LA-8912-C
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Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

Workshop on Hydrology of Crystalline Basement Rocks

Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

This work was supported by the US Department of Energy, Division of Geothermal Energy.

LA-8912-C
Conference

UC-66b
Issued: August 1981

Workshop on Hydrology of Crystalline Basement Rocks

Compiled and Edited by

Stanley N. Davis *

*Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ 87521.

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ABSTRACT

Porosity of crystalline rocks will decrease rapidly as a function of depth for weathered and partly weathered rock, which commonly is the first 20 m or so of rock penetrated. Data are not precise enough to define further decreases of porosity, which probably take place at greater depths. Permeability also decreases down to depths of at least 300 m, but decreases beyond about 100 m are not large. Again, data are not precise enough to define decreases of permeability beyond depths af about 300 m.

Various methods of testing boreholes have been developed that may give approximate values of porosity and permeability for crystalline rocks at great depths. Fracture detection by direct and indirect methods will give approximate magnitude and spacing of major fractures. Core inspection may also yield some information on fracture spacing. Packer tests will give apparent values of permeability for local zones, but many problems of interpretation exist. Injecting fluids into or pumping fluids out of boreholes for long periods of time and measuring the hydraulic responses in adjacent holes will yield data from which apparent permeabilities of large volumes of crystalline rocks can be calculated. Rather than pumping or injecting continuously, alternating pulses commonly yield better field data.

Less direct information concerning the hydrology of crystalline rocks may be obtained from (1) surface geophysical studies, (2) rock mechanics studies in mines, tunnels, boreholes, and other excavations into rock, (3) theoretical modeling of heat and fluid transport phenomena, and (4) geochemical studies of fluids and rock cores from great depths in crystalline rocks.

1. INTRODUCTION

The recovery of energy by the circulation of fluids from the surface through hot, but almost impermeable, rocks at great depths is commonly called the hot dry rock (HDR) method of geothermal energy utilization. The HDR concept has been developed most actively by researchers at the Los Alamos National Laboratory in Los Alamos, New Mexico. A key aspect of the HDR concept is the controlled circulation of fluids through artificially produced fractures in the hot rock. To do this, the undisturbed rock should be virtually nonpermeable, or if significant original permeability exists, its distribution in the rock should be understood sufficiently to allow necessary engineering modifications to be made to the fluid circulation and recovery systems. Consequently, the hydrology of these deeply buried rocks is of great practical interest.

In addition to interests in HDR energy recovery, the understanding of the hydrology of deeply buried crystalline rocks is critical to the design of nuclear waste repositories and energy storage systems, as well as to the interpretation of several geological phenomena including the origin of ore deposits and shallow-focus earthquakes. Although the workshop itself concentrated on only the hydrology of crystalline rocks, the participants were uniformly interested in focusing attention on those aspects of the hydrology that would be of potential use in the many practical and theoretical problems related to these rocks.

The workshop was held in the Arizona Inn near the University of Arizona on October 18 and 19, 1979. In addition to the 26 regular participants listed in Appendix A, 3 graduate students from the Department of Hydrology of the University of Arizona attended and contributed to the workshop. These students were Paul A. Hsieh, Elizabeth Jacobson, and Sharon M. Trost. The various arrangements for the workshop were coordinated by Ms. Trost.

The general organization of the workshop is given in Appendix B. Various subgroups were formed, which addressed restricted subtopics and prepared short position papers that have been edited to form the bulk of this report. In addition, individual reports were prepared by some of the participants. These are included as Appendixes C, D, and E.

Most of the workshop discussions were concerned with hydrologic properties of plutonic igneous and medium- to high-grade metamorphic rocks, loosely called crystalline rocks in this report. Even though the objective was to consider rocks that are currently at depths of between 1 and 10 km, the bulk of existing data on hydrologic properties of crystalline rocks has been obtained from much shallower depths. Consequently, considerable attention has been given to conditions at the shallower depths with the hope that some of the information will give useful suggestions of rock properties deeper within the Earth.

2. MEASUREMENTS IN RELATIVELY SHALLOW BOREHOLES (Contributors: Snow, Chairman; Davison; Hsieh; and Richardson)

2.1. The Fractured Rock Problem

The hydrogeologic properties of crystalline rock, and their differences with regard to sedimentary rock in particular, have to be fully realized before the planning of field testing to allow for reasonable and realistic interpretation.

The fact that crystalline rock has extremely low primary permeability, for most practical purposes almost negligible, increases the demand on more thorough characterization, definition, and classificaion of fractures and fracture systems. In modeling, the systems of small fractures might be assumed to be a primary permeability whereas the secondary permeability will be represented by major fractures. However, the fracture interconnections are more complex than in layered rock. Both the lack of primary permeability and the complex interconnections influence the scale of modeling and field testing as well as the need for three-dimensional solutions. Because the cost of drilling and testing at great depths is very high, it will be prudent to incorporate also an analytical modeling phase into a field program planning.

By the same token, to improve reliability of the field data, drilling and testing operations should be supervised by knowledgeable personnel, and the drilling and testing parameters recorded as accurately as possible.

The current drilling techniques quite often alter the in situ conditions. This alteration is due to local changes in the stress field as well as the intrusion of the drilling fluids into the fractures. The effects are mechanical (deposition of drill cuttings or erosion of natural fracture fillings), overall physical strain (induced by pressure and thermal changes) and chemical (fracture filling alteration caused by dissolution or precipitation). In a few test holes hydraulic fracturing has been experienced during drilling operation, particularly when tools are stuck downhole.

2.2. Fracture Definition in Boreholes

Direct inspection of cores will yield some information on fracture frequency but little quantitative information on fracture apertures. Fracture definition is limited at present to about 0.1-mm apparent aperture, using TV and seisview loggers. When refined depth location can be attained, short-interval packer injection testing will facilitate hydraulic identification of finer cracks, perhaps to the size of a few microns. Currently, the stretch of support systems more than 100 m long necessitates packer separations of 1 m or more, whereas a system of borehole wall benchmarks would permit identificaion of fine joints otherwise included with the matrix. (Matrix permeability should include principally the effect of microcracks as opposed to joints, the latter being defined as semiplanar ruptures, spanning the dimensions of the borehole diameter, that would be manifested as flat surfaces upon excavation of larger openings.) Certain tools promise improvements of resolution. These include detailed thermal logging of flowing systems, single and multihole tracer methods, and resistivity logging of fractures during hydraulic testing.

2.3. Hydraulic Testing in Boreholes

The most commonly used hydraulic test in boreholes is the constant pressure injection test. Hydraulic conductivity can now be measured (using steady-state analysis) approaching the matrix conductivity of crystalline rocks (10^{-10} to 10^{-9} cm/s).

Transient pressure testing appears to be a promising method for measuring conductivity of rocks with conductivities too low to be measured by constant head injection methods. The analysis of transient tests, however, requires taking into account the effects of storage. Currently, the origin and nature of storage in fractured rocks is ill-defined. Storage is likely dependent on both fluid and fracture compressibility. The interaction between water pressure and rock stress during transient injection test can be examined by transient finite-element modeling.

The perturbing effects of the drillhole on the medium are ill-defined. Whereas continuum-elastic analysis suggests that the effect is limited to a few hole diameters from the center of the core, the presence of deformable fractures inclined to the hole should be the subject of further investigation through modeling. Furthermore, the hydraulic perturbation of the potential field produced by the drilling fluid, or by the necessity of maintaining centripetal flow for the prevention of contamination, imposes constraints on subsequent hydraulic testing. In a nonlinear system, superposability is lost so that normalization or adjustment of results (conductivity and storage) to design conditions requires new modeling efforts.

2.4. Assessment of Rock Properties from Borehole Data

The assessment of rock properties remote from the borehole will always be an important objective, for reasons of economics as well as the preservation of *in situ* properties. Remoteness can be enhanced by employing flow tests of increased duration, by employing interference between adjacent holes, and by employing multihole tracer methods.

