COO-4054-1

FLUID TRANSPORT PROPERTIES OF ROCK FRACTURES AT HIGH PRESSURE AND TEMPERATURE

Progress Report

for Period July 1, 1976-June 30, 1977

T. Engelder and C. Scholz

Lamont-Doherty Geological Observatory

Palisades, New York 10964

March 1977

Prepared For

THE U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

UNDER CONTRACT NO. EY-76-S-02-4054

L-DGO Proposal No. 1522

DISCLAIMER

ABSTRACT

Herein we report the initial stages of our study of the fluid transport properties of rock at high pressure and temperature. Emphasis of this study is on the mechanical hydraulic interactions, in an attempt to understand the process of fracture closure and its influence on fracture permeability. To determine the fluid transport properties of a fracture we investigated the effect of surface roughness, geometry and filling on fracture permeability. Permeability of these fractures was measured at various effective normal stresses at room temperature. The law of effective stress appears valid for fractures without filling but permeability of filled fractures is more sensitive to confining pressure than pore pressure. Permeability of smooth surfaces varied 5 to 0.5 darcys over a range of effective stresses from 0 to 3000 bars. Filled fractures were an order of magnitude more permeable.

INTRODUCTION

Central to many proposed geothermal power extraction schemes is the need to transport large volumes of fluid through natural or induced fractures in rock, often at considerable depth within the crust and in areas of elevated temperature. In order to design and carry out such programs, a clear understanding is required of the fluid transport properties of rock at the appropriate temperatures and pressures, and of the factors that influence these properties.

Geothermal water is more likely to be derived from igneous or metamorphic rock than from sedimentary deposits. Since most of the fluid transport in such rock is expected to be born by fractures (joints and faults), the problems of dealing with flow is somewhat different than that encountered in usual hydrological practice. Furthermore, the high temperatures and pressures encountered in any but the shallowest geothermal projects will produce additional problems.

Although fluid flow through rock masses has been the subject of active research in the past decade, many fundamental problems remain poorly resolved. In addition, most past work has been directed towards surface engineering works, and the geothermal program requires information on fluid flow at higher temperature and pressure than has been considered before. We intend with what follows to briefly summarize present knowledge in this field and emphasize those problems to which we propose to direct ourselves.

It is customary to assume that a fracture in rock can be treated as a parallel plate opening, in which case the volume flow rate q is related to the pressure gradient by

$$q = \frac{e^3}{12\mu} \frac{dp}{dx} \qquad (1)$$

where e is the fracture opening and μ is viscosity (Romm, 1966). The permeability of a rock mass that contains a system of parallel fractures with spacing d is then

$$K = \frac{\gamma_o e^3}{12\mu d} \qquad (2)$$

parallel to the fracture system, where γ_o is the unit weight of fluid (see, e.g., Seraphim, 1968).

Equations 1 and 2 have formed the basis for much of the work on fluid flow through fractured rock (see, e.g., Snow, 1968), and has been reviewed by Wilson and Witherspoon (1970). Louis (1969), for example, has studied the applicability of this formulation to single fractures tested in the laboratory and has considered in some detail the effect of fracture roughness on (1).

There is, however, some doubt as to the applicability of equations (1) and (2) to flow in fractured rock at some depth in the crust, because of the effect of pressure in closing fractures. The fracture opening, e, is strongly dependent on normal stress across the fracture. Goodman (1968, 1974) and Goodman and Dubois (1972) have shown in the laboratory and Pratt _et al_. (1974) have shown in the field that fractures close rapidly under the action of an applied normal load, and that the normal force-closure curve is nonlinear. In the presence of an effective normal stress, the fracture walls will be in contact over part of their surface, and the flow path will be more tortuous than given by (1). This discrepancy with (1) and (2) will be expected to increase with applied normal force, since from friction studies we know that the real area of contact across a fracture will be given approximately by (for smooth fractures)

$$A_R = \frac{F}{p} \tag{3}$$

where F is the normal stress and p, the penetration hardness (Bowden and Tabor, 1964). Since, from (3), A_R increases with F, we might expect that at normal stresses greater than a few tens of bars the parameter e becomes meaningless except in a statistical sense.

One of the fundamental questions that remains to be answered, and to which we direct our work, is: _At depths in the earth where the effective normal stresses may lie in the range of 100 bars to_ several kilobars, are fractures sufficiently open to act as conduits for fluid flow? If a small amount of effective normal stress is sufficient to close off fractures as conduits then geothermal projects will be limited to areas in which the fluid pressure is anomalously high or injection pressures equal to the normal stress must be used in order to force fractures open. However, there is some reason to believe that nominally closed fractures may still be sufficiently open, even under moderate to high normal stresses, to transport fluid at substantial rates. If this is true, engineering requirements may not be as stringent as may otherwise have been thought.

