HYDRAULIC CONDUCTIVITY OF SANDSTONE UNDER DIFFERENT CONFINING PRESSURE

by

Banhan Charukalas

Submitted in Partial Fulfillment
of the Requirements for the Degree of
Master of Science in Geology

NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY

Socorro, New Mexico

December, 1975

ACKNOWLEDGEMENTS

The writer wishes to express his sincere gratitude to Dr. A. J. Budding who suggested the problem and acted as major advisor. His help during the period of his study and during the preparation of this paper is very much appreciated. The writer feels very deep in debted to Dr. C. R. Keizer for correction of grammar.

Gratitude is extended to Dr. A. R. Sanford who served as a member of the advisory committee, to Dr. J. R. MacMillan and Dr. A. Kumar for their suggestions.

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PURPOSE

Sandstones are important sources of ground water. It is therefore necessary to understand their properties. One method to study the behavior of ground water movement at depth in aquifers is through laboratory experiments.

It is the purpose of this paper to report the results of experiments on the hydraulic conductivities of sandstones under a wide range of confining pressures. Three upper Cretaceous sandstones were used in the experiments; Mesa Verde and Middle Mancos Sandstones from Carthage (Socorro County) and Point Lookout Sandstone from the San Juan Basin (McKinley County), New Mexico. Their properties are shown in Table 1.

Table 1 Summary of Experimental Data

Rock	K at confining pressure (psi) (cm/sec)				Original porosity (%)	New porosity at confining pressure (psi) (%)			
	1000	2000	3000	4000		1000	2000	3000	4000
Middle Mancos Sandstone 1)	4.0×10^{-7}	2.6×10^{-7}	1.9×10^{-7}	1.2×10^{-7}	12	11.1	10.9	10.6	10.4
Mesa Verde Sandstone 1)	10.1×10^{-7}	5.8×10^{-7}	3.8×10^{-7}	2.2×10^{-7}	14	12.6	12.3	12.1	11.7
Point Lookout Sandstone 2)	11.6×10^{-4}	8.0×10^{-4}	6.0×10^{-4}	4.9×10^{-4}	19	17.8	17.6	17.4	16.9

1) Pore pressure from ram.

2) Pore pressure from storage tank.

APPARATUS AND PROCEDURES

The triaxial compression apparatus was described by Durtsche (1973, Fig. 2). Core samples, approximately 1" diameter and 2.5" long, were placed between the upper and lower platen in the triaxial cell. Clamps and plastic jacket were used to prevent the confining oil from entering the core spaces (Fig. 1).

The triaxial load was supplied by electro-hydraulic pump with manual control (Fig. 2).

The initial confining pressure was 1000 psi in order to have enough sealing pressure betwween the plastic jacket and the core; this pressure was increased by 1000 psi increments. The maximum confining pressure was 4000 psi, corresponding to overburden pressure of 4000 feet.

Pore pressure must be high enough to force the water to pass to the core (Fig. 2). Since porosities of Middle Mancos and Mesa Verde Sandstones were less than that of Point Lookout Sandstone (pore pressure 45 psi), higher pore pressures were required (1500 and 1000 psi) for measurable flow rates (Fig. 6,7 and 8). The amount of water that pass through the core and the time were recored simultaneously and are shown in Fig.8, 9 and 10). The decrease in pore pressure with time was also recorded, and is shown in Fig. 6, 7 and 8).

The change of core length, which corresponds to a porosity change, was measured by LVDT (linearly variable differential transformer).

Fig. 1 Diagram of internal parts of Triaxial-cell pressure chamber (not to scale). P_c is confining pressure.