The ability to predict the degree of interconnection among fractures is severely limited from a single borehole, or even from multiple holes. There is as yet a poor understanding of the hydraulic effects associated with diversely oriented fractures. Heterogeneity and lack of fracture connections will likely manifest themselves as scale effects, so that the "effective permeability" of a rock mass will depend on the scale of interest. A possible approach to the study of the scale effect through models is to randomly generate fracture networks consisting of fractures of finite lengths and then compare the hydraulic conductivity of such a network to a network of continuous fractures. Such a study may reveal the magnitude of error owing to the assumption of continuity.

2.5. New Problems and Research

Hard rock systems seem to offer new and difficult problems in that the low frequency of fractures in many cases suggests a scale of heterogeneity that may negate the use of existing solutions in both the petroleum and ground-water fields. One important study should be the affect of scale (well spacing, fractures per meter of well base, mean permeability, etc.) on apparent homogeneity of a fracture flow system.

Another problem concerns quantitative estimation of porosity by either interference or tracer testing. For water-filled systems, tracer methods may be superior to pressure transient methods.

Another problem relates to the actual fracture patterns. It is likely that areas of high fracture density connect only tenuously, thus the conductivity of a large fracture system could be controlled by the low conductivity connections. Study of idealized models of fracture patterns could establish the composite conductivity of such systems.

3. MEASUREMENT AND INTERPRETATION OF DATA FROM DEEP BOREHOLES (Ramey, Chairman; Black; Jarolimek; and Neuman)

3.1. Well Testing

Several methods utilize water-level data from deep wells and boreholes for estimating the hydraulic properties of jointed rocks. Most of these methods treat the rock as a homogeneous and anisotropic porous medium. The problem thus reduces to determining the orientations and values of the principal hydraulic conductivities and other parameters, primarily storage. The methods can be classified as follows.

3.1.1. Layered Systems. Most existing tests assume that principal directions of hydraulic conductivities lie in the horizontal plane and the vertical direction, based on experience in sedimentary environments.

Horizontal Plane. This method assumes the use of data from fully penetrating pumping wells and several similar observation wells. The interpretation is based on a variation of the Theis model that assumes horizontal flow. Anisotropy can be eliminated by using a transformation of coordinates.

Vertical Plane. Here, the methods can be divided into those where a single formation is assumed to be anisotropic in the vertical plane, or where anisotropy arises due to layering (leaky aquifer systems).

Single Layer. The ratio of apparent conductivites, K_z/K_r, can be determined by creating vertical, as well as horizontal, flow conditions. This can be done by pumping partially penetrating wells or by testing well intervals isolated by packers. The interpretation relies on the effects of interference among wells. A single well method has been developed by Weeks, but it has not been tested widely.

Multiple Layers. The ratio method of Neuman and Witherspoon will yield the vertical K of low permeability layers in the vicinity of aquifers.

3.1.2. Fractured Systems. Hydrology techniques for fractured aquifers rely on the double porosity model (Streltsova) or on the idea of an equivalent single fracture (Gringarten).

Double Porosity Model. There are analytical solutions for the case of horizontal flow in a fractured aquifer, primarily by Streltsova. The double porosity assumption causes the type curves to exhibit an inflection, assuming that the early limb is due to water released from fractures, and the later limb due to release from blocks.

Equivalent Single Fracture. The idea in this model is that a naturally fractured aquifer may be represented as one in which the producing well is traversed by a single vertical or horizontal fracture of finite extent. Gringarten has developed methods for determining the equivalent fracture properties.

3.1.3. Field Engineered Systems. Several wells (at least three) at different orientations are drilled to estimate three-dimensional variations in hydraulic conductivity. One method attempts to determine the principal directions as well as values from three wells, which may or may not be oriented in the principal directions. Another method attempts to rely on fracture sampling data to determine principal directions, and three wells are subsequently oriented along these directions to obtain values of hydraulic conductivity.

3.2. Research Needs in Water Well Testing.

To obtain hydraulic conductivity (K) at depth, methods based on vertical boreholes must be developed. Both single well and interference test methods are needed to obtain a local K and degree of fracture interconnection as well as a larger scale effective K.

Tracer techniques are needed to determine porosities, velocities, dispersivities and their dependence on scale (spread of tracer).

Reliability of parallel plate models to predict K, or some aspects of K, should be tested.

In Short. A site at which crystalline rocks are similar to those of the proposed HDR, repository, or other development should be chosen for intensive field experiments. A large number of wells should be drilled into the site. The most up-to-date techniques should be used to characterize apertures, spacing, orientation, and microcharacteristics of fractures in the test site. The data should then be analyzed to attempt to answer the above needs.

3.3. Recent Trends in Instrumentation and Techniques for the Study of the Hydrology of Crystalline Rocks

The investigation of crystalline rock hydrology as part of nuclear waste disposal projects has introduced new expensive equipment and techniques into the field. This has involved the development of small-diameter versions of pre-existing equipment with necessarily high resolution. Small flow rate, high-head pumps powered hydraulically and pneumatically have been developed in Sweden and Canada. They have been designed to run between high-integrity small-diameter straddle packer systems in conjunction with downhole water density packages and multiple transducers. The systems currently being developed worldwide are about equally divided between wire-line and tubing-run systems. Most drilling techniques have been used ranging from rotary percussion to reverse flushed diamond drilling, together with air and water as flushing fluids. Many studies of the hydrologic characteristics of crystalline rocks have detailed radius/permeability and time/permeability variations, which have been related to borehole drilling rather than the natural characteristics of the rock. Considerable effort is now being directed towards sorting out the artificially caused effects from those related to the in-place nature of the rocks.

3.4. Useful Techniques from the Petroleum Industry

Although a host of wireline borehole devices is used to measure physical attributes of formations near the wellbore, fluid flow measurements remain the only practical method for detection of connectivity of the permeable zones, the conductivity and storage capacity of these zones, and the existence of various important system boundaries. Single well production and build-up tests are used to measure permeability, well condition, presence of fractures, and mean pressure (pore volume) on a per-well drainage area basis. Interference tests involving two or more wells are often run to determine the distribution of permeability and presence of flow barriers or boundaries. Interference tests may be either continuous flow, one flow and recovery after shut in, or pulsed with intermittent production and shut in. Either constant rate or constant pressure production solutions (type curves, equations, etc.) are available. These tests are in popular use today to characterize formations targeted for enhanced oil recovery.

Popularity of interference testing is recent. The reason involves a fortunate combination of developments in several fields. Development of high-precision pressure gauges, development of small high-capacity computers, and improvement in mathematical methods make sophisticated interference testing and analysis possible. This technology is developing rapidly today and offers the promise of expanding usefulness, including the study of fractured crystalline rocks.

3.5. Research Needs in the Petroleum Industry

The following checklist gives the general nature of major research needed in petroleum engineering to better define the hydrology of dense, fractured rocks.

(1) Improvements in drilling techniques.

(2) Planning of the field programs should include a phase of analytical modeling based on preliminary data.

(3) Improvement and development of downhole logging techniques aimed to fracture characterization.

(4) Improvement of test systems (single-hole, two-hole, group-holes).

(5) Research and development in instrumentation (sensors, detectors) and their installation.

4. HYDROLOGIC PROPERTIES OF CRYSTALLINE ROCKS AS INTERPRETED BY GEOPHYSICS AND FIELD GEOLOGY (Contributors: Nur, Chairman; Bird; Petersen; Sbar; and Simmons)

4.1. Introduction

In general, geophysical exploration methods provide estimates of spatial distributions in a rock volume of various physical properties from physical measurements made on limited portions of the surface bounding the volume. These can be the Earth's free surface or the cylindrical surfaces of boreholes. The physical measurements typically involve the application of some sort of physical field from the surface and the measurements of the medium response, also on the surface. Commonly some sort of inversion method is employed to obtain the physical properties, by matching the controlled input and the observed output. Further analysis is, of course, required to relate the estimated physical property to the actual state of the rock.