EXPERIMENTAL APPROACH

The initial phase of our study is to determine the hydraulic characteristics of "model" fractures as a function of effective confining pressure at 25°C. Our scheme involves isolating three characteristics of a fracture which we think will most influence the fluid flow along the fracture. These characteristics are: (1) surface roughness; (2) surface geometry; and (3) surface filling. An *in situ* fracture consists of some combination of these three characteristics (Figure 1). By knowing how these three characteristics independently influence fluid flow we may suggest which of the three is most important in keeping fractures open at depths in the earth where effective

FRACTURE PERMEABILITY

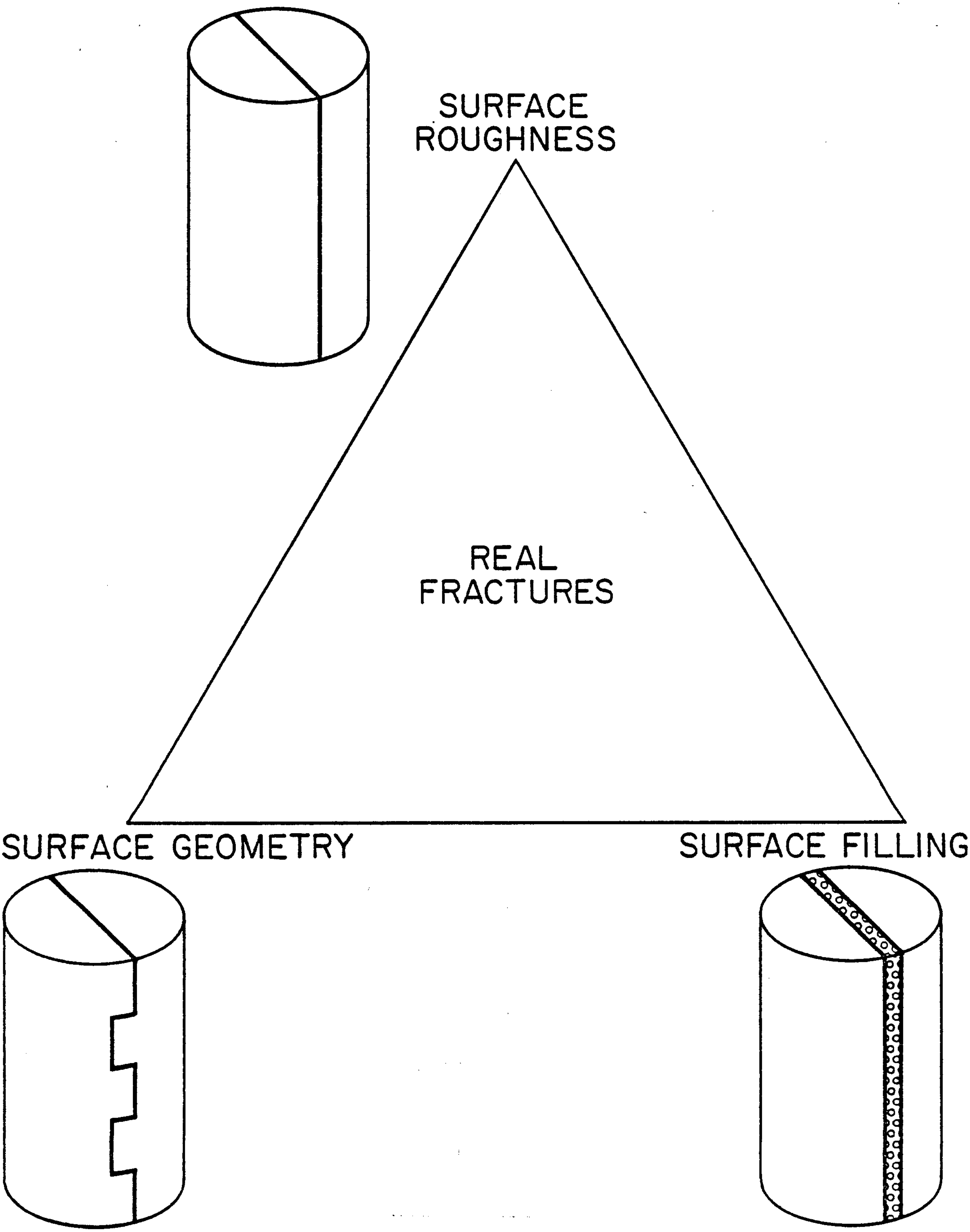


FIGURE 1

normal stresses are greater than 100 bars.

Surface roughness is an important parameter in controlling fluid flow along extension fractures. Surface filling is an important parameter for shear fractures which contain gouge generated during frictional sliding. Surface geometry will probably not be as important a parameter in influencing fluid flow along a single fracture but may be significant when considering fluid communication through a highly jointed rock where the path of the fluid has many corners to turn.

EXPERIMENTAL TECHNIQUE

This proposal is largely concerned with measuring permeability of single fractures in the laboratory under controlled conditions of pressure and temperature. The experiments are conducted in a triaxial deformation press equipped with a 2" bore pressure vessel capable of 10 kb and 1000°C. For these experiments, kerosene is used as the pressure medium. Silicone oil will be used as the pressure medium for temperature experiments to 300°C. An internal furnace will be used.