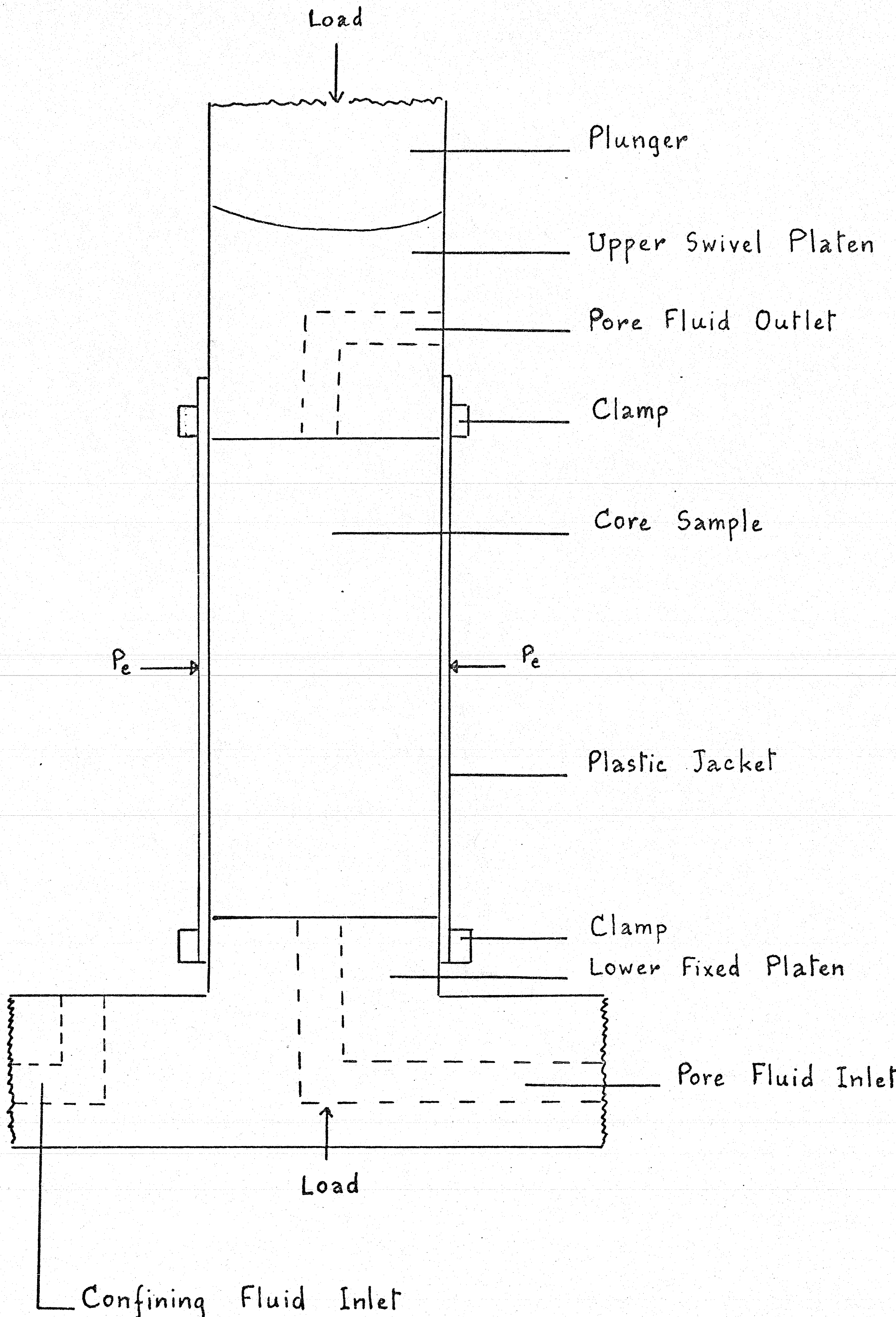
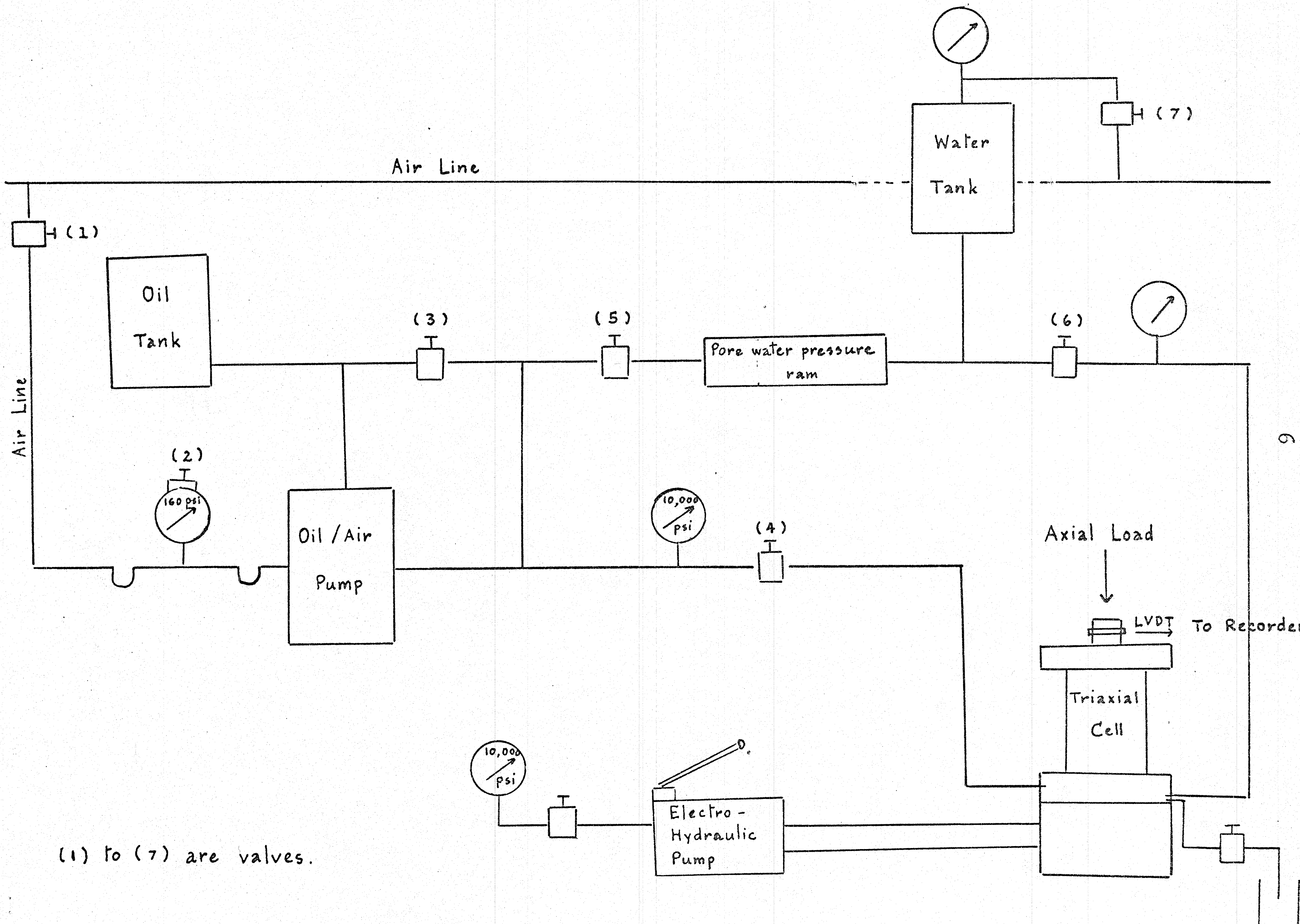

Load
Plunger
Upper Swivel Platen
Pore Fluid Outlet
Clamp
Core Sample
P_e
P_e
Plastic Jacket
Clamp
Lower Fixed Platen
Pore Fluid Inlet
Load
Confining Fluid Inlet

Fig. 2 Diagramatic sketch of experimental equipment.



(1) to (7) are valves.

CALCULATION OF

HYDRAULIC CONDUCTIVITY

The hydraulic conductivities were calculated by the use of Darcy's law.

$$Q = KA\frac{\Delta h}{L}$$

Q = the flow of water through the core in cm^3/sec.

A = cross-sectional area of the core in cm^2.

L = length of core in cm.

Δh = the different in head between the top and bottom of the core in cm.

Δh in cm. can be calculated from the initial and final pore pressure by the following relation:

$$P_1 = \frac{\text{Initial Pore Pressure} + \text{Final Pore Presure}}{2}$$

$$P_2 = \text{Atmospheric pressure} = 14.7 \text{ psi}$$

$$\Delta P = P_1 - P_2 \text{ , psi}$$

where 1 psi = 2.31 ft. of water, and 1 ft. = 30.48 cm.

$$\Delta h = P \times 2.31 \times 30.48 \ (=) \text{ cm. of water.}$$

POROSITY

It was assumed that the sandstone sample consisted of grains of quartz which has density of 2.65 gm/cm^3.

$$D_c = \frac{m_c}{V_c}$$

D_c = density of core sample

m_c = mass of core

V_c = volume of core sample

$$D_q = \frac{m_q}{V_q}$$

D_q = density of quartz

m_q = mass of quartz

V_q = volume of quartz

and

$$m_c = m_q$$

$$\text{Porosity} = \frac{V_c - V_q}{V_c} = \frac{D_q - D_c}{D_q}$$

POROSITY CHANGE

From the LVDT measurements the reduction in length of the core, Δh, can be determined after applying confining pressure (horizontal or lateral) and axial load (vertical or longitudinal). The change of volume of the core and the porosity change were calculated from D_o and ΔL.

Given:

L_o = original length of the core

D_o = original diameter of the core

ΔL = the reduction in the length of the core

ΔD = the reduction in the diameter of the core

E_{long} = longitudinal strain

E_{lat} = lateral strain

ΔV = volume change.

The confining pressure and axial pressure were kept approximately the same during the experiment. Therefore, the latitudinal strain is equal to the longitudinal strain, or

$$E_{lat} = E_{long}$$

and $$\frac{\Delta L}{L_o} = \frac{\Delta D}{D_o},$$

or $$\Delta D = D_o \frac{\Delta L}{L_o}$$

The original volume of the core is $\frac{\pi}{4}D_o^2L_o$.

The volume of the core after strain is $\frac{\pi}{4}(D_o - D_o\frac{\Delta L}{L_o})^2(L_o - \Delta L)$.