One of the least developed areas of the application of geophysical methods is fractured rock mass. Because interpretation of the response is always somewhat nonunique and the relation between physical properties and the state of fractured rock is very poorly known, a large amount of research can and should be done in this area.

This portion of the workshop report evaluates what can be done with geophysics and techniques of field geology to determine or help to determine

(1) Amount of water and its properties as a function of depth in the crust.

(2) Porosity and permeability.

(3) Processes that create or annihilate porosity and permeability.

(4) State of stress.

(5) Change of pore pressure, porosity, permeability, and flow with time.

The methods that might be employed are reviewed and then the main results to date are summarized. Finally, new techniques are suggested that might be developed to improve knowledge of the hydraulic state of the crust.

4.2. Current and Experimental Geophysical Methods

At present, several geophysical methods appear to be capable of providing information that is pertinent to the hydraulics of the crust. The most important methods are discussed briefly in the following sections of this report.

4.2.1. Electrical. A wide range of electrical and/or electromagnetic techniques is currently available for estimating electrical conductivity as a function of depth. Magnetotelluric, audio-magnetotelluric, resistivity, and dipole-dipole methods are presently in use. Obviously, the hydraulic permeability must be related to electrical conductivity to use the data. Unfortunately, a unique relationship does not exist; and the interpretation of electrical data involves such items as temperature, salinity of fluids, and the type and amount of rock alteration present. The three primary research needs are (1) improvement in three-dimensional analysis of data, (2) field studies, including drilling of regions in which conventional interpretation yielded erroneous results, and (3) stronger sources for dipole-dipole methods such as superconducting coils.

4.2.2. Seismic Velocities. The relationship between seismic velocities and permeability is through the mutual effect cracks in rock have on both physical properties. The effect on seismic velocity is most pronounced for dry cracks. For saturated rock, the seismic velocities satisfy the law of effective stress. At low effective stresses, shear velocities are like their dry value, whereas compressive velocities are significantly higher. At high effective stresses, cracks close and both velocities approach their intrinsic, crack-free value. The greater the difference between the *in situ* and intrinsic value, the greater the crack porosity and hence permeability.

To quantify the relationship between seismic velocity and permeability requires knowledge of the intrinsic velocity. Laboratory and borehole velocity measurements are necessary to establish the scale effect of various sized cracks. Laboratory measurements can establish microcrack occurrence; borehole measurements can define the positions of joints; and seismic measurements can help establish the nature of regional fracture patterns. These different measurements, if made in the vicinity of short- and long-term hydrologic testing of drill holes, could establish the use of seismic velocities for regional mapping of permeability.

4.2.3. Seismic Wave Attenuation. Recent studies of the mechanisms responsible for seismic wave attenuation in porous and cracked rocks with fluid have shown conclusively that the dominant mechanism is the local fluid flow induced by the passing wave. This flow involves viscous energy dissipation, that is, energy which is extracted from the wave, causing it to diminish in amplitude with travel distance.

The attenuation of shear waves is also particularly large at low effective stress, which is the difference between confining and pore pressure. Consequently, precise seismic wave attenuation measurements may be useful in delineating regions with cracks and fluids, particularly at high-pore pressure (if they exist).

No adequate methods for accurate attenuation measurements exist currently. Several methods may possibly be used to provide the necessary resolution: short-period surface waves, high-frequency body waves in refraction, or high-frequency reflection seismology using wide spreads.

4.2.4. Seismicity. Artificial stimulation of earthquakes by controlled changes in the injection of water in wells or variation in the water level in reservoirs can yield information on several parameters of hydrologic interest at depths to 10 km and possibly deeper. In particular, estimates may be made of the pore pressure at depths based on the assumption of a connection to the surface. The migration of earthquakes in time not only yields an estimate of permeability but may provide insight into the three-dimensional nature of the migration of a pressure front. The influence of the stress field on the migration can be inferred from fault-plane analyses.

4.2.5. Gravity and Magnetics. Gravity and magnetic surveys provide constraints on the three-dimensional distribution of rock types. Under favorable conditions, the rock types to depths of 10 km can be estimated reliably. Furthermore, the presence of faults, their attitude, and vertical extent can be determined from such data. Many areas in the United States have existing surveys that are of suitable quality for the interpretation of regional geology.

Three primary research needs related to gravity and magnetic methods are: (1) regional gravity surveys of greater detail and accuracy, (2) Jorat inversion of combined geophysical data sets, and (3) theoretical modeling of three-dimensional bodies.

4.2.6. Heat Flow. Heat flow in shallow boreholes in crystalline rock can be a measure of deeper permeability when the holes are located in part of a ground-water system in basement rocks. Extremely high heat-flow values in discharge zones are good indications of a deep circulation system. Quantification of permeability from heat-flow measurements may be possible through numerical modeling.

4.2.7. Crustal Deformation. A variety of surface deformation phenomena have been observed and explained that are related to the changes in pore pressure in the crust. Subsidence due to fluid withdrawal from aquifers or reservoirs is quite common. Typically, surface subsidence is 1/20 to 1/40 of the lowering of the hydraulic head in confined aquifers in alluvium. Our knowledge of rock deformation due to changes in pore pressure might, therefore, eventually be used to infer hydrological parameters from crustal deformation changes. At present, neither theory nor data are sufficiently adequate for this purpose.

4.2.8. Surface Tilt. Measurement of tilt is essentially a small-scale technique for mapping the migration of fluid away from a borehole. It is a relatively new method, and the resolution has yet to be determined. Such tilt measurements may eventually be used to infer the permeability of water-bearing zones in crystalline rocks.

4.2.9. In Situ Experiments. A definite need exists for a controlled experiment that lies in scale between laboratory and regional studies. The use of an area of exposed rock, probably granite, is suggested so that detailed mapping of fractures at the surface can be done. A number of shallow (~200 m) boreholes would be drilled at close enough spacing to define the structure and for controlled tests of permeability without severely modifying the environment. The situation would then be suitable for performing any number of geophysical tests for calibration and for evaluation of new methods.

4.3. Geological Studies

A number of geological studies are needed to understand better the nature and hydrologic significance of fractures and other features in crystalline rocks. Two general areas of investigation are given below.

4.3.1. Geological Study of Joints, Fracture Lineaments and Faults. Much has been said about the spatial and temporal distribution of joints, joint patterns, and lineaments. What we actually know is, in contrast, extremely limited. Because much of crustal hydraulics is quite likely controlled by existing joints, fractures, and faults, these features should be studied *in situ* wherever possible. The most important problem is the question of depth of jointing and fracturing, and the ability of the joints and fractures to sustain hydraulic flow.

Furthermore, the role of these features probably cannot be evaluated without understanding their origins. This understanding will require combining field observations with testable mechanical models in a variety of rock types such as layered sandstones, granites, and alternating soft and hard sedimentary rocks.

Finally, more extensive studies of in situ permeability of fractures, as well as faults are necessary. It is becoming apparent, that the permeability of most fault zones in crystalline rocks is systematically anisotropic--with easy flow parallel to the fault plane, and slow or no flow perpendicular to the fault plane. Additional field tests for anisotropy along faults must be made to determine whether the magnitude of this effect increases with the amount of offset, possibly due to increased fault gouge accumulation.

4.3.2. Deep Crystalline Rock Environment. The permeability of crystalline rock in the 1- to 10-km-depth range must involve to some extent: (1) deformation processes that may tend to open fluid conduits such as microcracks, joints, faults, and breccia zones and (2) healing processes that tend to close them such as flow and precipitation. The resultant permeability will depend on the relative rates of the two competing processes. Regions of active tectonic deformation or active igneous intrusion may exhibit the highest permeability for any given set of temperature, pressure, and chemical conditions.