The experimental setup is drawn in Figure 2. The sample is a cylinder of 3 cm diameter, 10 cm long, split by a vertical fracture and jacketed in either copper or polyurethane. Pore pressure is introduced to the top of the fractured specimen through port A and taken from the bottom through port B. Confining

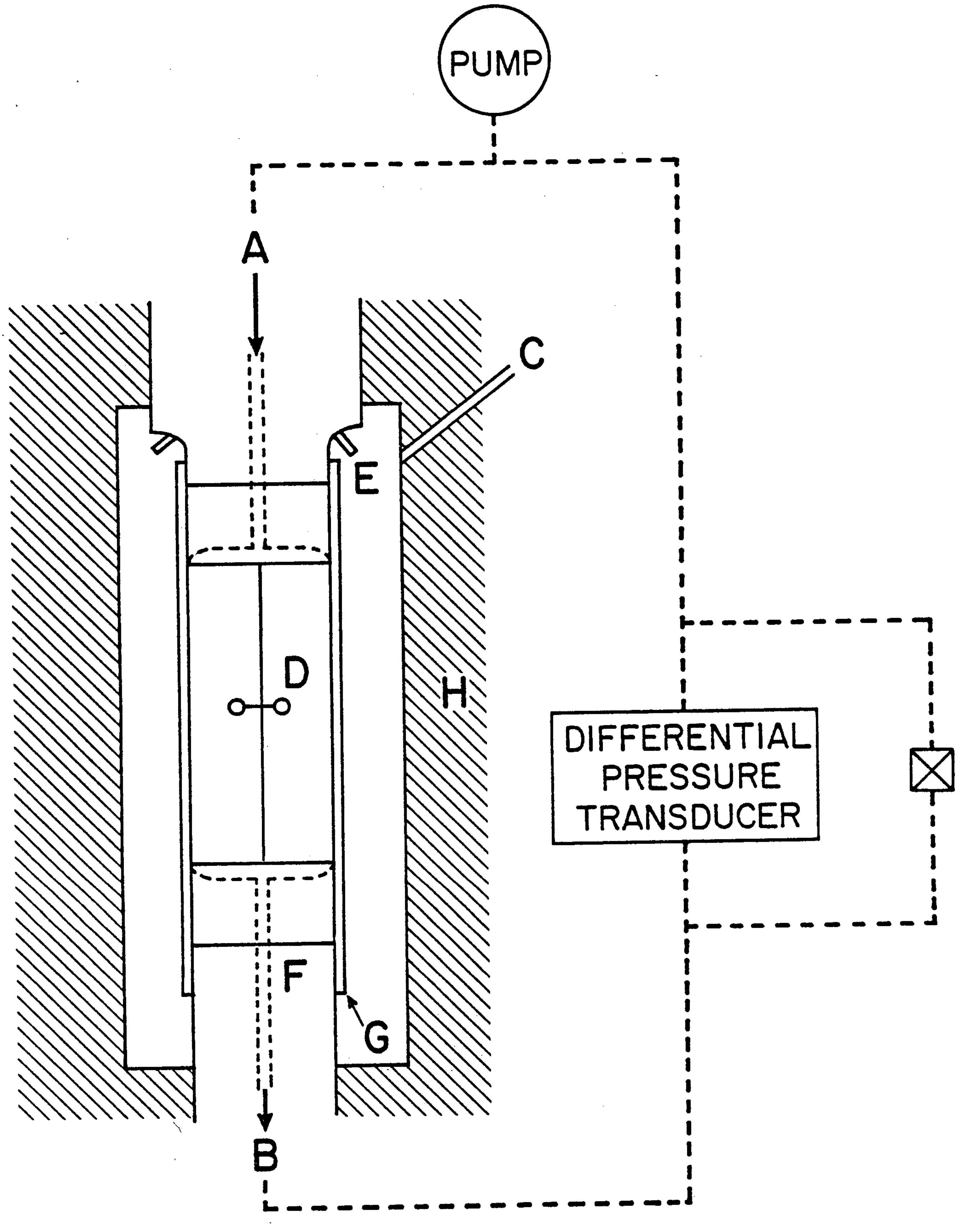


FIGURE 2

pressure is introduced through port C. The confining pressure system is capable of 5 kb, and the pore pressure system, 3 kb. A stainless steel shim will be used to restrain the jacket from intruding the fracture. An extensometer, D, will be mounted across the fracture to measure closure. There are 8 electrical feedthroughs (E) to allow a variety of measurements inside the vessel.

The permeability measurements are made with a modified version of the technique of Brace *et al*. (1968). Since it is difficult to measure fluid volumes under pressure, permeability will be measured by inducing a small step increase over the ambient pore pressure at port A, and measuring the transient decay in the relative pore pressure between ports B and A. The step in pore pressure is required to be much smaller than the total pore pressure, because of the effect of pore pressure on permeability. Since we measure the decay rate of pressure, we test the applicability of Darcy's law routinely. The measurements are made with a specially constructed differential pressure transducer capable of detecting differences of 0.1 bars under ambient pressures as high as 5 kb. Either fixed head or falling head tests can be made.