The change in volume, ΔV, is therefore $\frac{\pi}{4}D_o^2L_o - \frac{\pi}{4}(D_o - D_o\frac{\Delta L}{L_o})^2(L_o - \Delta L)$.

$$\Delta V = \frac{\pi}{4}D_o^2L_o - \frac{\pi}{4}\left[D_o^2 - 2D_o^2\frac{\Delta L}{L_o} \quad D_o^2\left(\frac{\Delta L}{L_o}\right)^2\right](L_o - \Delta L)$$

Since ΔL is very small compared to L_o, the term $D_o^2(\frac{\Delta L}{L_o})^2$ are neglected and

$$\Delta V = \frac{3}{4}\pi D_o^2\Delta L$$

PREVIOUS WORK

Hydraulic conductivities may be determined both by field and by laboratory methods.

Field pumping tests in wells are used for determining aquifer coefficients of permeability by hydrologists (cf. Theis, 1963). The well is pumped at a constant rate, and the drawdown is measured at the same time. A graph of time of pumping versus drawdown is plotted, and the hydraulic conductivity is calculated by applying Theis's equation.

Croft et al. (1971) described a method for calculating permeability from resistivity curves of electric logs of water wells. They correlated the graph for estimating the permeability from the grain size analyses of Jones and Buford (1951) with the observation of Alger (1966) that the smaller the grain size, the smaller the value of the formation factor of the aquifer (Croft et al., 1971, Fig. 1). They constructed a graph of permeability versus formation factor (Fig. 2). The formation factor (F) is the ratio R_o/R_w, where R_o is the resistivity of water - saturated rock and R_w is the resistivity of the water in the well. By reading R_o and R_w from the electric log of the well they calculated the formation factor F, then determined the permeability from the graph (Croft et al., 1971, Fig. 2). The values of permeabilities obtained by this method were comparable to the permeabilities obtained from the pumping tests.

Another method often used by drainage engineers for determining hydraulic conductivity (or permeability) in situ is the auger hole method (cf. Luthin, 1966). This method consists of digging an auger hole into the soil below the water table. After first determining the elevation of the water table by allowing the water surface in the hole to reach equilibrium with the soil water, the hole is pumped out to a new water level elevation; then the rate of rise of water in the hole is measured. From these measurements the hydraulic conductivity is calculated.

In the laboratory, hydraulic conductivities of unconsolidated materials are measured by an instrument called a permeameter (cf. Bear, 1972). For consolidated materials, petroleum engineers use an air permeameter to measure permeabilities of oil - bearing rocks (cf. Leverson, 1965). Crook et al. (1971) developed the "four point test" by applying Darcy's law for a quick determination of permeability using water. The method required the measurements of the time for known amounts of water (1, 2, 3 and 4 ml.) to permeate through the cylindrical core. The core must not be less than 4 cm long and 2.54 cm in diameter in order to keep the pool of water shallow, so the difference in the head of the water is approximately equal to the length of the core and time for water to permeate into the core is small (Crook et al., 1971, Fig. 6). The permeability for each measurement was calculated by using equation (5) (Crook et al., 1971). The permeability of the core was taken as the average value of the four calculated permeabilities.

Relatively little has been reported in the literature on the effect of confining pressure on the properties of sandstones.

An increase of confining pressure on the cores produced a decrease in permeabilities to air and porosities of oil-bearing sandstones (cf. Fatt and Davis, 1952, Fatt, 1953, Wyble, 1958, and McLachie et al, 1958). Their experiments showed that the decrease in permeability on the confining pressure was not systematic. For Bradford Sandstone with an average porosity of 11 % at 5000 psi confining pressure, the permeability decreased 50 % (Wyble, 1958, Fig. 3). For Weir Sandstone with a porosity of 15 % at 5000 psi confining pressure, the permeability decreased 65 % (Wyble, 1958, Fig. 4).

Handin et al (1963) measured the permeabilities of Berea Sandstone (Missippian) by a capillary-pressure method and changes in porosities by a triaxial compression test. The original porosity of the sample was 18.2 %, they calculated the permeability of 217 millidarcys (2.2×10^{-4} cm/sec) and the porosity change under confining pressure at 2000 bars was 17.6 % (Handin et al, 1963, Table I).

Early studies were done on samples using an air apparatus. The study by Daw (1971) involved the use of water.

He developed a modified Hoek-Franklin triaxial cell to measure samples of rock of low permeability (10^{-3} to 10^{-10} cm/sec). The Hoek-Franklin triaxial cell is smaller and more convenient for the testing than the one used in the present study, which is shown in Fig. 1 (Hoek and Franklin, 1968, Fig. 1). The modified Hoek-Franklin triaxial cell was designed for the permeability measurement purpose (Daw, 1971, Fig. 1). The original steel loading platens were replaced by solid brass cylinders designed to retain a 1 in. long sample, and each cylinder contain a 5 mm diameter flow channel. He also observed that for measurements using a liquid with rock of low permeability (less than 10^{-5} cm/sec) high injection pressures were required to provide conveniently measurable flow rates and correspondingly higher pressures were required on the plastic jacket.

Fig. 3 Hydraulic conductivity vs. confining pressure on Middle Mancos Sandstone.