Both field and experimental studies could contribute information on these processes. Field studies would include examination of fracture geometry, time sequence and filling chemistry in rocks of relatively well-known ages, pressure-temperature history, and water and rock chemistry. Specific experimental studies of deformation and fracture-healing might be used to supplement field observations.

4.4. Conclusion

We suggest that several geophysical and geological methods, some of which are well established and others which have not been developed as yet, might provide new data on the hydraulics of the crust to a depth of 10 km or so. These include electrical methods, high-resolution seismic velocities, attenuation of seismic waves, gravity and magnetics, study of seismicity, heat flow, in situ controlled experiments, crustal deformation, surface tilt, and geological studies of joints, fractures, and faults and filled cracks in metamorphic rocks.

5. ROCK MECHANICS RELATED TO HYDROLOGY OF CRYSTALLINE ROCKS (Contributors: Brace, Chairman; Cook, Cornet, and Daemen)

5.1. Introduction

It is generally agreed that discontinuities exist in rocks. The dimensions of these discontinuities range from micrometers to kilometers. Their importance hydrologically is that they constitute the major conduits for fluids flowing through rocks and provide spaces for some fluid storage. Insufficient information is available about all of these discontinuities to characterize them completely. Even if this were not so, determining the hydrologic properties of a rock mass from a complete knowledge of the discontinuities in it could prove to be a formidable task. Accordingly, the main emphasis is to endeavor to measure the hydrologic properties of a rock mass from boreholes in some manner that ensures that the measured values are relevant to the problem in question. Such direct measurements become uncertain when the properties of large volumes of rock *in situ* need to be known, especially in many crystalline rocks that are commonly very heterogeneous in relation to the structure that determines their hydrologic properties.

5.2. Prediction of Permeability from Cavity Shape

Flow of fluids through rocks at the rates observed requires an interconnected pore space or network of cavities. Can permeability be predicted if cavity geometry is known? Some results suggest that it can for centimeter-sized samples, but that the procedure will have little or no applicability for rock masses of 10- to 100-m dimensions.

The significant cavities in small samples of intact sedimentary and crystalline rocks are intragranular pores and cracks, and apertures range from a millimeter down to a fraction of a micron. These cavities can be studied with the optical and electron microscope and apertures measured for a representative sample. A number of studies have shown that permeability, k, can be determined from

$$k = \frac{\bar{w}^2}{c} \eta^x \quad , \tag{1}$$

where $\bar{w}$ is an averaged aperture, η is interconnected porosity, c is a constant, and x a power that ranges from 1 to 2.

An immediate problem in the use of Eq. (1) is how to determine $\bar{w}$ from the range of values of w, which are measured for a particular rock. Most current thinking is that the geometric mean should be used, but the basis for this conclusion is obscure. One recent study showed that geometric mean aperture of some 500 cavities when used in Eq. (1) predicted k to about an order of magnitude over a range of permeability from 10 nanodarcys to 1 darcy. Thus, prediction of k from cavity geometry in small samples is possible, within limits. But can this be applied to a rock mass? Presumably Eq. (1) might hold, as long as cavity shapes were simply scaled-up versions of the microcavities of small samples.

An immediate and overwhelming problem is determination of cavity shape in a rock mass. No analogous procedure for making a series of sections exists underground, as in the laboratory, at least at current budgets. Borehole observations are practically the sole source of information, and measurement of fracture aperture has so far been rather unsuccessful in a borehole. Neither conventional logs, nor present spinner logs, nor nonoptical, nor acoustic devices seem to yield meaningful values of $\bar{w}$, that is, in the sense of prediction of k. Davis showed clearly during this workshop that actual fracture conductivities were largely unrelated to apparent $\bar{w}$ as measured at the borehole. Thus, in contrast to laboratory samples, neither the geometry of single cavities nor a meaningful average can be obtained at this time.

We conclude that the prediction of permeability of rock masses from measured fracture geometry is not now feasible, although work on logging $\bar{w}$ in boreholes should continue. At present, the permeability and porosity of large volumes of deeply buried crystalline rocks can only be estimated with some confidence by hydraulic measurements made in the field within deep boreholes.

5.3 Effects of Stress

From field experience and from laboratory studies, the stress across discontinuities is known to affect their dimensions and, therefore, their hydrologic properties. Fundamentally, this is a coupled problem because it is the effective stress, that is, the difference between the total stress and the fluid pressure, that is of significance. This problem possesses also an additional degree of complexity, in so far as the state of stress is generally deviational and, probably, has a significant effect on the hydraulic connectivity between most discontinuities. This affects importantly the permeability tensor of the rock.

Unfortunately, measurements of hydrologic properties in the field usually are not accompanied by measurments of the complete state of stress. Accordingly, endeavors to define hydrologic properties of rock in terms of observed properties of the discontinuities may be confounded by the absence of information concerning the state of stress.

Boreholes are the principal means of gaining access to a rock mass for hydrologic measurements. Because of the costs of drilling deep boreholes, exploratory measurements and research often is done in boreholes only of the order of 100 m in depth. Surface effects, including anomalous and unmeasured states of stress, may have a dominant and misleading effect on the results of shallow experiments of this kind.

Finally, it is recommended strongly that the determination of the complete state of stress in the rock is an important component of any measurement of *in situ* hydrologic properties.

5.4. Problem of Borehole Disturbances

Boreholes, and in fact all excavations, constitute a significant disturbance of the natural state of the rock. Although a complete discussion of the problem was beyond the scope of the workshop, its importance was emphasized repeatedly during the meetings. The following checklist was prepared to outline the extent of the problem and, perhaps, give some direction to much needed research that should be undertaken.

5.4.1. Influence of Drilling Method

- energy transmitted to the rock
- stress field induced in the rock during drilling, e.g., starting from thrust and torque
- drilling methods: cable, rotary, percussion, diamond coring, etc.
- fluid effects:
  mechanical, pressure, flow (erosion), temperature, physico-chemical

5.4.2. Changes in Stress Field

- permanent: both core and hole
- transient: at hole bottom

5.4.3. Depth of Zone Influenced by (Excavation) Drilling

- hole surface: "contamination," "cleaning," mudcaking, etc.

- depth of stress field changes: static
  - influence around circular hole
  - influence through penetration in pre-existing discontinuities
  - influence through formation of new discontinuities
- influence depth of dynamic effects
  - drilling shocks
  - pumping pressure pulses

5.4.4. Influence of Explosives During Excavation

- static
  - radial cracking/gas pressure
  - rock pulverizing
- dynamic effects of stress pulses

5.4.5. Possible Research Topics Related to Disturbances Caused by Drilling

- study of microfracturing of rock samples recovered from boreholes drilled by several methods
- laboratory study of rock samples subjected to (elastic) stress pulses

5.4.6. A Conclusion. An explanation for unexpected disparities might be found in enhancement or concealment of permeability owing to the complex effects associated with various excavation methods.

5.5. General Recommendations for Laboratory Research

Laboratory studies form an important element in hydrogeologic investigations relevant to waste isolation, hot dry rock, and other energy resource applications. Several directions of research that seem promising are suggested.

5.5.1. Meter to tens-of-meter scale experiments of the sort done by Gale, Iwai, and Pratt of flow through artificial and natural fractures, as a function of fracture geometry, effective pore stress, shear stress, aperture, and secondary minerals along the fractures.

5.5.2. Studies devoted to understanding the many geochemical aspects of water moving through rocks including:

- water-rock interaction, particularly those that alter cavity shapes;
- pressure solution and deposition phenomena, particularly as a function of temperature.

5.5.3. Continued study of the fundamental relationships between permeability and electrical conductivity, particularly as a function of effective pressure.