To determine the permeability of fractures we have assumed that Darcian flow occurs along the fracture. Darcy's law for flow through a medium is characterized by the equation

$$q = \frac{kA}{\mu} \frac{P_1-P_2}{L} \tag{4}$$

where q is the volumetric flow rate, k is the permeability, μ is the dynamic viscosity, A and L are the cross-sectional area and length of the sample and (P_1-P_2) is the difference in pore pressure across the sample (P_1 = high pressure side). We must assume a linear pressure gradient across the sample and a flow rate which is only a function of time. Given a small pressure pulse on one side of the sample, the pulse decays with time according to the equation

$$(P_1-P_2) = e^{-\alpha t} \tag{5}$$

where,

$$\alpha = \frac{kA}{\beta V \mu L} \tag{6}$$

where β is the isothermal compressibility of the pore fluid and V is the volume of the pore fluid reservoir at the low pressure end of the sample. To determine fracture permeability we solve the equation

$$k = \frac{\alpha \beta \mu L V}{A} \tag{7}$$

α is the slope of the plot of the log of (P_1-P_2) versus time.

For our initial experiments we used kerosene as the pore fluid. Its isothermal compressibility and viscosity as a function of pressure are well known. The advantages of using kerosene as a pore fluid are that it is chemically inert with respect to the rock and it is not corrosive at high pressures.

The samples we used for the initial tests included Barre granite and Grimsby sandstone. The former was used for the fracture permeability tests where the permeability of the granite is so low ($\sim$ 100 md) that the decay of pore pressure pulses can be attributed solely to fluid flow along the fracture. The calcite cemented sandstone from Medina, New York is used as a control for measuring whole rock permeability.

EXPERIMENTAL RESULTS

(a) Fracture with a planar surface. To test the effect of surface roughness on fracture permeability (k), we plan a number of tests using planar cuts in cylinders of Barre granite. The planar cuts will be ground to various roughnesses using grinding wheels made of various grits.

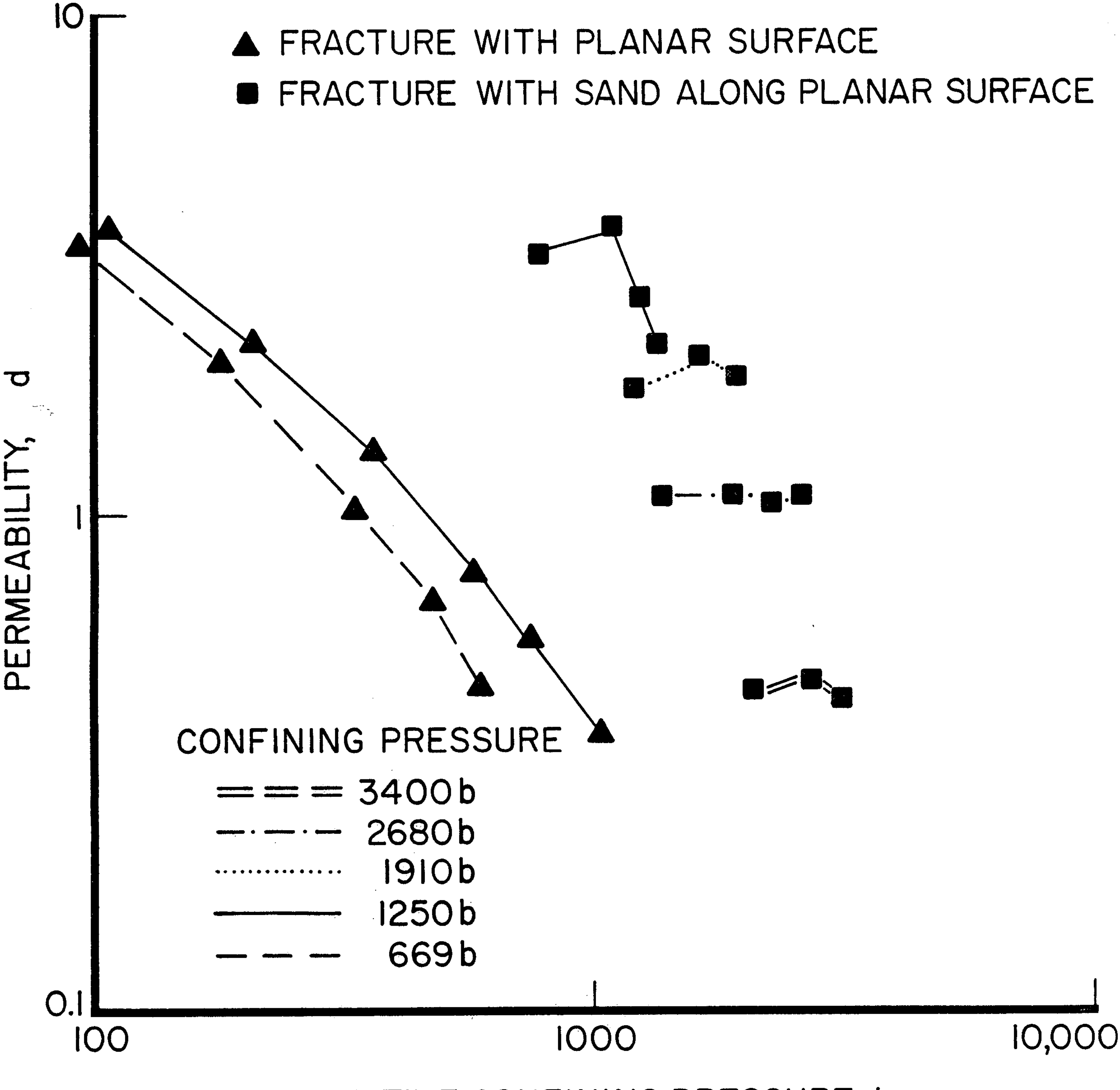
For the initial tests we prepared surfaces polished with 1000-grit polishing compound. This polished surface represents the smooth end member in a suite of surfaces ground to various roughnesses.

