LABORATORY INVESTIGATIONS ON THE HYDRAULIC AND THERMOMECHANICAL PROPERTIES OF FRACTURED CRYSTALLINE ROCKS

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LABORATORY INVESTIGATIONS ON THE HYDRAULIC AND THERMOMECHANICAL PROPERTIES OF FRACTURED CRYSTALLINE ROCKS

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INTRODUCTION

The safe underground storage of radioactive wastes requires an understanding of the behavior of crystalline rocks under the influence of thermal and hydraulic stresses. The success of a repository will depend upon the use of such information in design and development considerations. Fracture systems in such rocks play a dominant role in the thermomechanical, as well as the hydraulic, behavior. Lawrence Berkeley Laboratory (LBL) is therefore conducting laboratory studies to investigate the laws of fluid flow in fractures, the dependence of fracture conductivity on the size of the sample tested, and the thermomechanical properties of both intact and discontinuous samples in crystalline rocks. This work provides support to the Geologic Repository Program of the Office of Nuclear Waste Isolation (ONWI) and is part of the Fractured Rock Studies Project and the Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns in Crystalline Rock(1) of LBL.

STRESS-FLOW BEHAVIOR AND THE CUBIC-LAW OF FRACTURE FLOW

Models of fracture flow are generally based on the analogy of flow between parallel plates. For steady, laminar, isothermal flow, the flux per unit head can be expressed as:

$$Q/\Delta h = \frac{C}{f}(2b)^3 \qquad (1)$$

where Q is flow rate; Δh is difference in hydraulic head, C is a constant depending upon flow geometry and fluid properties, f is a factor accounting for roughness and/or nonparallelism, and 2b is the fracture aperture. Equation (1) expresses the "cubic law" for fracture flow. Its validity has been established for laminar flow through open fractures (i.e., fractures where the surfaces are not in contact)(2,3). It is important to establish whether or not the cubic law holds for closed fractures in which the surfaces have some degree of contact and the effective aperture depends upon the stresses acting across the discontinuity. To address this question, LBL, the University of California, Berkeley, and the University of Waterloo have performed tests on fractures artificially induced in intact samples of basalt, granite, marble, and other rocks. Radial and straight flow of water through fractures subjected to normal stress at ambient conditions has been studied(3,4,5). Data from straight flow in fractures in granite is typical and will be used here to summarize the results.

Figure 1 shows the geometry of a 0.121 m wide, 0.207 m long, and 0.155 m high sample. A straight flow field was obtained by closing the sides, keeping the ends open, and injecting water through a small hole into a groove across the middle of the fracture plane(4). LVDT's mounted across the fracture measured normal displacements. Normal stresses were applied in cycles of increasing and decreasing load. Figure 1 shows the relationship between stress and permeability. $Q/\Delta h$ decreases with increasing load and repeated loading cycles further reduce the flow rate, but the fracture does not completely close.

To check the validity of equation (1) it is necessary to know the true fracture aperture 2b. Equation (1) can be restated:

$$Q/\Delta h = \frac{C}{f}(2b_d + 2b_r)^n \qquad (2)$$

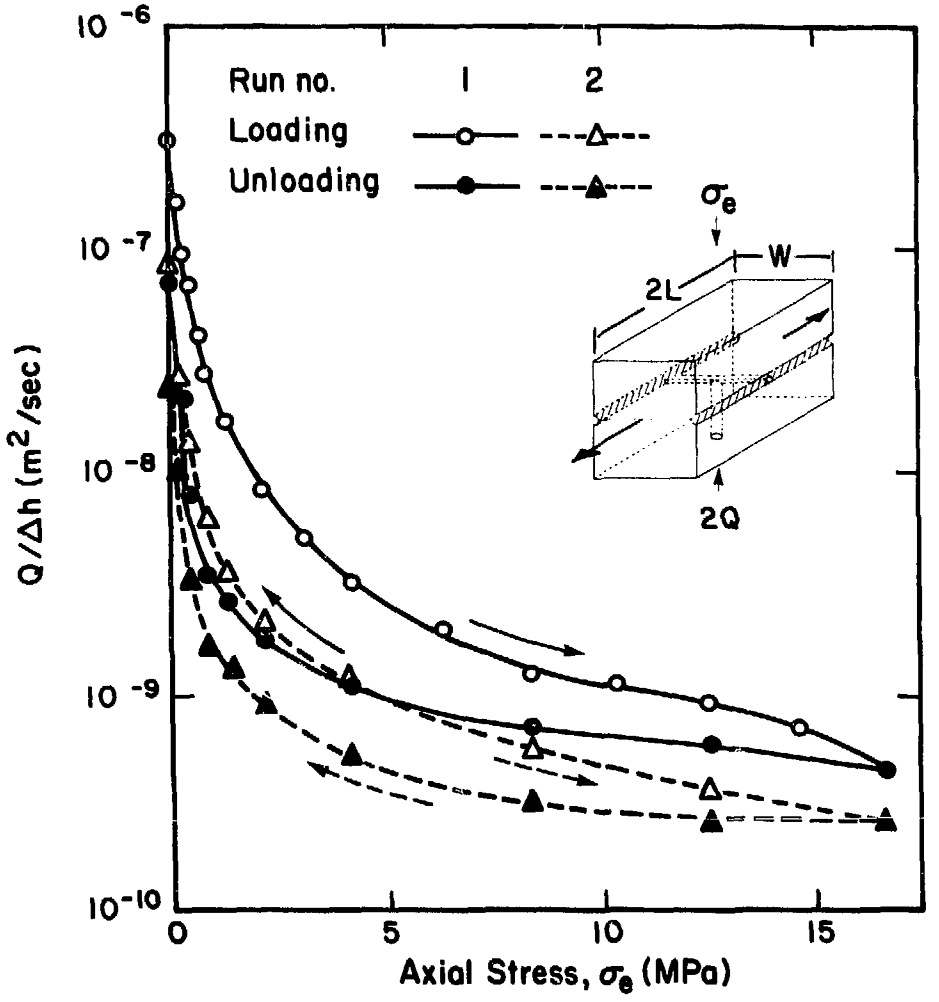

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Figure 1. Stress-flow relationships; straight flow in granite.

where: $2b_d$ is the apparent aperture after a given stress history and is determined from the net fracture deformation, ΔV; and the maximum fracture deformation, ΔV_m, due to application of large stress; and $2b_r$ is the residual aperture after application of large stress (see Figure 2). If f is assumed unity, then the unknowns n and $2b_r$ can be determined$^{(6)}$. Table 1 shows the results of the analyses (fitted values of n and $2b_r$) and includes values of $2b_r$ calculated by assuming equation (1) is valid. The separately calculated values of $2b_r$ agree closely and $n \cong 3$ which demonstrates the validity of the cubic law.

Table 1. Results of least squares fit for parameters of n and $2b_r$.

Sample	Run	Fitted n	Residual Aperture Fitted µm	Residual Aperture Calculated[1] µm
Granite[2]	1	3.04	9.0	7.9
	2	3.03	6.7	6.7
	3	3.01	11.6	11.4
Granite[3]	1	3.07	5.1	4.4
	2	3.04	4.0	3.2
	3	3.06	13.1	10.9
Basalt[3]	1	3.08	10.5	10.0
	2	3.10	10.8	10.4
	3	3.05	9.9	9.8
Marble[3]	1	3.06	2.5	4.0
	2	3.06	2.2	4.0
	3	3.01	18.2	18.1