6. THE POSSIBLE CONTRIBUTIONS OF MODELING TO THE UNDERSTANDING OF THE HYDROLOGY OF CRYSTALLINE ROCKS (Contributors: Donath, Chairman; Haitjema; Norton; and Petersen)

6.1. Introduction

The question posed to the working group on modeling was, "What is the state of the art in modeling efforts to predict permeability in the upper crust of the Earth?" In considering this question, the group chose not to address in detail the question of how flow in fractured media is modeled but, rather, the general approaches that modeling can take to predict permeability distributions in real systems. Comments made during the workshop have emphasized the difficulty of extrapolating laboratory or data from borehole tests to much larger volumes (the scale effect). It would appear, therefore, that two general complementary modeling approaches might be pursued -- to develop predictive capability of large-scale systems through (1) the successful modeling of fossil systems in which geologic conditions, parameters, and processes comparable to those thought to exist in the active (real) system were operative; and (2) to model analytically the effects of orientation, length, and other fracture parameters on flow in simple systems. As understanding and successful prediction of small, controlled real systems develops, the fracture modeling of more complex systems of fractured media evolves. The second modeling approach could likely be used to place limits on the distribution of permeabilities that might exist in the large-scale real system, whereas the first approach might provide the volume-averaged permeability.

6.2. Modeling of Fossil Systems

Estimates of rock permeability in active and fossil geologic systems are currently done through a combination of theoretical, numerical, and observational methods that account for chemical, mechanical, and thermal energy transport through fractured rocks. The objective is to identify measurable parameters that are a function of rock permeability and to delimit, as closely as possible, the values of these parameters such that the range of permeabilities that could account for the observations can be defined. Initial and boundary conditions for the numerical models are defined for an environment in which a thermal anomaly (loosely defined) occurs. A first approximation in the observed variations of temperature, pressure, and fluid flux for the time duration of the anomaly can be made by assigning a permeability to the system. Given these state variables and the data on reaction rates between minerals and aqueous solutions, the gains and losses of chemical components can be compared. The rate data provide a "clock," which constrains the time duration of the processes. Comparisons of calculated and measured chemical and thermal variations permit refinement of rock permeability values. The fossil system with its accessible and measurable features along with the numerical analog that adequately explains the observations, permits the estimate of transport parameters, such as permeability, to be made in inaccessible portions of the Earth's crust for which only indirect (seismic, resistivity, etc.) or limited (core data) observations are available.

6.3. The Use of Computer Modeling to Predict "Permeability" in the Upper Crust

Many predictions of permeability performed in the field of ground-water flow are based on mathematical models. These models may vary from the basic application of Darcy's law to more complicated solutions for nonequilibrium flow of ground water toward wells. In performing pumping tests the surrounding area is always included in the model. This is done by making a choice out of equations for unconfined, confined, or semiconfined flow. If adequate boundary conditions such as canals or lake boundaries exist, they can be represented in the model.

Before the interpretation of field data with respect to the permeability of fissured rock, new models should be developed. To cope with the complexity of the flow phenomenon in fissured rock, computer models with numerous simplifying assumptions may be designed to study the basic principles of flow through this medium. However, the physical properties that will be included in the computer model should be modeled as accurately as possible. This is necessary to avoid the introduction of unexpected errors. Analytical functions have proved to be quite successful in modeling ground-water flow including flow through heterogeneities.* These analytical functions may be

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*Modeling double aquifer flow using a comprehensive potential and distributed singularities. Part I, Solution for homogeneous permeabilities. Part II, Solution for inhomogeneous permeabilities, O.D.L. Stract and N. M. Haitjema, Department of Civil and Mineral Engineering, University of Minnesota, submitted for publication in Water Resources Research, July 1979.

applied to modeling flow through assemblies of (intersecting) highly permeable cracks in rocks having very low permeabilities.

The approach indicated above may lead gradually to more and more advanced models of flow through fissured rock. The basic understanding gained from these models, and the models themselves, may guide in the collection and interpretation of field data used for determining "permeabilities" of fissured rocks.

7. GEOCHEMICAL INTERPRETATIONS OF THE HYDROLOGY OF CRYSTALLINE ROCKS (Contributors: Rosholt, Chairman; Davis; Marine; and Vidale)

7.1. Introduction

Hydrologic properties of deep crystalline rocks can be inferred from the results of geochemical studies. Past hydrogeologic conditions are recorded to some degree by the presence or absence of soluble species in the rock and by vein and fracture fillings. Generally this information will suggest conditions several hundreds of thousands to several million years before the present. Information concerning more recent hydrologic conditions can be obtained from the geochemistry of the water that is commonly encountered in rock fractures. A highly saline water filling fractures would suggest slow water circulation provided the near-surface water in the region is fresh. If the chemistry of the water can be associated with particular dated geologic events such as sea level fluctuations, some information on the age of the water, and hence the rate of possible water motion may be obtained. Radionuclides and products of radioactive decay found in the water will also give some information useful for water dating. This topic is covered in more detail below.

Although not discussed in detail, it should be noted that the geochemistry of the water in the small fractures of the crystalline rocks is an important aspect of the interpretation of several types of downhole tests, such as tracer tests and electrical resistivity measurements. Therefore, careful geochemical studies of the native waters are a prerequisite to the proper evaluation of all deep test holes in the crystalline rocks.

The following questions are posed to help identify the status of knowledge and possible lines of research effort.

First, regarding the data base: Are there compilations of water analyses for samples known to be in equilibrium with crystalline rocks? Are such compilations organized by geologic province, lithology of rocks, depth of sample?

Second, regarding the rates and processes of the change of dissolved solids in water in equilibrium with crystalline rocks, several lines of inquiry can be imagined.

- Could a study be made of the total dissolved-solids content and of ionic composition of ground water that has entered crystalline rocks by recharge of surface precipitation and streams, versus recharge from fairly highly mineralized ground water from sedimentary rocks?

The goal for such a study might be to compare rates of dissolution from rock to water and rates of adsorption and mineral alteration.

- Have any studies compared ground-water composition in equilibrium with rocks of similar lithology but widely different ages -- for example, old Precambrian and Cretaceous granites? Can estimates of gross rates of leaching by ground water be made from such studies?
- Temperature-dependent rates of solution are very important to geothermal systems, many of which involve crystalline reservoir rocks. The dependence of SiO_2 dissolution on temperature is fairly well known. However, the rates of leaching of calcium from granitic versus metamorphic rocks (gneiss, schist, metasedimentary rocks of moderate metamorphic grade) would be of interest. Both absolute concentrations and mineralogical location of calcium should be different for the various lithologies.

7.2. Dating of Ground Water

Dating of ground water provides a hydrologic tool to be used with other techniques to contribute to the understanding of the hydrogeologic system. Dating cannot be used independently to arrive at that understanding. The dating of water in near-surface hydrogeologic systems can use atmospherically derived radionuclides; however, because their amount decreases with age, there is a practical limit beyond which their use becomes quite tenuous. The use of distinctive nuclides generated within the rock and transferred to the water may be more useful for the dating of ancient water in deeper systems.

There is an increasing amount of dating of ancient ground water being done by various organizations. Most of this work has been in metamorphic/granite terranes at depths of less than 1000 m, which are basically cold systems. It would be useful to develop such methods of dating water in geothermal systems although the techniques of collecting representative samples can be expected to be more complex. Again, the purpose of dating water is to understand the hydrogeologic system and is not primarily an end in itself.

Approximate dates of water in deep cracks will be useful for the general understanding of the overall permeabilities of deep crystalline rocks. Although fracture apertures and historical hydraulic gradients are needed before approximate hydraulic conductivities can be obtained, the water velocities derived from water dating in numerous test holes in the region can be useful in obtaining a rough approximation of zones of maximum water circulation.

Under ideal conditions, with the reconstruction of past gradients and independent measurements of fracture porosities, hydraulic conductivities can be estimated.