We observe that although k decreases rapidly with $\bar{P}$, that these samples, with a single smooth mated fracture, have a permeability of 0.3 darcy at 1 Kb effective normal stress. This value is three orders of magnitude higher than the whole rock permeability and supports our original premise that fractures can remain efficient fluid transport paths even while supporting high effective normal stresses.

Data for these planar surfaces are shown in Figure 3 where log k is plotted against log effective confining pressure ($\bar{P}$). To a rough approximation the law of effective stress is valid and the offset of our two curves for the k of planar surfaces is a measure of experimental error. The plot suggests that the relationship between k and $\bar{P}$ does not fit the equation for a power law.

(b) Fracture with a filling separating the planar surfaces. To test the effect of surface fillings on k, we plan a number of tests using planar cuts separated by surface fillings of various sizes and compositions. The compositions of the filling will include quartz, calcite, and clay particles as well as mixtures. The particle size of the fillings will vary from sand to clay.

For our initial tests we chose to start with a filling of quartz sand known as Ottawa sand. Data for the sand filled fracture are shown in Figure 3. The law of effective stress was not valid for these tests as k appears to depend on the confining pressure and is apparently not greatly affected by large changes in pore pressure. A filling of quartz sand increases the permeability of a fracture by as much as two orders of magnitude at the same effective confining pressure (Figure 3).



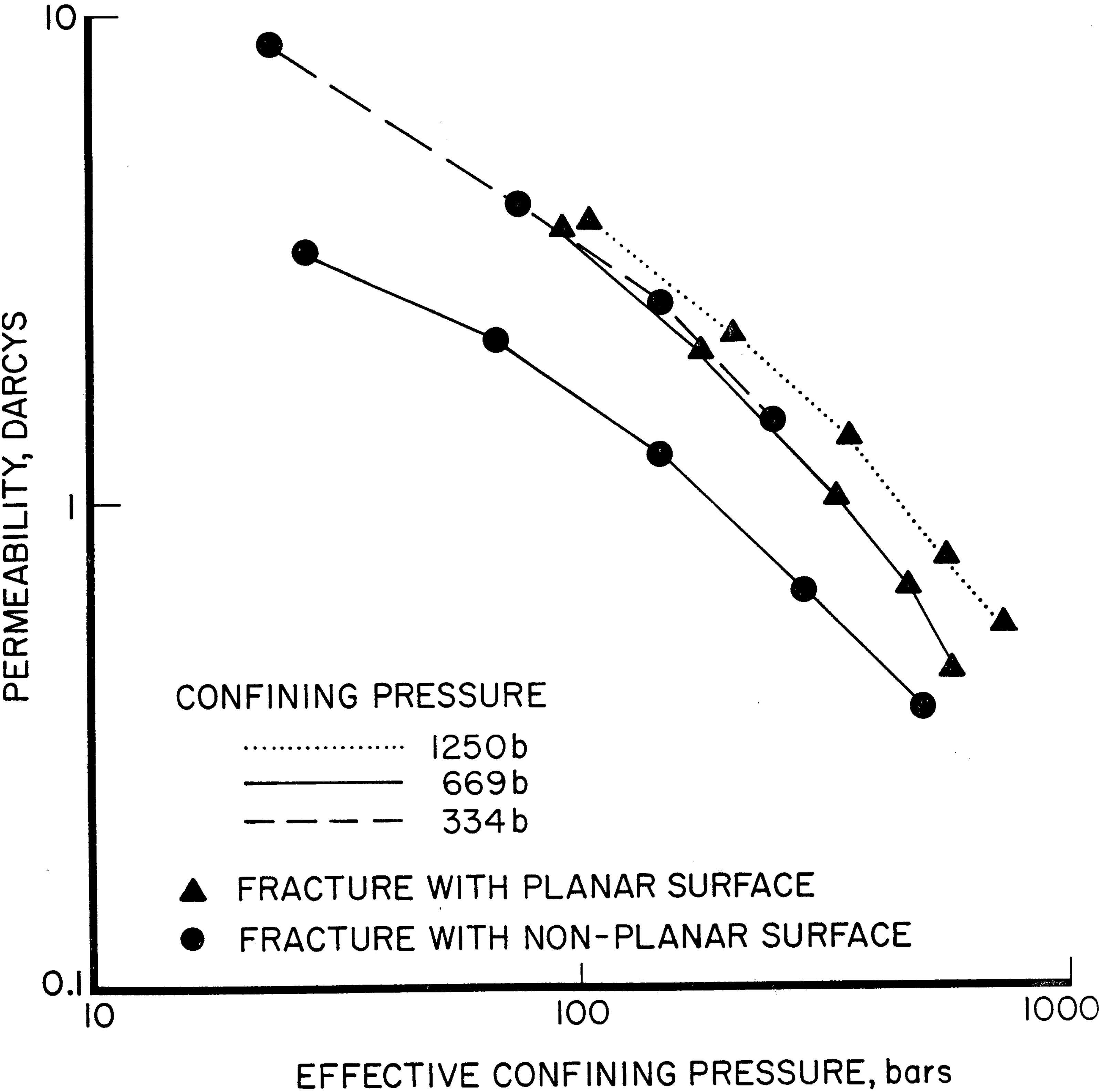
10
1
0.1
FRACTURE WITH PLANAR SURFACE
FRACTURE WITH SAND ALONG PLANAR SURFACE
PERMEABILITY, d
CONFINING PRESSURE
3400 b
2680 b
1910 b
1250 b
669 b
100
1000
10,000
EFFECTIVE CONFINING PRESSURE, bars

