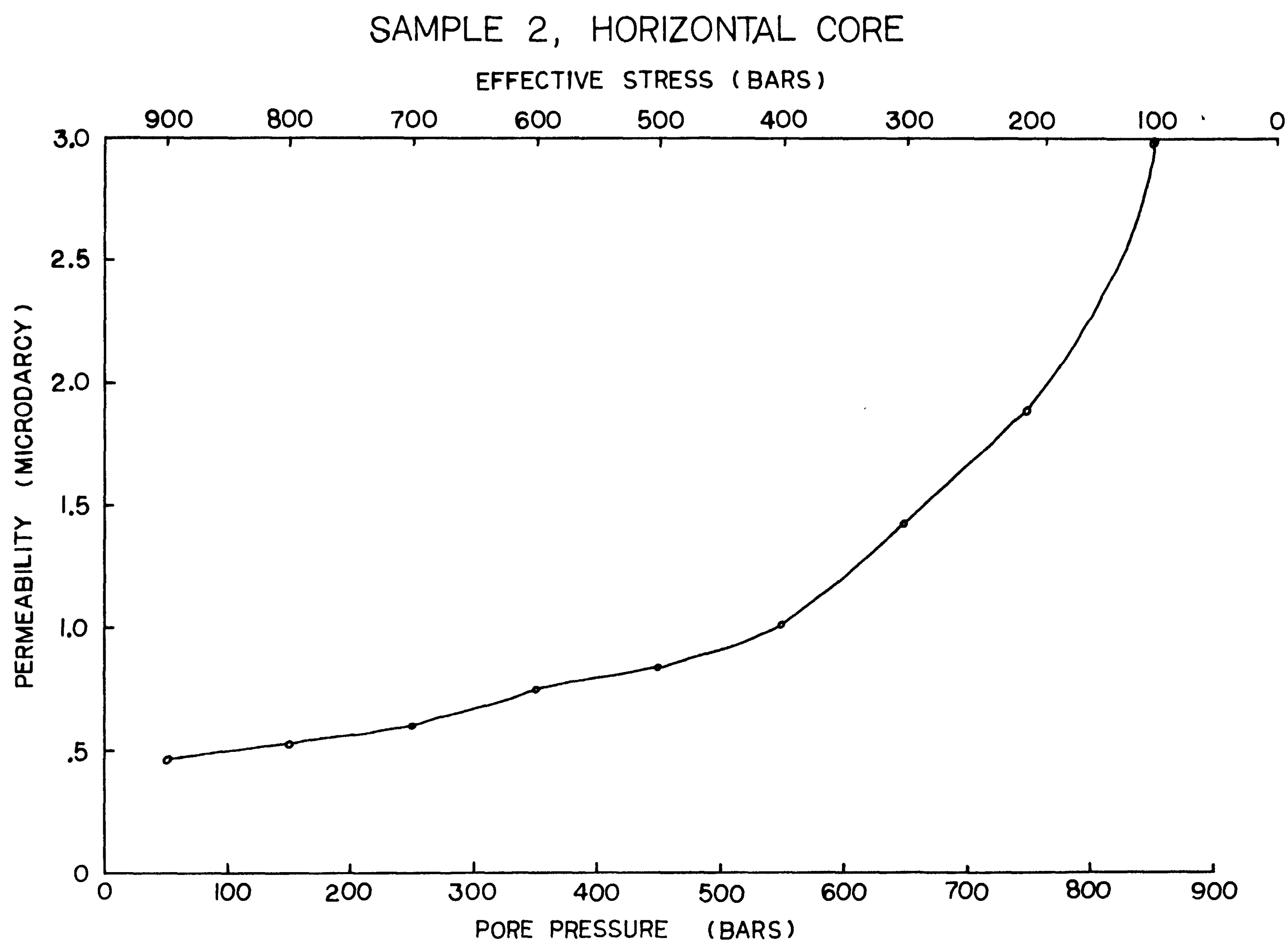
SAMPLE 2, HORIZONTAL CORE
EFFECTIVE STRESS (BARS)
900 800 700 600 500 400 300 200 100 0
3.0 2.5 2.0 1.5 1.0 .5 0
PERMEABILITY (MICRODARCY)
0 100 200 300 400 500 600 700 800 900
PORE PRESSURE (BARS)

Figure 3.