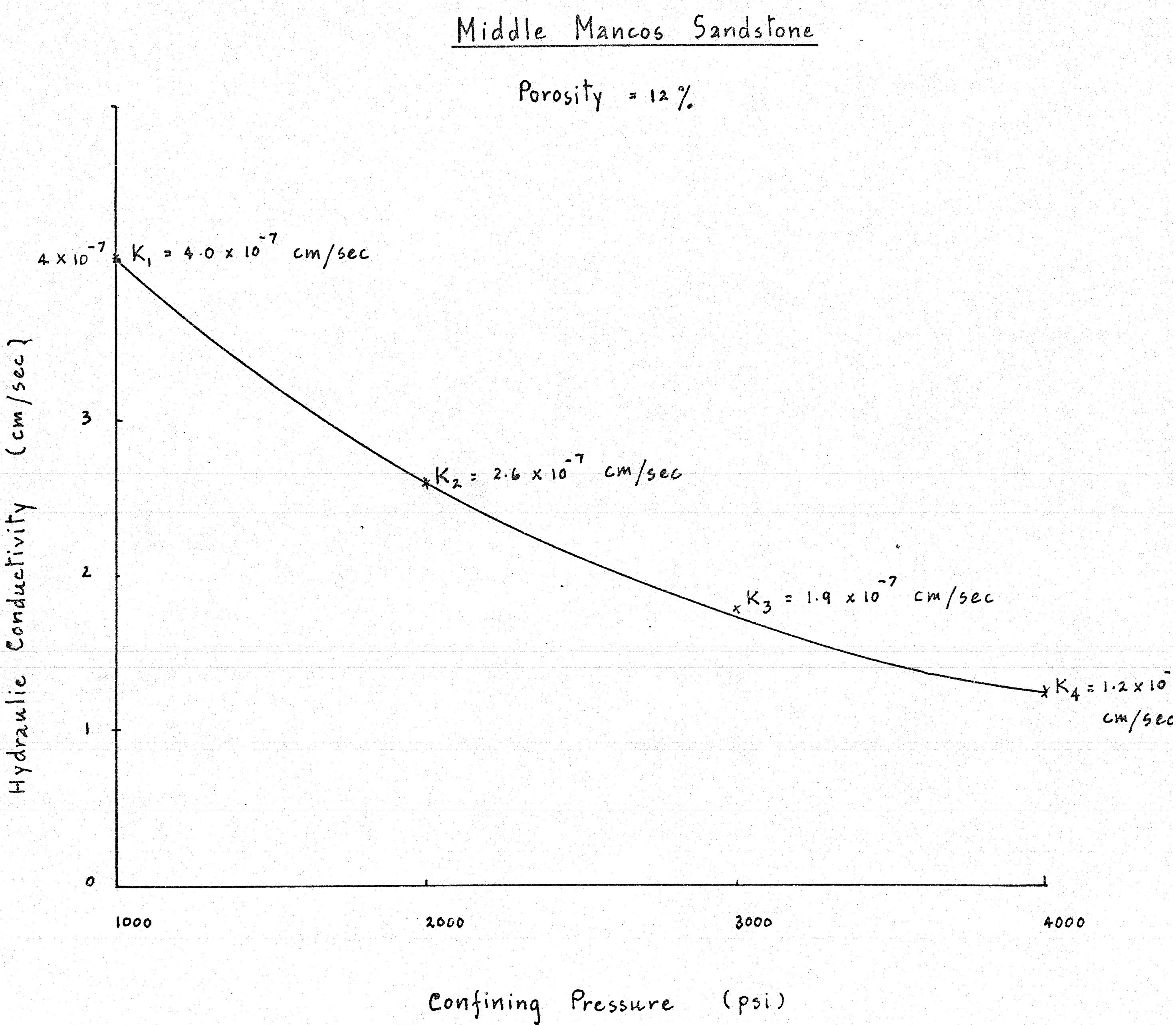

Middle Mancos Sandstone
Porosity = 12%
4 x 10^-7
K1 = 4.0 x 10^-7 cm/sec
K2 = 2.6 x 10^-7 cm/sec
K3 = 1.9 x 10^-7 cm/sec
K4 = 1.2 x 10^- cm/sec
3
2
1
0
1000
2000
3000
4000