1 calculated from equation (1)
2 with straight flow
3 with radial flow

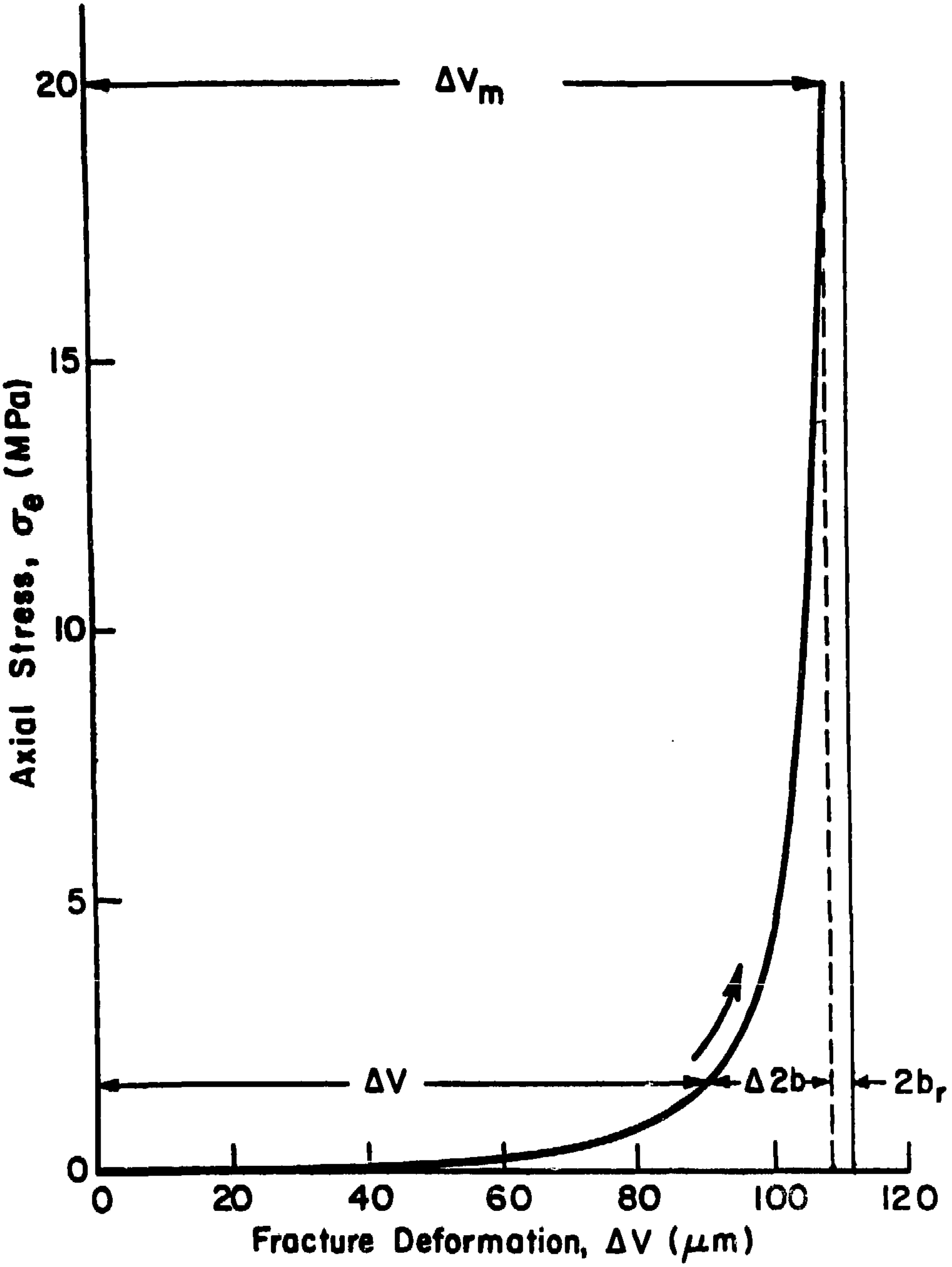

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Figure 2. Stress-deformation behavior of fracture.

By adopting $n = 3$; values of f and $2b_r$ can also be determined from equation (2)(6). Table 2 shows that values of $2b_r$ obtained in this way agree even more closely with values calculated from equation (1). The computed values of f are reasonable and all greater than unity which agrees with previous research results(4,7).

Table 2. Results of least squares fit for parameters of f and $2b_r$.

Sample	Run	Fitted f	Residual Aperture Fitted μm	Residual Aperture Calculated[1] μm
Granite[2]	1	1.21	8.8	7.9
	2	1.15	6.6	6.7
	3	1.04	11.6	11.4
Granite[3]	1	1.49	4.8	4.4
	2	1.29	3.8	3.2
	3	1.32	12.4	10.9
Basalt[3]	1	1.45	9.8	10.0
	2	1.65	9.9	10.4
	3	1.28	9.6	9.8
Marble[3]	1	1.36	2.2	4.0
	2	1.36	1.8	4.0
	3	1.05	18.2	18.1

1 calculated from equation (1)
2 with straight flow
3 with radial flow

Figure 3 shows experimental results expressed in the form of equation (1) and in the alternate form relating friction factor, Ψ, to Reynolds number, Re (4,7). Good agreement with the cubic law is shown over a wide range of flow rates. It is concluded that, in simple fractures unaffected by weathering or shear movement, the cubic law is valid without regard to rock type for closed