FIGURE 3

(c) Non-planar fractures. To test the effect of surface geometry on k, we plan a number of tests using surfaces of various shapes. We plan tests using samples with interlocking teeth and samples with cavities of various shapes.

Initial tests included samples with square teeth which were 0.65 cm high and 1.2 cm wide (Figure 1). The square teeth are interlocking and were lapped together 600# grit to provide very close tolerances between teeth. Data for the samples with interlocking square teeth are shown in Figure 4. k was calculated using the sample length, not the actual distances of fluid flow. To a rough approximation the law of effective stress is valid for the permeability of these samples. As was the case for samples with a planar surface the trend in log k versus log $\bar{\bar{P}}$ does not plot as a power law. For both types of surfaces the permeability decreases faster than the effective confining pressure (Figure 4).

The experimental variation between tests using samples with teeth appears larger than was measured for samples with planar surfaces. The fractures with square teeth are less permeable than those with planar fractures. However, if the actual distance of fluid flow is measured for the sample with square teeth and that distance used in the permeability calculation, we find that k is about the same or even a little larger



10
1
0.1
PERMEABILITY, DARCYS
10
100
1000
EFFECTIVE CONFINING PRESSURE, bars
CONFINING PRESSURE
1250b
669b
334b
FRACTURE WITH PLANAR SURFACE
FRACTURE WITH NON-PLANAR SURFACE

FIGURE 4

than for samples with planar surfaces (Figure 5). The reason k may be a little larger for samples with teeth is that fracture closure is less because of the mismatch between surfaces.

(d) Permeability of sandstone. As a control we measure k for a solid sample of sandstone. Figure 6 shows the variation of k with $\bar{P}$ for both hydrostatic conditions and differential states of stress. At an effective confining pressure of 100 b and $\dot{e} = 10^{-4}$, the fracture strength of Grimsby sandstone is 2.2 kb. An increased k accompanies dilatancy prior to failure.

DISCUSSION AND OUTLINE OF IMMEDIATE GOALS

The accuracy of fracture permeability measurements to date is limited by any ability to measure the true cross-sectional area of the fracture. It may never be possible to measure a true cross-sectional area but the cross-sectional area may be estimated by measuring fracture closure. We plan to measure fracture closure by attaching an extensometer across the fracture. This will enable us to measure the relative closure and thus change in relative cross-sectional area as a function of confining pressure. We view the measure of fracture closure as the key problem in future work and will treat it accordingly.