7.2.1. Noble Gases. For most elements transferred from the rock to the water, the physical and geochemical controls must be well understood to deduce an age. Although the geochemical controls must be known, they are perhaps less critical if the noble gases are used than in the case of other compounds or elements. The radioactive decay of uranium and thorium produces helium and other noble gases at a known rate, and thus the helium concentration can be used for dating if the transfer rate from the rock to the water can be assumed constant and if the helium is not preferentially removed from the water. The support for the assumption of a constant release rate for helium comes from other hydrogeologic information.

Calculations of the production of noble gases other than helium indicate that their use will be more difficult because of the low amount to be formed even in very old waters.

The most critical parameter in age calculations from noble gases dissolved in ground water is their transfer rate from the rock to the water under different geohydrologic and geochemical conditions. A first attempt at developing an understanding of any constraints imposed on the dates by this factor should be through a series of laboratory experiments. Once conducted, these should be compared against field data, which should be collected as part of normal geothermal and waste repository investigations.

Such a laboratory program, including chambers to simulate various hydrologic conditions, might be accomplished for $200,000 in less than 2 years.

In conclusion, the use of noble gases for dating of ground waters should be conducted as a minor part of each geothermal and waste repository investigation. The added costs are insignificant. Furthermore, a laboratory program to study the role and the controls of transfer rates from rock to water should be started as a specific project against which field data can be compared.

7.2.2. Atmospherically Generated Radionuclides. Several radionuclides that originate by cosmic-ray interactions in the atmosphere are potentially useful for dating ground water. Nevertheless, as noted above, the concentrations of these nuclides will diminish with time, thus making the dating of the water progressively more difficult as water increases in age. Radionuclides

TABLE 7-1

RADIONUCLIDES ORIGINATING IN THE ATMOSPHERE

Nuclide	Half-life (years)
^{14}C	5.73×10^{3}
^{32}Si	100-500[a]
^{36}Cl	3.0×10^{5}
^{39}Ar	269
[b]^{41}Ca	1×10^{5}
[b]^{79}Ca	6.5×10^{4}
[b]^{81}Kr	2.1×10^{5}

[a]Published values range from about 100 to 500 yr, with the lowest values being the latest to be published.
[b]Analytical evidence for significant amounts in water has not been established.

that have been proposed for dating waters older than 1000 yr are listed in Table 7-1.

7.3. Geochemistry of Rock Cores

The naturally occurring radionuclides in rocks provide key data for assessing long-term integrity and nature of the permeability of crystalline rocks. In geochronology, the most commonly used radioactive decay schemes are ^{40}K-^{40}Ar, ^{87}Rb-^{87}Sr, ^{238}U-^{206}Pb, ^{235}U-^{207}Pb, ^{232}Th-^{208}Pb, and ^{207}Pb-^{206}Pb. Recrystallization of host minerals, isotopic redistribution among mineral phases, diffusion, and especially fluid migration can affect the integrity of the decay systems. The U-Pb systematics are particularly valuable in detecting the effects of fluid flow in rocks. In crystalline rocks, a significant fraction of uranium may be labile because it resides along grain boundaries and in minerals that become degraded as a result of radiation damage. Thus, some uranium is readily removed from these labile sites, should any fluids move through the rocks. This potential mobility of uranium provides a direct means for determining the long-term impermeability of crystalline rocks. Geologically recent gains or losses of parent or daughter nuclides result in anomalous parent-daughter ages; however, the $^{207}Pb/^{206}Pb$ ages are not changed significantly. However, $^{207}Pb/^{206}Pb$ ages that agree with other radiometric ages are not proof of closed system conditions over the last 100 Myr because they (Pb^{207}/Pb^{206} ratios) are inherently insensitive to uranium loss. The most common anomalous result caused by fluid migration is higher lead-uranium ratios than those required for the age of the rock because of uranium loss.

Highly deformed areas such as the Granite Mountains, Wyoming have been fractured to significant depth, and open-system behavior of the lead-uranium systems is evident to depths of at least 410 m (Stuckless and Ferreira, 1976). Thus, crystalline terranes that have undergone repeated tectonic events, especially at high crustal levels, should be viewed with considerable caution as deep fracturing and fluid flow may have compromised their natural physical and isotopic integrity.

Less expensive assays that can provide clues for preliminary exploration for suitable crystalline rocks by identification of labile uranium are based on disequilibria between pairs of long-lived radiogenic daughter products within the ^{238}U decay chain. This characteristic may be observed by comparing Ra-equivalent U values (radium-equivalent uranium obtained by γ-ray spectrometry) with chemical uranium contents (Stuckless and Nkomo, 1978).

8. GENERAL CONCLUSIONS

8.1. Introduction

A workshop that involves almost 30 productive scientists and engineers will generate more useful ideas in 3 days of formal and informal conversation than can possibly be recorded accurately in a report of reasonable length. The highest value of such a workshop is, therefore, to provide a focus on a particular set of technical questions as a means to educate and stimulate the individual researchers attending the workshop. Nevertheless, an attempt is made in this section of the report to summarize briefly some of the most important ideas presented in informal conversation as well as those given in the preceding sections of this report.

8.2. Some Difficulties Encountered with Hydrologic Research of Deep Crystalline Rocks

Difficulties and limitations of hydrologic research of deep crystalline rocks must be understood clearly prior to the start of such research. At least four general categories of problems exist. First, research is very costly. Although significant theoretical and laboratory-based work remains to be done, the most active frontier is, and should be, research based on direct field measurements made at depths of interest. Sinking shafts or drilling to such depths is very expensive. Existing mines and drill holes are rarely satisfactory for ordinary purposes of hydrological research. Geologically, the most severe limitation of existing holes is the fact that such holes in crystalline rocks are primarily related to mineral exploration, and this exploration is, in turn, concentrated in areas of faults, fractures, intrusions, and other atypical features that might invalidate broad generalizations drawn from research in these areas.

A second difficulty is one of not being able to make the proper basic field measurements even under ideal circumstances. As yet, a satisfactory method of determining directly the aperture of small but important fractures in dense rocks is lacking. Many mechanical as well as theoretical difficulties exist with the proper measurements of *in situ* rock properties such as state of stress, effective porosity, capacity for storage, and permeability.

A third, and related difficulty, is one of scale. Hydrologic flow systems in many crystalline rock masses at intermediate depths, 0.2 to 2 km and possibly deeper, are probably dominated by rather isolated zones of permeability, which may be separated from adjacent zones by several tens to several hundreds of meters. Proper definition of these zones by vertical boreholes is a difficult or even impossible task unless these zones can be located prior to drilling by geological or geophysical techniques. Even extensive horizontal drifts driven out from deep vertical shafts may not give statistically valid information concerning these permeable zones. Notwithstanding these critical problems of the collection of field data, an even greater problem is related to the theoretical question of how to construct predictive models of groundwater flow even if the proper field data were collected.

A fourth difficulty, which is discussed briefly in our report, is caused by the disturbance of the natural stress field by all methods of drilling, excavation, and subsequent sampling. Changes in the stress field will in turn cause strain that is concentrated commonly along fractures in the rocks. Owing to the sensitivity of fluid flow to the aperture of fractures, strains of only a few micrometers may be highly significant in affecting the hydrology of crystalline rocks. Although such strains may be localized near the holes or excavations, many *in situ* testing and sampling techniques are most sensitive to these near-field effects.

8.3. Some Unresolved Differences of Opinion

The participants in the workshop represented a large number of technical and scientific fields. As a consequence, many different perspectives concerning the hydrology of crystalline rocks existed and many questions remained unresolved, primarily owing to the lack of proper field data. Two of the questions are mentioned briefly below.