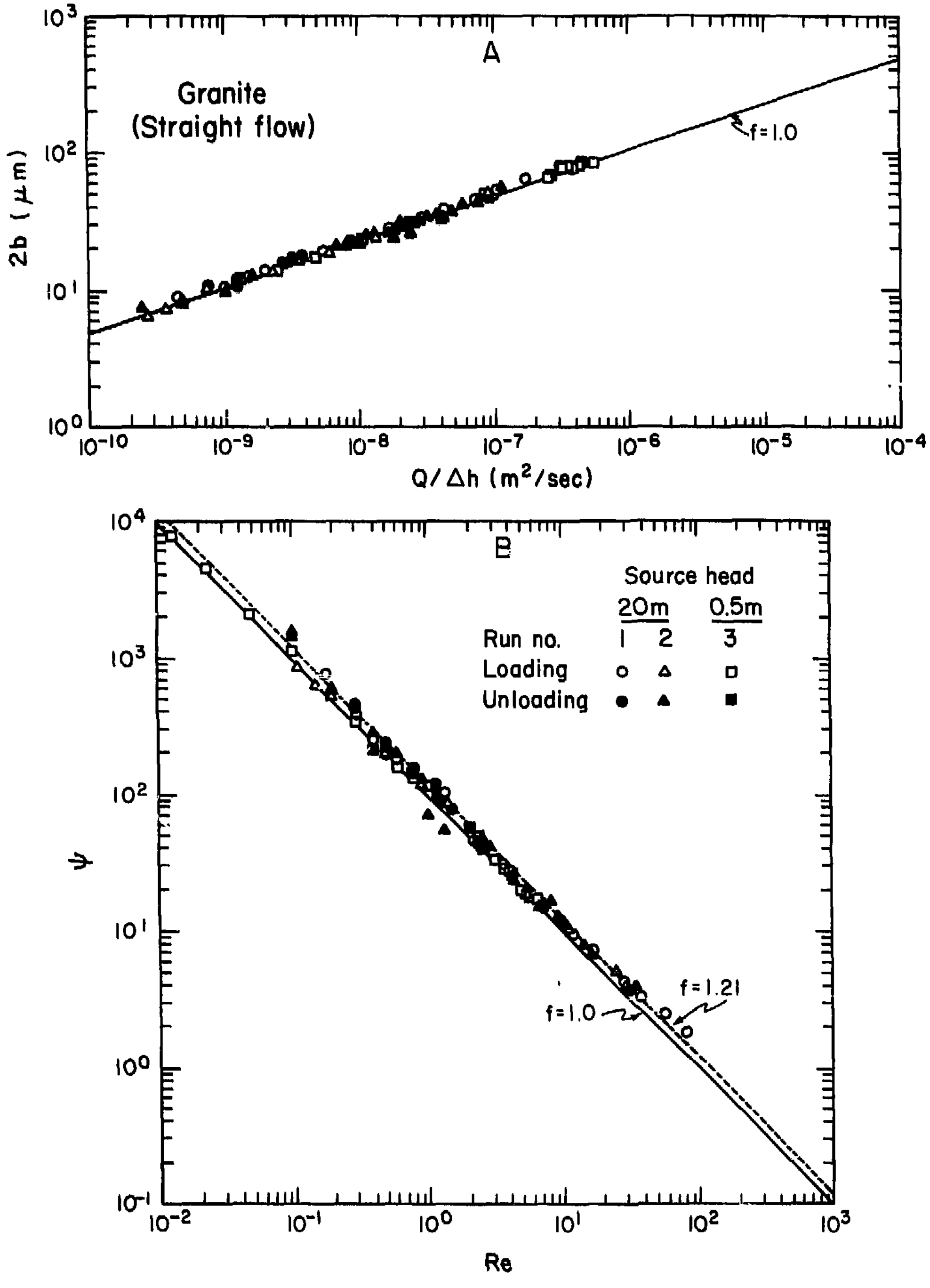

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Figure 3. Comparison of experimental results for straight flow through tension fracture in granite with cubic law.

as well as open fractures. Permeability is uniquely defined by fracture aperture, regardless of stress history. The relationship between roughness and/or nonparallelism is linear and accounted for by the factor f in equation (1).

EFFECT OF SAMPLE SIZE

The fracture permeability studies included radial flow tests on 0.95 m diameter by 1.9 m high cores(3,5). These tests used LBL's large triaxial testing facility (Figure 4). The machine has 5.2 MPa confining pressure and 17.8 MN axial loading capacities. Figure 5 compares stress-flow relationships obtained from these tests with results from smaller samples(4) and from in situ tests on 1 m^2 fractures(8). At high normal stresses a limiting conductivity is reached indicating that a limiting fracture aperture is approached(9). This limiting fracture conductivity increases with increasing fracture area. This suggests that measured fracture conductivity is sample size-dependent and tests on small specimens may yield unconservative underestimates of permeability.

For a systematic investigation of sample-size effects, LBL and the University of Waterloo are gathering specimens of naturally fractured rock ranging in diameter from 10 cm to 92 cm diameter. Figure 6 shows a massive block of granite at the Charcoal Black quarry, Cold Spring, Minnesota, from which a 0.91 m diameter by 1.83 m high sample containing a fracture at mid-height will be cut.