Hydraulic Conductivity (cm/sec)
Confining Pressure (psi)

Fig. 4 Hydraulic conductivity vs. confining pressure on Mesa Verde Sandstone.

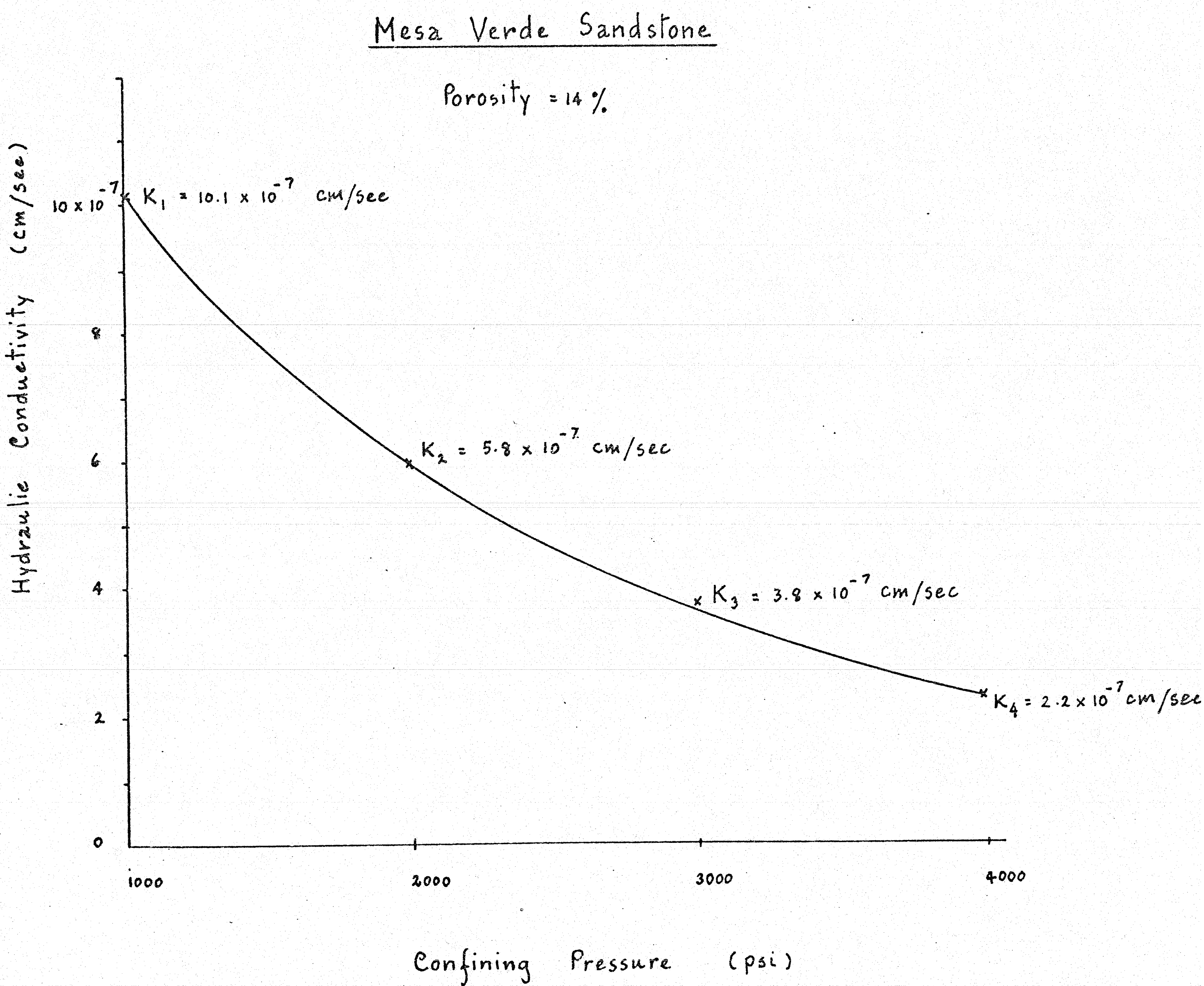
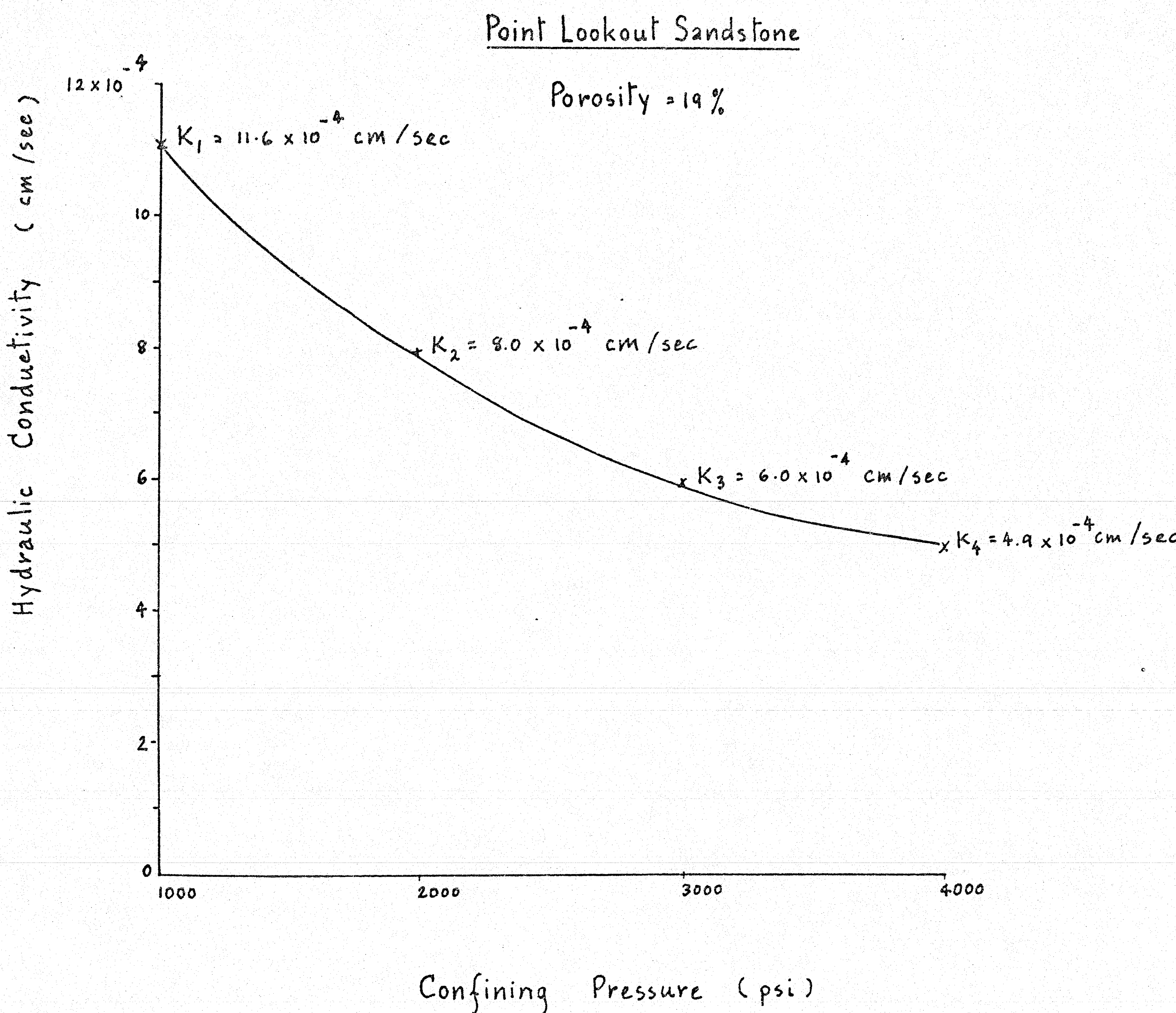