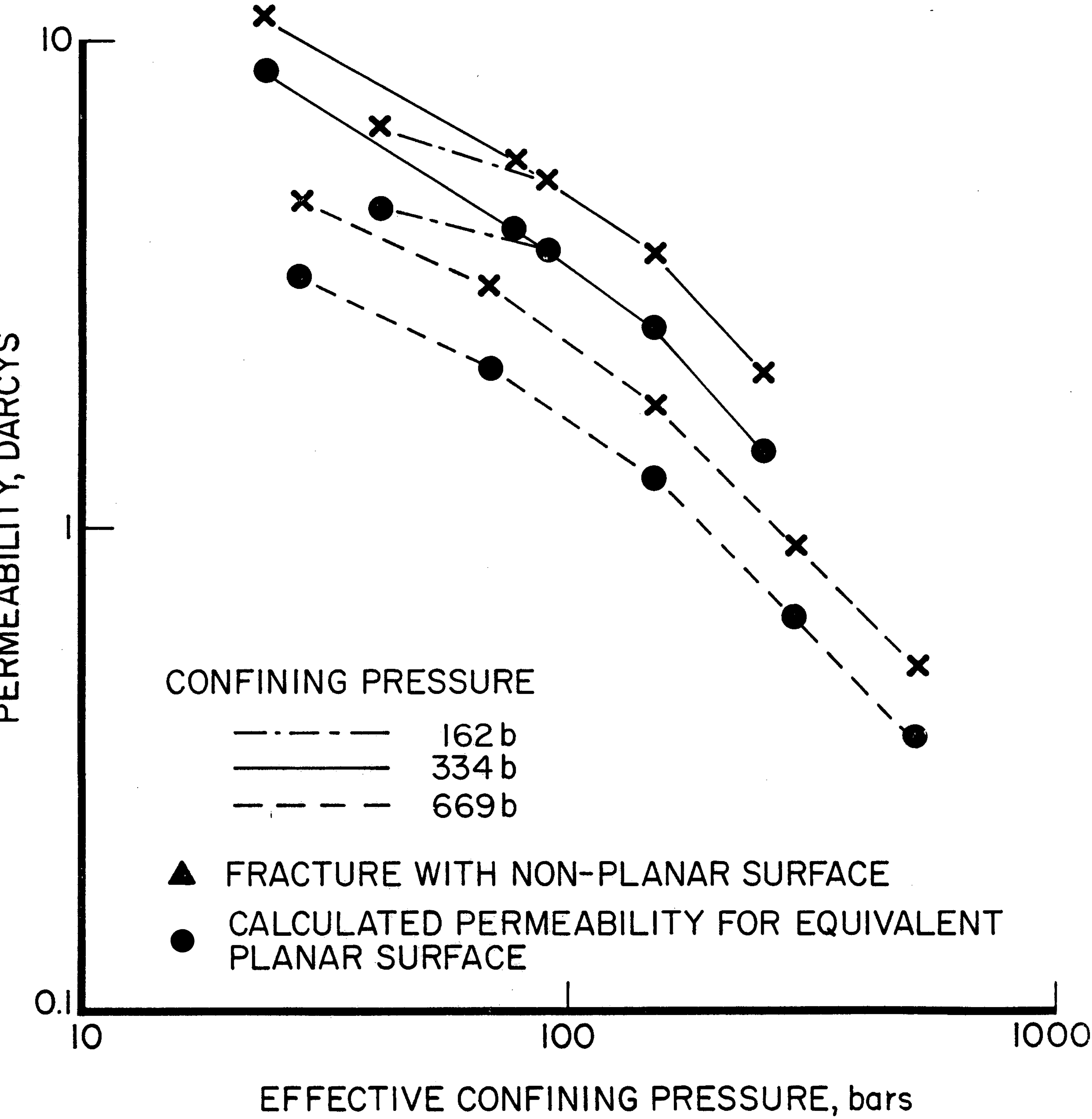
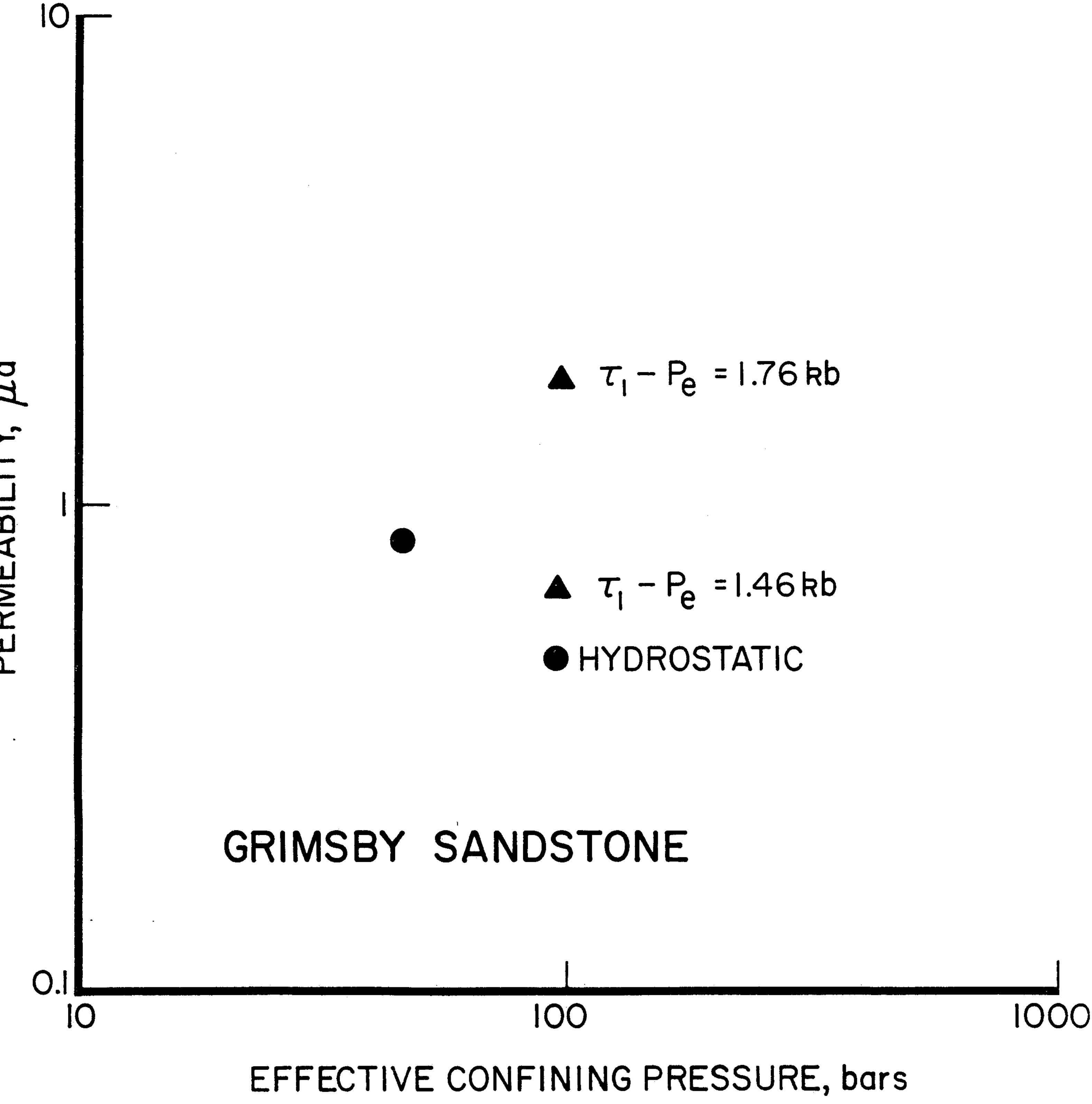