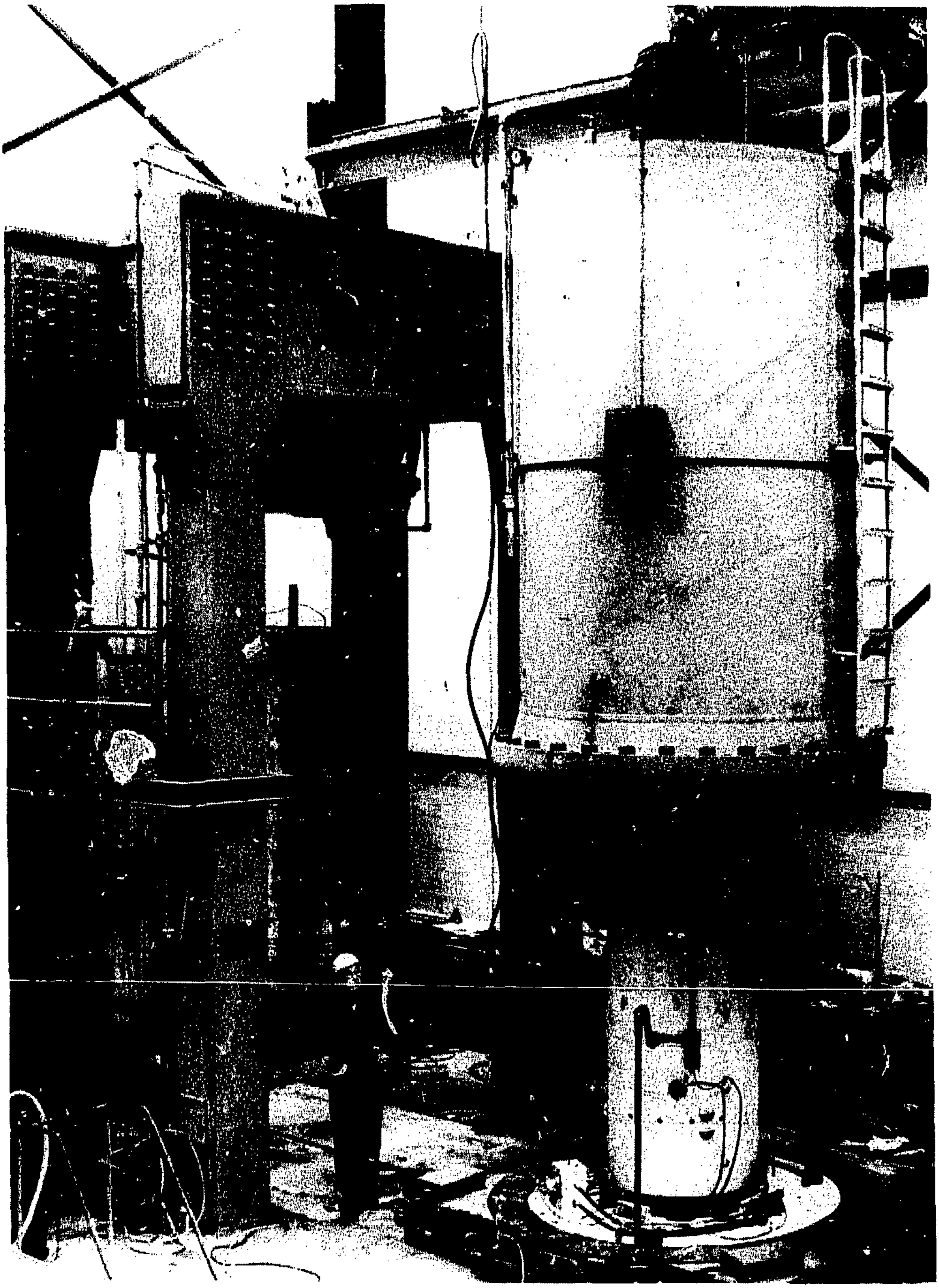

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Figure 4. Large triaxial machine.