8.3.1. Decreasing Permeability with Depth. Perhaps the most critical question relates to possible systematic changes in rock "permeability" with depth. All participants recognized the wide statistical scatter of available data and the general lack of data below depths of 1 km. However, some participants felt that small but significant decreases of permeability probably take place beyond depths of 500 m; others disagreed or felt that, if such decreases exist, they are not significant from a practical point of view.

8.3.2. Permeability at Great Depths. Another interesting question is related to the nature of permeability at great depths, say from 2 to 10 km. Clearly, crystalline rocks at great depths do, at some point in time, have significant permeabilities, probably related to small fractures permeating the rock. There is, nevertheless, a considerable difference of opinion as to the length of time these fractures are open. Petrologic evidence indicates that many fractures heal with time. Is the expected time interval during which fractures remain open measured in hundreds of years, thousands of years, or millions of years? The question is unresolved.

8.4. Two Unique Suggestions

Numerous suggestions for research are contained in this report. Only two of these suggestions, however, are repeated here as a conclusion to this report. The emphasis on these suggestions is not because of their relative importance, because many of the other suggestions have equal or greater value. The emphasis is considered appropriate, nevertheless, because they are more or less outside the list of research topics normally discussed in connection with the hydrology of crystalline rocks.

8.4.1. Modeling with Paleohydrologic Data. Crystalline rocks that were at one time buried at great depths are now exposed at or near the surface. Positions of ancient boundaries, petrologic evidence of fluid transport, paleotemperature indicators, and other present-day information can be used to set limits on the extent of water migration during the time the rocks were buried at great depths. If enough of these studies are completed, reliable information might be obtained on the variations of hydrologic conditions to be expected at depth in crystalline rocks.

8.4.2. Analyses of Leachable Uranium. After plutonic rocks have been thoroughly solidified and are much nearer the surface than during the original formation, active ground-water circulation may leach uranium from surfaces along fractures in the rock. The extent of this leaching, and indirectly the extent of water migration, can be estimated by comparing the concentrations of various uranium daughter products with the concentrations of the parent uranium. Using calculations of disequilibrium, some estimates of the time taken for this leaching can be made. Thus, limits might be set on the "permeability" of the rocks if estimates of both the volume of water circulated and the time of circulation can be obtained.

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APPENDIX A

LIST OF PARTICIPANTS

Dr. John H. Black
Environmental Pollution Section
Institute of Geological Sciences
Building 151, Harwell Laboratory
Oxfordshire OX11 ORA
ENGLAND

Telephone Abingdon 235-24141
Extension 2575
Telex Number 83135

Dr. Dennis Bird
Department of Geosciences
University of Arizona
Tucson, AZ 85721

602-626-1419 or 626-1819

Dr. W. F. Brace
Department of Earth and
Planetary Sciences
Massachusetts Institute of
Technolgy
Cambridge, MA 02130

617-253-3391

Dr. N. G. W. Cook
Hearst Mining Building
University of California at Berkeley
Berkeley, CA 94720

415-642-3846

Dr. F. M. Cornet
Institut de Physique du Globe
Tour 24
Universite P. et M. Cure
4 Place Jussieu
75230 Paris Cedex 05
FRANCE

(1) 336-2525 or (1) 329-1221
Ext. 4700 (Poste)

Mr. Jaak Daemen
Department of Mining and Geological
Engineering
University of Arizona
Tucson, AZ 85721

602-626-2501

Dr. Stanley N. Davis
Department of Hydrology and Water
Resources
University of Arizona
Tucson, AZ 85721

602-626-3068

Mr. Cliff Davison
Inland Waters Directorate
Environment Canada
562 Booth Street
Ottawa, Ontario K1A OE7
CANADA

613-593-6354

Dr. Fred A. Donath
Department of Geology
University of Illinois
Urbana, Illinois 61801

217-333-7135

Mr. Hendrick M. Haitjema
Department of Civil and Mineral
Engineering
University of Minnesota
Minneapolis, MN 55455

612-376-2948 or 376-7630

Labor Jarolimek
Senior Staff Consultant
D'Appolonia Cons. Engrs., Inc.
10 Duff Rd.
Pittsburgh, PA 15235

412-243-3200

Dr. I. Wendell Marine
Savannah River Laboratory
E. I. DuPont de Nemours & Co.
Aiken, SC 29801

803-725-3469

Dr. Shlomo P. Neuman
Department of Hydrology and
Water Resources
University of Arizona
Tucson, AZ 85721

602-626-4434

Dr. Denis Norton
Department of Geosciences
University of Arizona
Tucson, AZ 85721

602-626-1419 or 626-1819

Dr. Amos M. Nur
Department of Geophysics
Stanford University
Stanford, CA 94305

415-497-3716

Ms. Carol Petersen
Geothermex Inc.
1760 Solano Ave., Suite 209
Berkeley, CA 94707

415-525-7096

Dr. Henry J. Ramey, Jr.
Petroleum Engineering Department
Stanford University
Stanford, CA 94305

415-497-4744

Dr. Randall M. Richardson
Department of Geosciences
University of Arizona
Tucson, AZ 85721

602-626-4950

John Roshalt
U.S.G.S.
Box 25046, Mail Stop 963
Denver, CO 80225

303-234-4021

Dr. Marc L. Sbar
Department of Geosciences
University of Arizona
Tucson, AZ 85721

602-626-4849

Dr. Gene Simmons
Department of Earth and
Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139

617-253-6393

Dr. Eugene S. Simpson
Department of Hydrology and
Water Resources
University of Arizona
Tucson, AZ 85721

602-626-1855

Dr. David T. Snow
6235 Turret Drive
Colorado Springs, CO 80907

Dr. Rosemary Vidale
CNC-11, MS 514
Los Alamos National Laboratory
Los Alamos, NM 87545

505-667-4985

Dr. Herbert F. Wang
Department of Geology and Geophysics
University of Wisconsin
Madison, WI 53706

608-262-5932

Dr. Herbert F. Wang
Department of Geology and Geophysics
University of Wisconsin
Madison, WI 53706

608-262-5932

Mr. Francis West
Geological Applications Group, G-9
Mail Stop 983
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545

505-667-7075 or 667-6711

APPENDIX B

PROGRAM SCHEDULE AND PROGRAM ORGANIZATION

Workshop On Hydrology Of Crystalline Basement Rock

October 17, 18, and 19, 1979
Arizona Inn, 2200 East Elm
Tucson, Arizona

Wednesday, October 17

7:30-9:30 Informal social gathering and reception. Spouses are invited. Catlin Room, Arizona Inn.

Thursday, October 18

Safari Room, Arizona Inn.
9:00-9:15 - Greetings and general remarks. Dr. S. Davis and Mr. F. West.
9:15-9:45 - Basic data from drill holes and tunnels.
9:45-10:30 - Inferences from water dating.
10:30-10:45 - Coffee
10:45-11:15 - Possible contributions from hydologic models.
11:14-11:45 - Evidence from deep geothermal systems.
11:45-1:15 - Lunch
1:15-1:45 - Evidence from theoretical rock mechanics.
1:45-2:15 - Evidence from experimental rock mechanics.
2:15-2:45 - Evidence from surface geophysics.
2:45-3:00 - Interpretation of drill-hole data.
3:30-4:00 - Downhole measurement devices.
4:00-4.30 - General discussion from the floor.
4:30-4:45 - Organize working groups for Friday morning.
6:30-8:30 - Evening meal. African Room, Arizona Inn. Spouses are invited.

Friday, October 19

8:45-10:15 - Working session and description of the French and Canadian programs.
10:15-10:45 - Coffee.
10:45-11:45 - Working session.
11:45-1:15 - Lunch, Safari Room, Arizona Inn.
1:15-4:30 - Summary of working groups.
4:30-4:45 - Closing remarks.

Saturday, October 20

Safari Room, Arizona Inn.
9:00-11:00 - Small working group of volunteers to complete rough draft of report.