Mesa Verde Sandstone
Porosity = 14 %
Hydraulic Conductivity (cm/sec)
10 x 10^-7
8
6
4
2
0
K1 = 10.1 x 10^-7 cm/sec
K2 = 5.8 x 10^-7 cm/sec
K3 = 3.8 x 10^-7 cm/sec
K4 = 2.2 x 10^-7 cm/sec
1000
2000
3000
4000
Confining Pressure (psi)

Fig. 5 Hydraulic conductivity vs. confining pressure on Point Lookout Sandstone.



Point Lookout Sandstone
Porosity = 19%
12 x 10^-4
10
8
6
4
2
0
Hydraulic Conductivity (cm/sec)
K1 = 11.6 x 10^-4 cm/sec
K2 = 8.0 x 10^-4 cm/sec
K3 = 6.0 x 10^-4 cm/sec
K4 = 4.9 x 10^-4 cm/sec
1000
2000
3000
4000
Confining Pressure (psi)

Fig. 6 Pore pressure vs. time on Middle Mancos Sandstone.

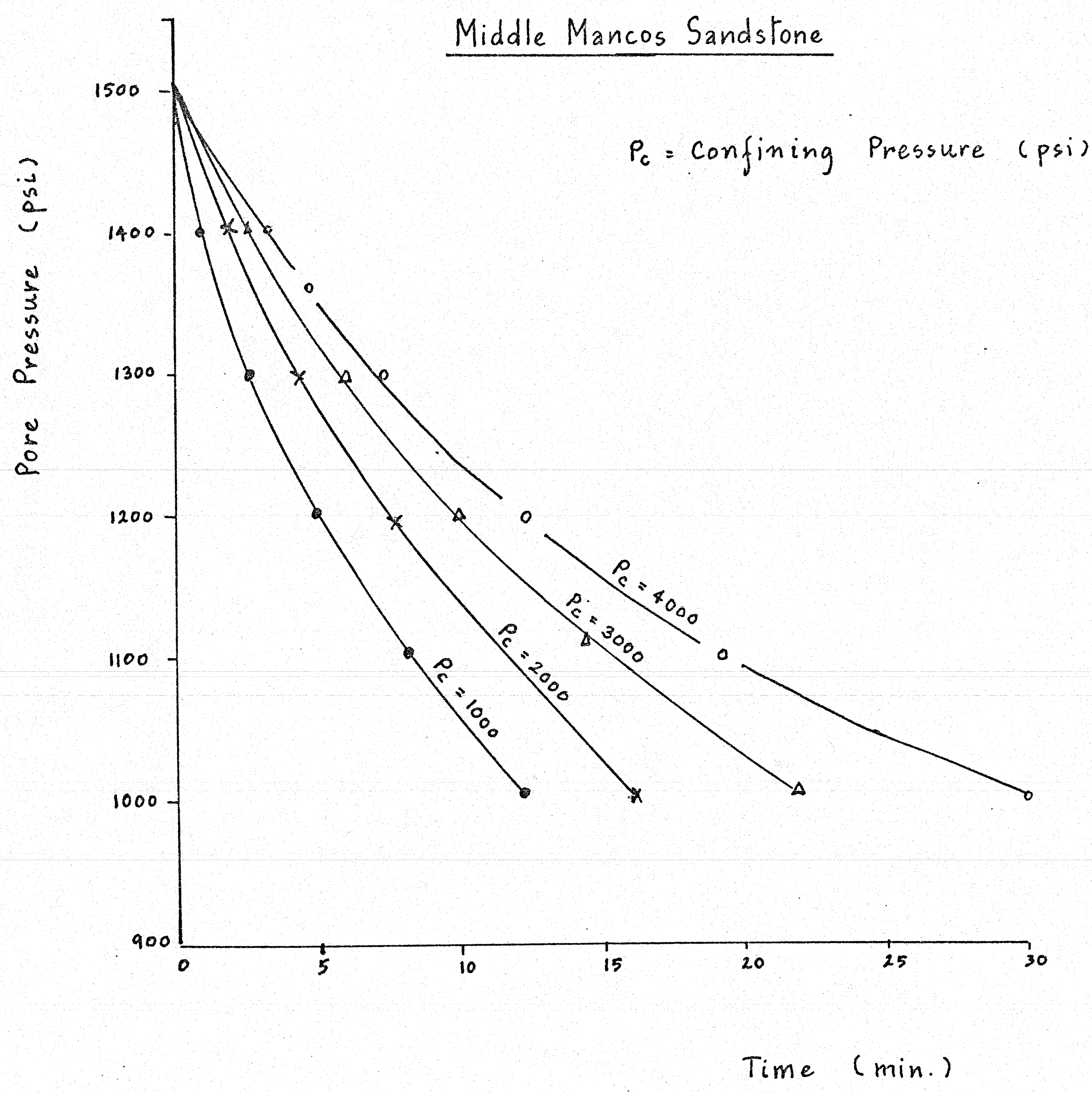
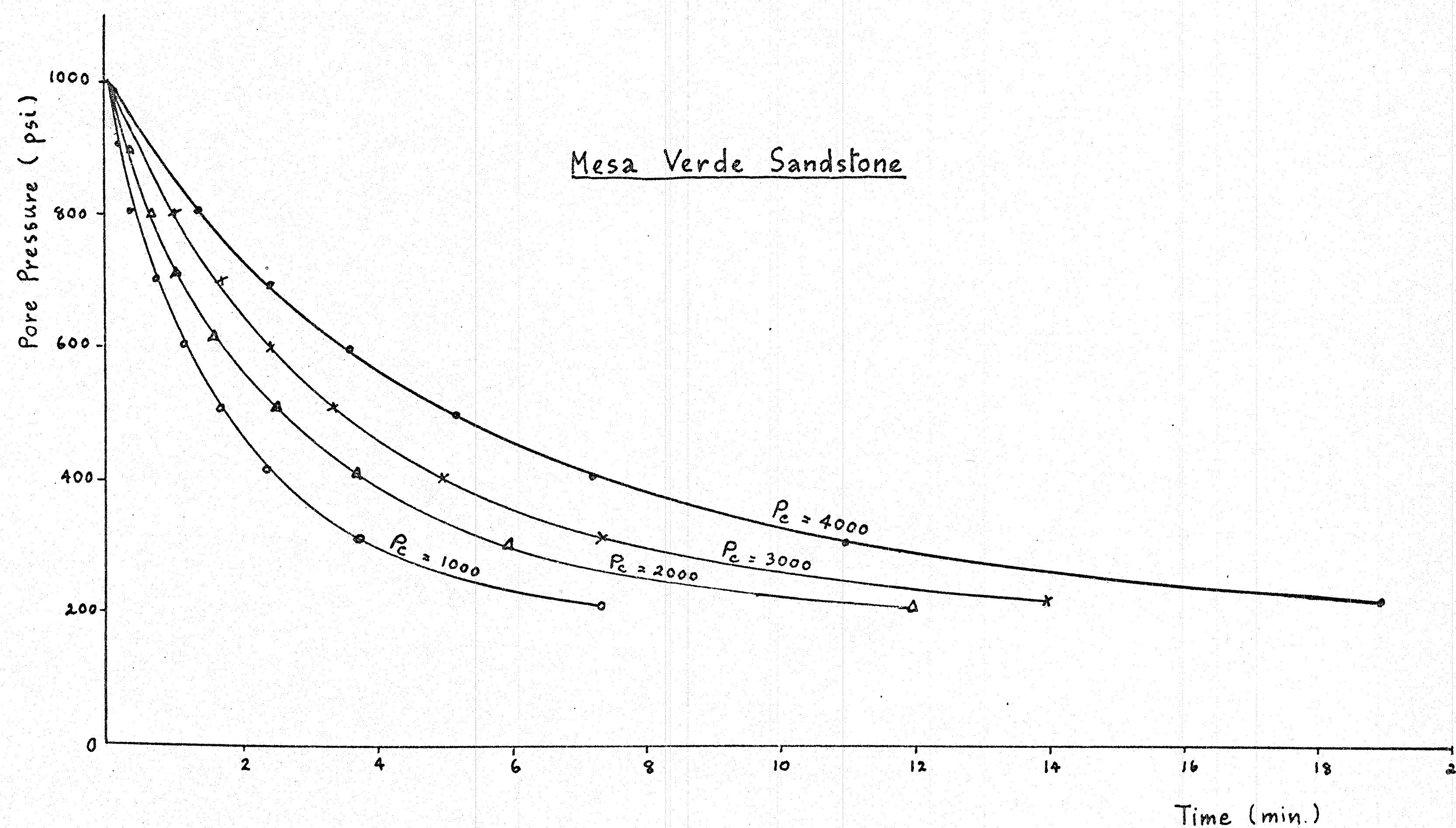

Middle Mancos Sandstone
Pc = Confining Pressure (psi)
Pore Pressure (psi)
1500
1400
1300
1200
1100
1000
900
0
5
10
15
20
25
30
Pc = 4000
Pc = 3000
Pc = 2000
Pc = 1000
Time (min.)

Fig. 7 Pore pressure vs. time on Mesa Verde Sandstone.



Mesa Verde Sandstone
Pore Pressure (psi)
1000
800
600
400
200
0
2
4
6
8
10
12
14
16
18
20
Time (min.)
P_c = 4000
P_c = 3000
P_c = 2000
P_c = 1000

Fig. 8 Amount of water vs. time on Middle Mancos Sandstone.