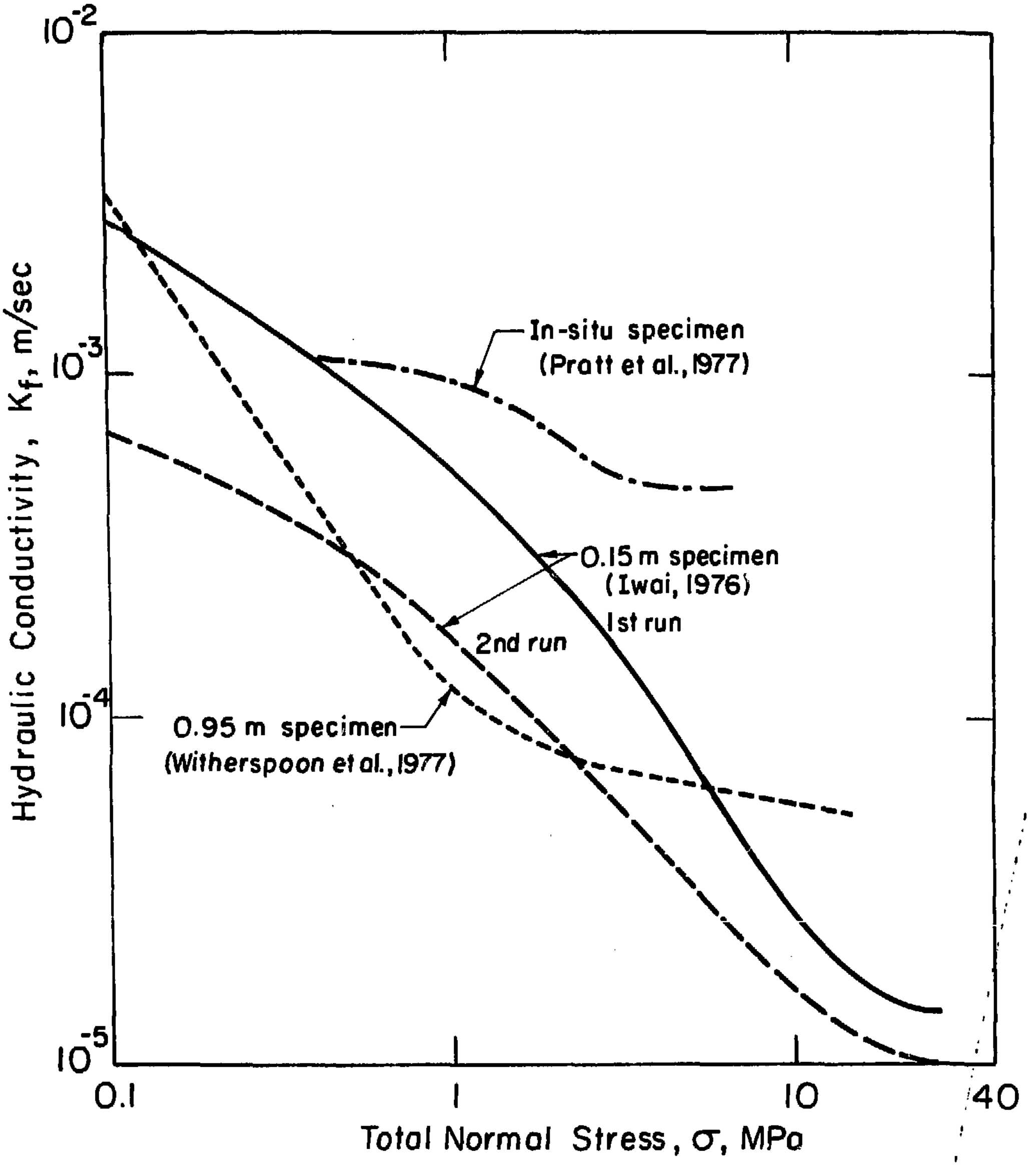

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Figure 5. Stress-flow relationship from various size specimens.

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Figure 6. Fractured block of charcoal black granite.

ULTRA-LARGE STRIPA CORE

A 0.94 m diameter by 1.78 m high granite core has been obtained from the Stripa mine in Sweden. The 3629 kg core has been capped with reinforced concrete and the fracture geometry mapped over the surfaces and from a 7.62 cm diameter hole drilled through the long axis (see Figures 7 and 8). The fractures are 1 mm or less wide and filled with chlorite, calcite, and altered muscovite mineralization. Fracturing is pervasive, but based on preliminary falling head packer tests, the flow paths are dominated by the major intersecting horizontal (A through C) and steeply inclined (D through F) fracture sets. Permeability testing of this core under axial load in the large triaxial machine will assist in understanding the hydrology of the Stripa mine and allow comparison of simple radial flow model results with data from a complex system of natural fractures.

THERMOMECHANICAL ROCK PROPERTIES

Field investigations at Stripa(10,11) have produced a number of interesting results which cannot readily be explained by thermoelastic theory. For example, thermal expansion of the granite adjacent to the emplaced heater canisters is measured to be less than half that predicted for intact rock. Furthermore, it is widely believed that the strength of rock is size-dependent, and limited experimental data support the view that the strength(12) and hydraulic conductivity of discontinuities(9) depend strongly on size, at least in the range from centimeters to about a meter.