PERMEABILITY, DARCYS
10
1
0.1
10
100
1000
EFFECTIVE CONFINING PRESSURE, bars
CONFINING PRESSURE
162 b
334 b
669 b
FRACTURE WITH NON-PLANAR SURFACE
CALCULATED PERMEABILITY FOR EQUIVALENT PLANAR SURFACE

FIGURE 5



10
1
0.1
10
100
1000
PERMEABILITY, μd
EFFECTIVE CONFINING PRESSURE, bars
$\tau_1 - P_e$ = 1.76 kb
$\tau_1 - P_e$ = 1.46 kb
HYDROSTATIC
GRIMSBY SANDSTONE

FIGURE 6

Future steps in our experimental program are as follows:

(1) We will complete our data set measuring the effects of surface roughness, geometry and filling as a function of effective confining pressure at room temperature.

(2) We will gather a data set testing the effect of elevated temperature on all of the above parameters.

(3) Then we will use a chemically active fluid to measure time dependent changes in fracture permeability for the above parameters.

(4) Finally we plan to complete our data set by sampling the permeability of natural fractures.

REFERENCES

Bowden, F., and D. Tabor, Friction and Lubrication of Solids, Oxford, 1964.

Brace, W. F., J. B. Walsh and W. T. Frangos, Permeability of granite under high pressure, J. Geophys. Res., 73, 2225-2236, 1968.

Goodman, R. E., and Y. Onishi, Undrained shear testing of jointed rock, Rock Mechanics 5, 129-149, 1973.

Goodman, R. E., The mechanical properties of joints, Proc. Third Cong. Int. Soc. Rock Mech., Denver, IA, 127-140.

Goodman, R. E., and J. Dubois, Duplication of dilatancy in analysis of jointed rock, J. Soil Mech. and Found. Div. Proc. ASCE, 98 (SM4), 399-422.

Louis, C., A study of groundwater flow in jointed rock and its influence on the stability of rock masses, Rock Mech. Research Rept. No. 10, Imp. Coll. of Science and Technology, London, 1969.

Pratt, H. R., H. S. Swolfs, and A. D. Black, Properties of in situ jointed rock, Final technical report of Environmental Sciences Division, U.S. Army Research Office, Durham, North Carolina, under contract DAH CO4 72 C 0049.

Romm, E. S., Fluid flow in fractured rocks, Nedra, Moscow, 1966.

Seraphin, J. L., Influence of interstial water on the behavior of rock masses, in Rock Mechanics in Engineering Practice, Wiley, New York, 00. 55-97, 1968.

Snow, D., Fracture deformation and changes of permeability and storage upon changes in fluid pressure, Quart. Colo. School of Mines, 6, 244, 1968.

Wilson, C. R., and P. A. Witherspoon, An investigation of laminar flow in fractured rocks, Geotechnical report No. 70-6, Univ. of California, Berkeley, 1970.