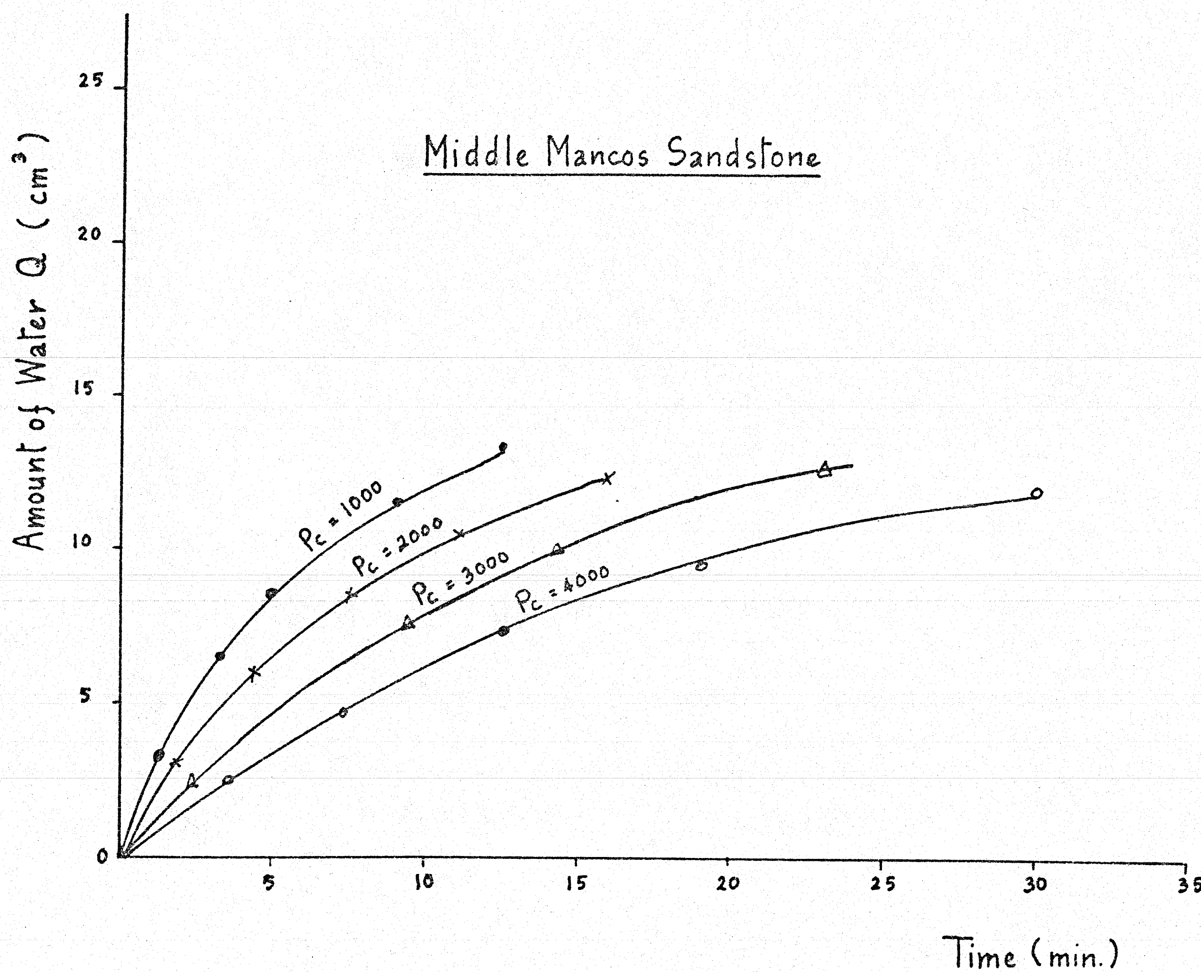
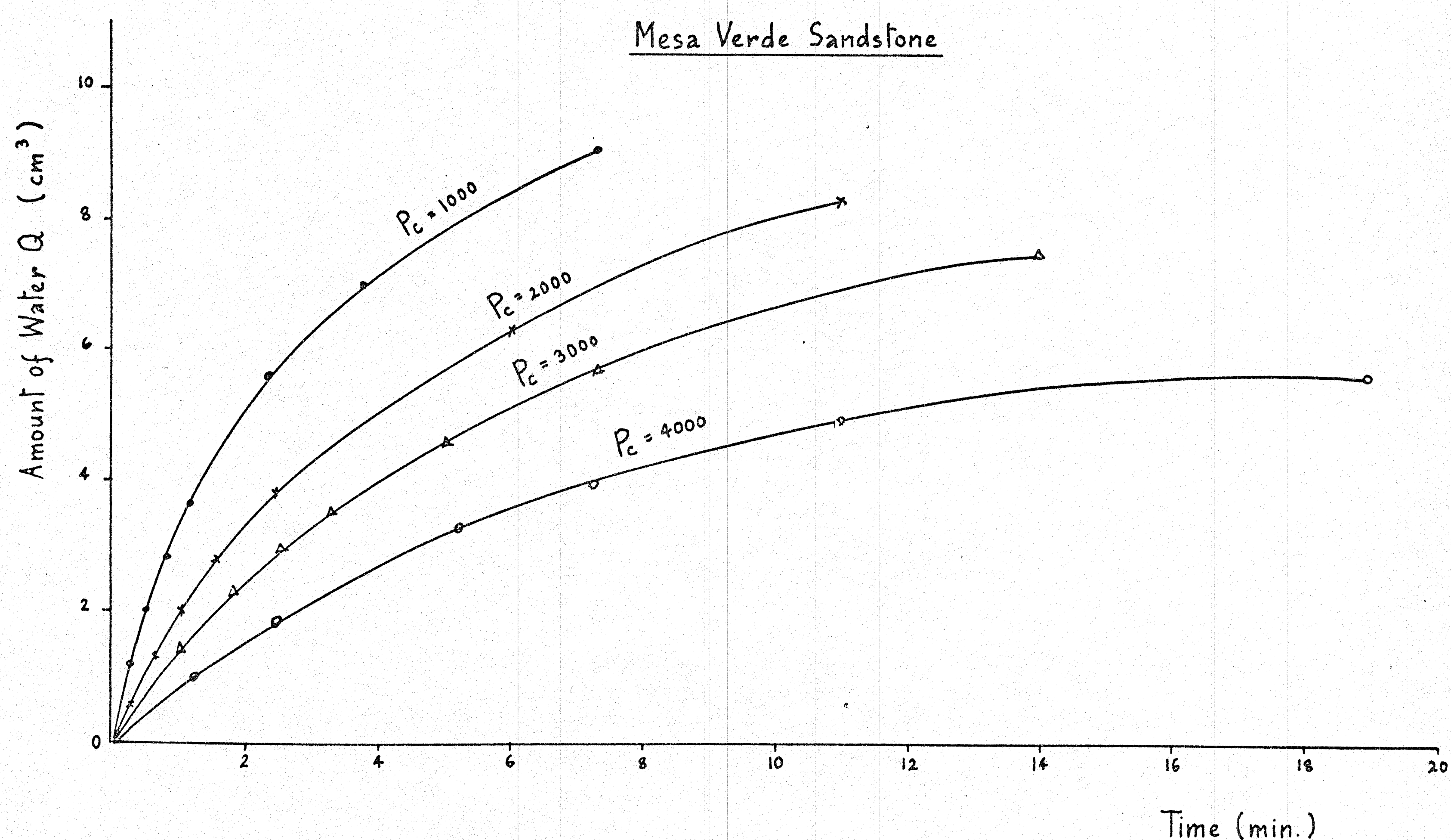
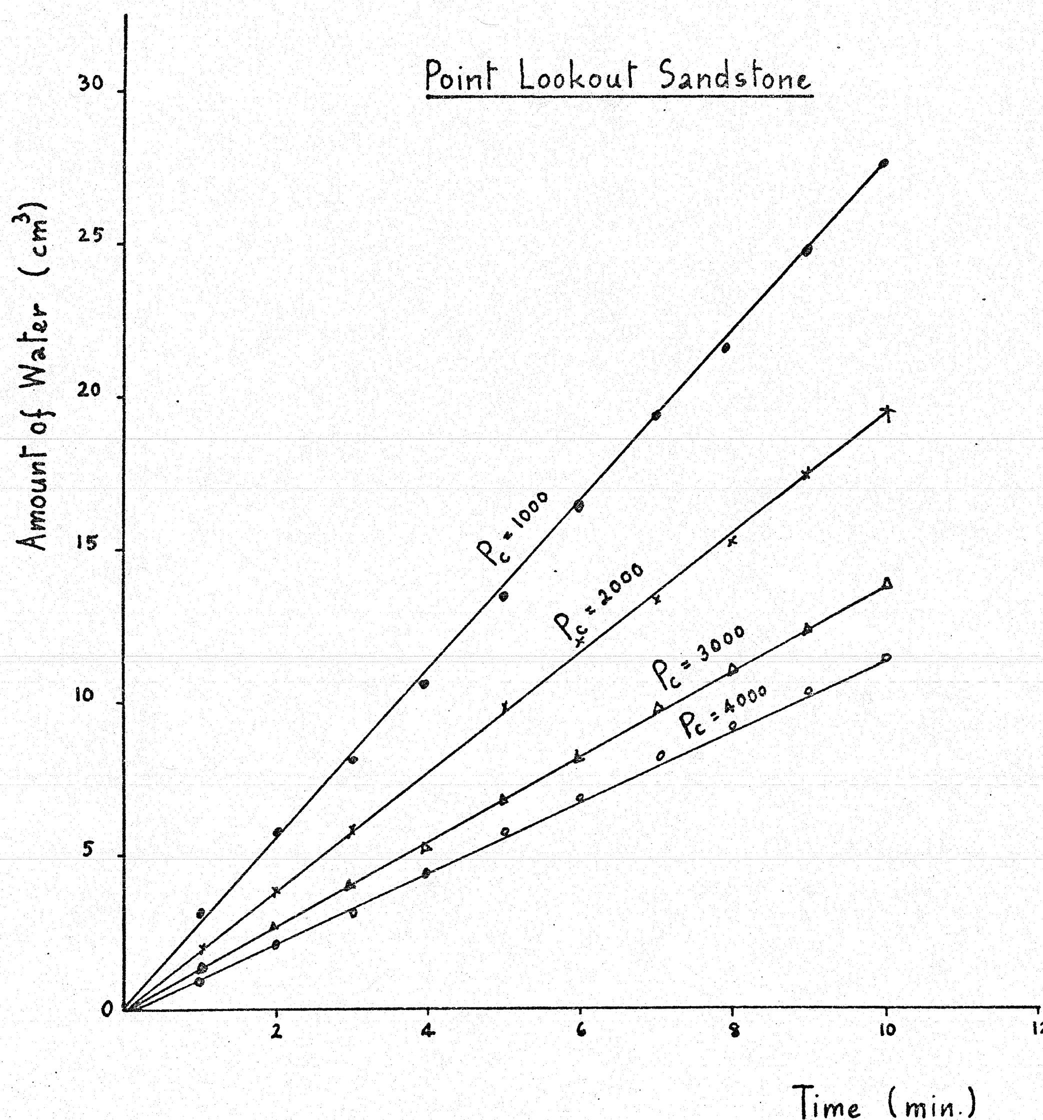