An attractive method of endeavoring to resolve and understand these differences involves laboratory testing of the thermomechanical properties of rock

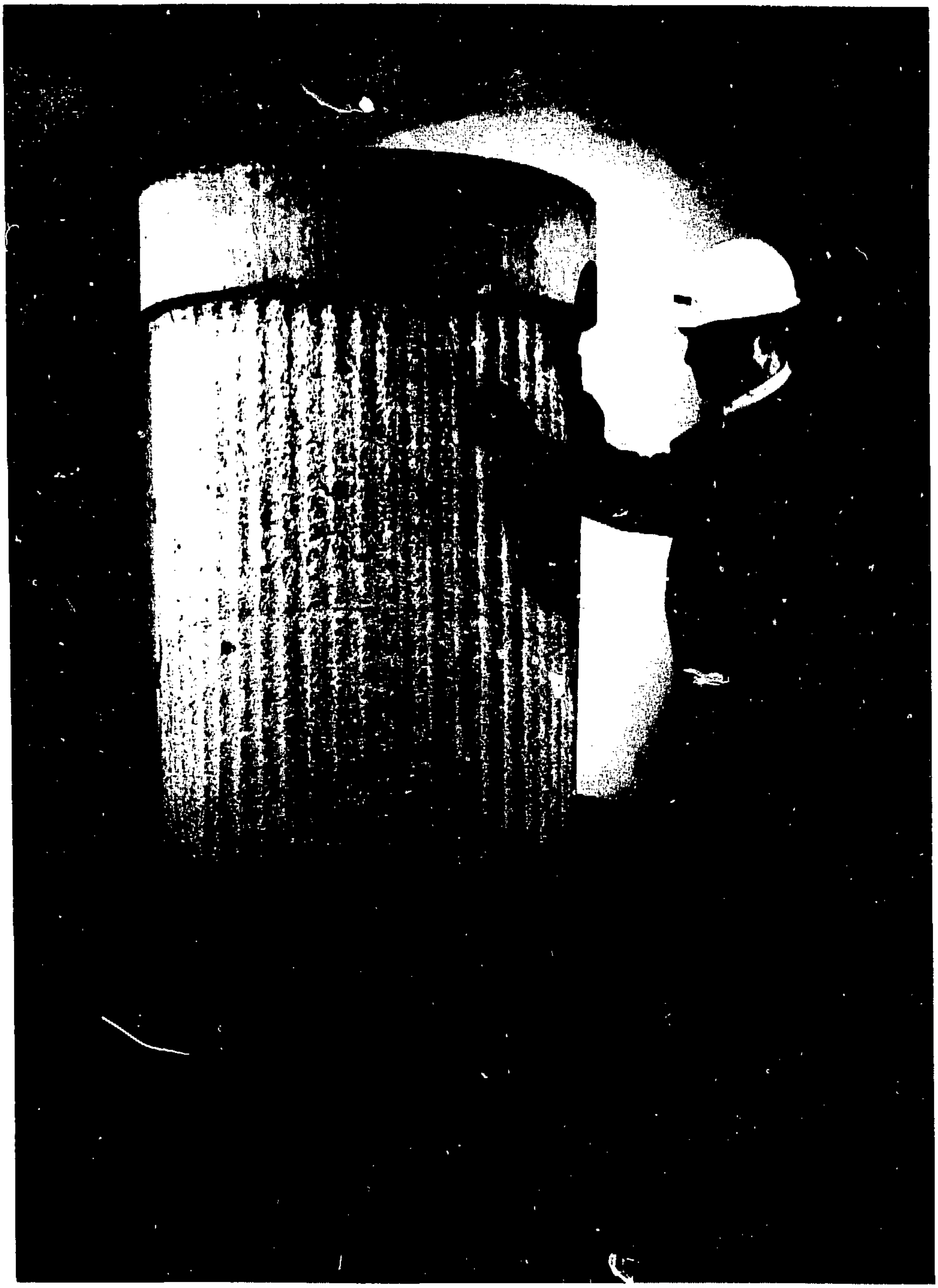

Figure 7. Ultra-large Stripa core. CBB 796-8236

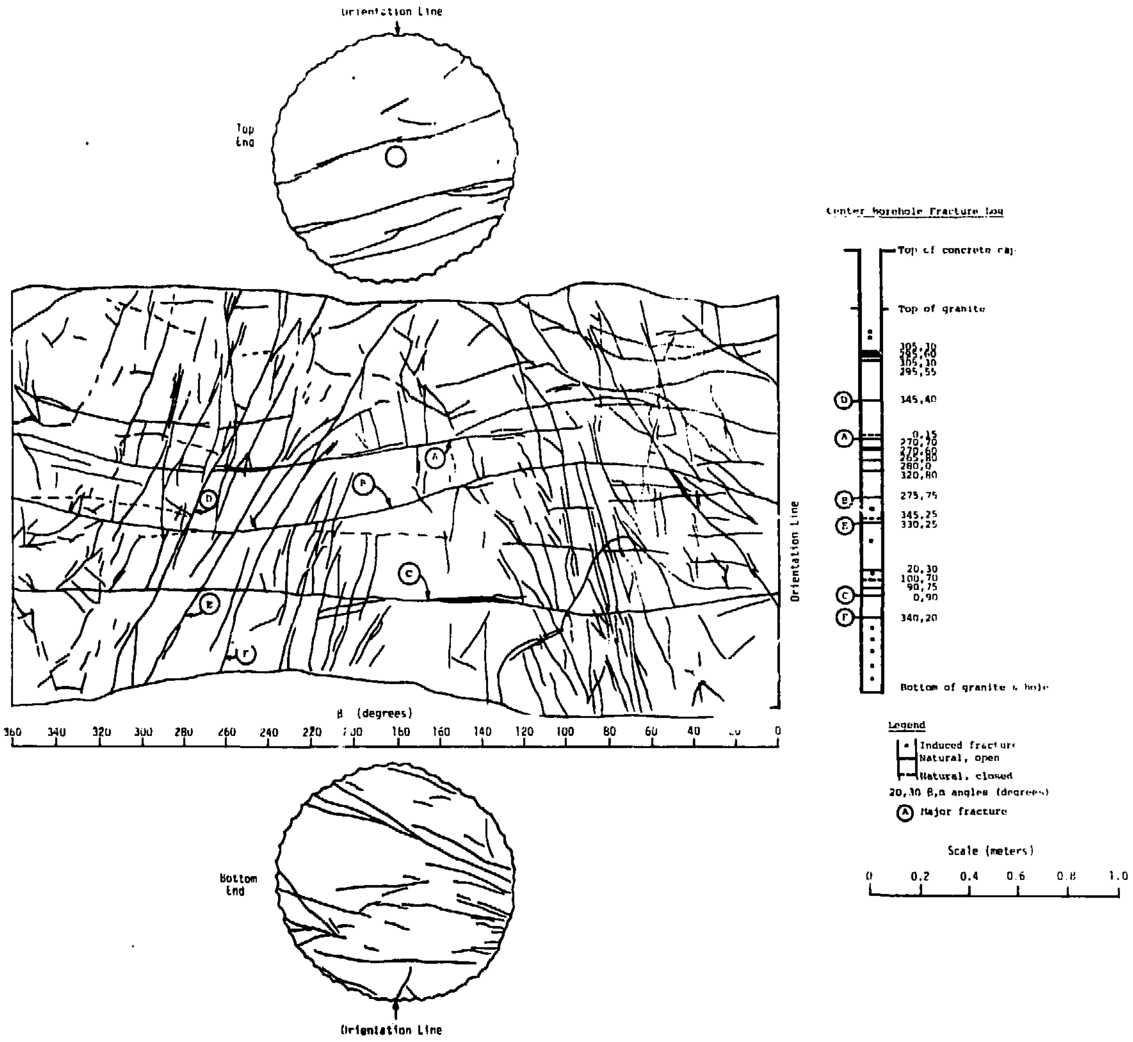

Figure 8. Fractures in the ultra-large Stripa core.

specimens of intact and discontinuous rock. LBL is pursuing this problem in two related efforts. A small-scale testing maching capable of handling samples from 0.05 to 0.15 m (2-6 in) in diameter is nearing completion and will be operational in FY '80. Large quantities of oriented core have been collected in Stripa and are now ready for testing at Berkeley. The measurements will include: thermal expansion, thermal conductivity, Young's modulus, and Poisson's ratio at confining pressures up to 140 MPa and axial loads up to 2.7 MN. The system can operate at temperatures up to 200°C.

The second effort involves a much larger testing facility that is only in the planning stages. We have a preliminary design for a triaxial cell capable of handling rock specimens up to 0.76 mm (30 in) in diameter and 2.28 m (90 in) in height. The cell is being designed to operate at temperatures up to 300°C, and confining pressures up to 70 MPa and will be built to operate in the load frame of the machine shown in Figure 4.

This new test cell will enable the size effect phenomena for both mechanical and thermomechanical loading to be studied in detail on intact and fractured rock specimens. It should be noted that although such large-scale tests are orders of magnitude more expensive than typical laboratory tests on specimens measuring centimeters in diameter, they are also orders of magnitude less expensive, quicker and more certain than the only other alternative, namely, heavily instrumented field experiments. The principal scientific advantage of large-scale laboratory tests over field tests is that the specimen being tested and the conditions of stress, strain, temperature, and pore fluid pressure and chemistry can be well controlled and defined over wide ranges of these conditions, which is never the case in field tests.

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