Middle Mancos Sandstone
Amount of Water Q (cm³)
Time (min.)
Pc = 1000
Pc = 2000
Pc = 3000
Pc = 4000
0
5
10
15
20
25
30
35

Fig. 9 Amount of water vs. time on Mesa Verde Sandstone.



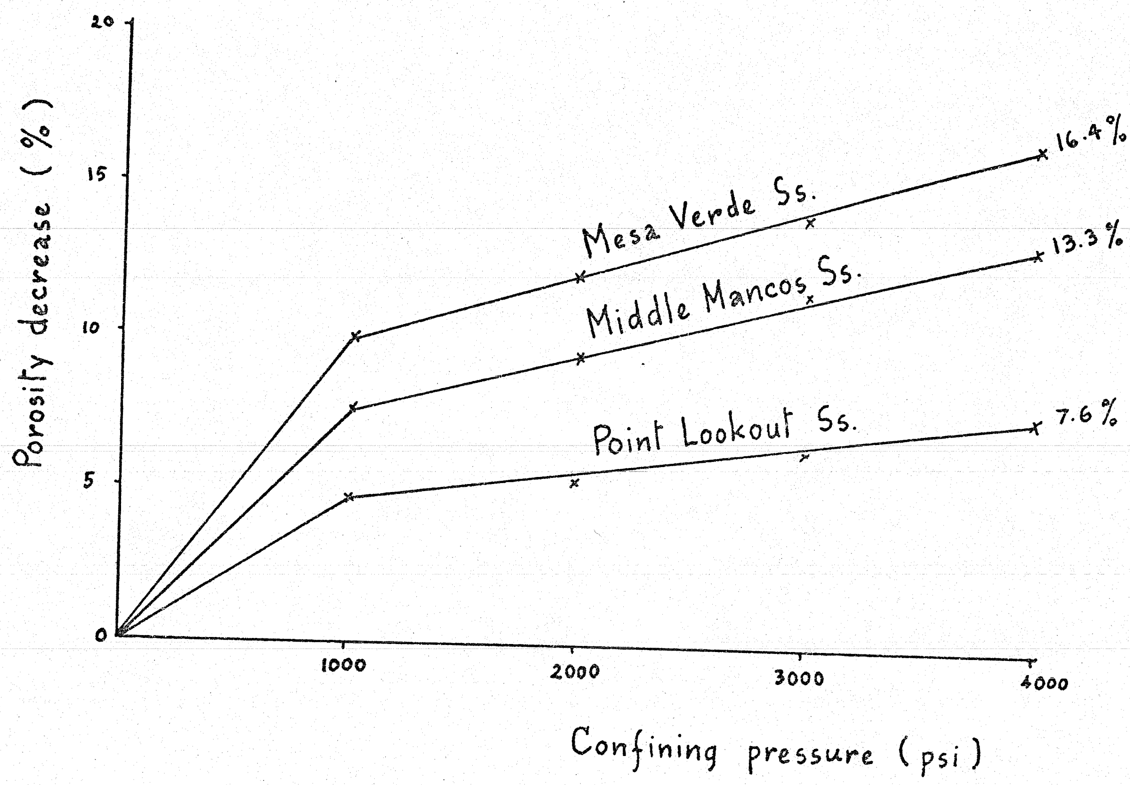
Mesa Verde Sandstone
Amount of Water Q (cm³)
Time (min.)
$P_c = 1000$
$P_c = 2000$
$P_c = 3000$
$P_c = 4000$
0
2
4
6
8
10
12
14
16
18
20

Fig. 10 Amount of water vs. time on Point Lookout Sandstone.



Pore Pressure from storage tank (45 psi)

Fig. 11 Percent porosity decrease vs. confining pressure on Mesa Verde, Middle Mancos and Point Lookout Sandstones.



<u>Original porosity</u>

Mesa Verde Ss.	= 14 %
Middle Mancos Ss.	= 12 %
Point Lookout Ss.	= 19 %

RESULT AND CONCLUSION

A summary of experiments for each sandstone are shown in curves (Fig. 3 to 11). The data listed and curves include the experimental condition of confinining pressure, pore pressure, hydraulic conductivity and porosity of samples. The hydraulic conductivity at 1000, 2000, 3000 and 4000 psi for Middle Mancos and Mesa Verde Sandstones (Fig. 3 and 4) were calculated by taken the average the flow rate for each 100 psi pore pressure drop (Fig. 6, 7, 8 and 9). The hydraulic cnductivities for Point Lookout Sandstone (Fig. 5) were calculated from the flow rate at constant pore pressure (45 psi).

Although it has been shown that there is no close correlation between permeability and porosity (cf. Crook, 1973, Fig. 4), these experiments suggest that higher hydraulic conductitities are associated with more porous rocks.

The experimental results show that hydraulic conductivities and porosities of sandstones decrease as the confining pressure increases (Fig. 3, 4, 5 and 11). Rates of asymptonic decrease in hydraulic conductivities of sandstones varied from formation to formation. Rapid decrease takes place over the range of confining pressure 1000 - 3000 psi and a more gradual decreases above this range. Therefore, the study of ground water hydrology of different sandstones aquifers must into account the behavoir of rock that make up of each aquifer. The study of hydraulic conductivities of sandstone over this range of confining pressure (up to 4000 psi) is useful up to 4000 feet.

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