Possible Discussion Groups

1. Geophysics
2. Hydrogeology
3. Borehole testing methods
4. Rock mechanic - both laboratory and theoretical
5. Geochemistry and petrology
6. Modeling - fluid flow and general transport equations

Possible Outline of Group Reports

1. Introduction.
2. Summary of type of "hard data" available.
3. General inferences that can be drawn from these data.
4. Summary of the most critical unknown aspect of the topic (related to hydrologic characteristics of the rock).
5. A proposed research project to answer some of the critical questions. (Limited to $200,000 and 2 years (?) not counting drilling costs.) Give rough time and cost estimates.
6. Conclusions, if appropriate.

APPENDIX C

DISCUSSION ON HYDRAULIC FRACTURE PROPAGATION; CONSEQUENCES FOR IN SITU STRESS MEASUREMENTS

(R. H. Cornet, I.P.G. Paris)

1. A NUMERICAL MODEL

A numerical model, based on the displacement-discontinuity technique proposed by Crouch (1976) and on the critical strain energy release rate fracture criterion proposed by Irwin (1957), has been constructed (Cornet, 1979). In this numerical technique, the displacement field is expressed by the classical Neuber-Papkovitch representation. Exact solutions for the stresses and displacements in an infinite, or semi-infinite, medium caused by a normal or tangential uniform displacement along a line segment are derived. These solutions are then taken singly or are combined to construct solutions to any boundary value problem. This provides a set of linear equations relating boundary stresses and boundary displacements to a set of displacement-discontinuities. The variation of strain energy, which results from the prescribed boundary conditions, is obtained by direct application of Clapeyron's strain energy theorem, which states that when a body is in equilibrium, the strain energy of the deformation is equal to one-half the work done by the external forces through the displacements from the unstressed state to the state of equilibrium.

With this model, a pressurized fissure is represented by a set of displacement-discontinuities, the length of which is adjusted to the displacements and pressure gradient in the fissure. The surfaces of these elements are allowed either to get separated or to slide against one another; in this latter case friction is taken into account. The path that the fissure follows as it propagates is derived from a computation of the maximum strain energy release rate as follows: 1) the strain energy associated to the presence of the crack in its original configuration is determined, 2) the strain energy variations caused by various virtual crack extension configurations are computed (a new displacement-discontinuity with a constant length and different orientation with respect to the last discontinuity is added at the tip of the crack) and, 3) that which provides the largest strain energy release rate is chosen as crack path.

Obviously this model applies only to perfectly brittle, linearly elastic materials. Further, only quasistatic adiabatic fracturing processes can be considered since kinetic energy is not taken into account.

It has been found that if a fracture initiates perpendicularly to the major principal stress direction, in the direction of the minimum principal stress, it extends in its own direction provided the pressure gradient in the fissure is negligible. If the pressure in the fissure is maintained uniform and constant up to the crack tip during the fracturing process, instability is observed. If the pressure is maintained uniform but its magnitude is decreased so as to keep the fracture stable, a critical length exists for which the fissure deviates from its original orientation and becomes aligned with the regional minimum principal stress direction. If one assumes a free surface energy of 86 J/m^2, (Hardy, 1973) the critical length of a crack that propagates perpendicularly to the direction of a uniaxial stress of magnitude 100 bars, is 6 m (for $E = 7.10^5$ bars, $\nu = 0.25$, crack increments equal to 0.3 cm). Indeed, for this critical crack length, the angular variation of the strain energy release rate is less than a few units for a million so that, in fact, heterogeneity of the rock becomes the critical factor governing fracture orientation. When a pressure gradient develops in the fissure, a similar conclusion is reached except that the critical crack length becomes shorter and the angular variation of the strain energy release rate more significant.

2. LABORATORY EXPERIMENTS

Laboratory tests have been conducted to verify experimentally these numerical results. Cubic blocks of granite have been used to investigate the influence of various pressurization rates on the propagation of oil-filled fissures oriented perpendicularly to a uniaxial compressive load. It was found that, for a given applied uniaxial load, the fissure developed its own orientation when the pressurization rate was slow enough, and that the fissure became aligned with the applied load direction for pressurization rates faster than a critical value, which depends on the uniaxial load magnitude. A new fracture developed in the direction of the applied load orientation for pressurization rates faster than a second critical value (Fig. C-1).

It can be concluded that, for *in situ* measurements, not only can a fracture change its orientation as it propagates away from the borehole, but also that old fractures may be reopened, whatever their orientation, provided the

σ	$\dot{V}$	P	FRACTURE TYPE
bars	10^{-3} cm³/s	bars	
35	53,5	129	
56	4,5	133	
56	9,0	154	
56	27,0	173	
70	7,0	144	
77	1,5	131	
77	53,5	188	

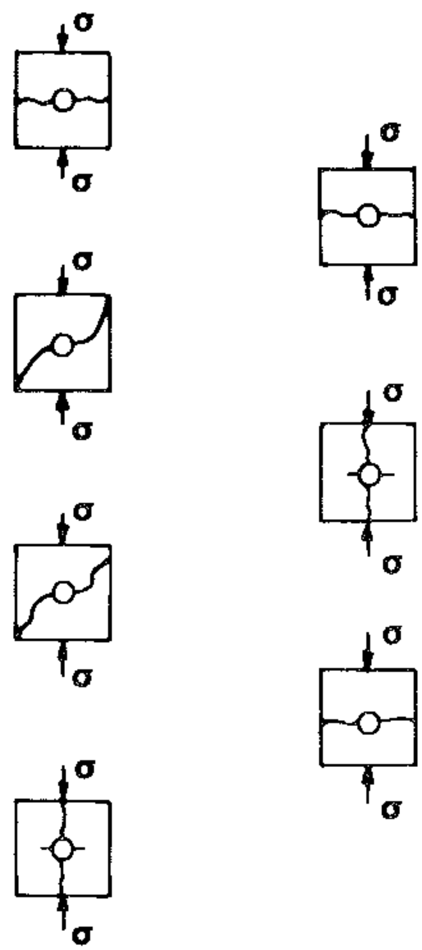

Fig. C-1.
Fracture type as influenced by flow rate ($\mathring{V}$) for various normal stress conditions (σ); P = maximum borehole pressure reached during injection.

fluid viscosity and the pressurization rate are such that fluid percolation occurs.

3. PRELIMINARY FIELD RESULTS

A 200-m-deep, 165-m-diam borehole, drilled in granite, has been used for investigating *in situ* both initiation and propagation of hydraulic fractures. Results presented here are still very preliminary; however, they may help outline some of the difficulties and some of the successes met in field testing.

On site, the granite is covered by a <5-m-thick soil layer; it can be seen on the surface at a few places. Fractures were mapped on 12 areas with outcrops near the test site; 4 major fissure orientations have been identified (see Fig. C-2).

Eight fractures were created with a straddle inflatable packer (see Table C-I) in an area thought to be homogeneous (defined as such through thermal logging, video logging, and permeability measurements). For the 186-m-deep fracture, gel and propping agents were used; the shut-in pressure was found stable during more than 3 hours. All other hydraulic fractures were created with water.

Geophysical techniques were applied to try to locate the fracture away from the wellbore:

(1) by mapping surface potential variations associated with the injection of salty water (8 g/ℓ) when 500 mv are injected into the ground through two electrodes (one is the borehole tubing, the other one is a surface electrode 500 m away from the well); and

(2) by locating induced acoustic and microseismic activity. For this purpose various kinds of sensors were installed:

- twelve 3-component seismometers (linear output in velocities for a 0.5- to 125-Hz frequency range) located on a 200-m radius circle centered on the wellbore;
- six hydrophones (linear in the 100- to 3000-Hz domain) installed in shallow boreholes that extended 1 m below the water table and were located along various azimuths from the wellbore at distances ranging from 10 to 80 m;
- one surface geophone (one vertical component, linear in a 10- to 2500-Hz domain) located 50 m away from the well.

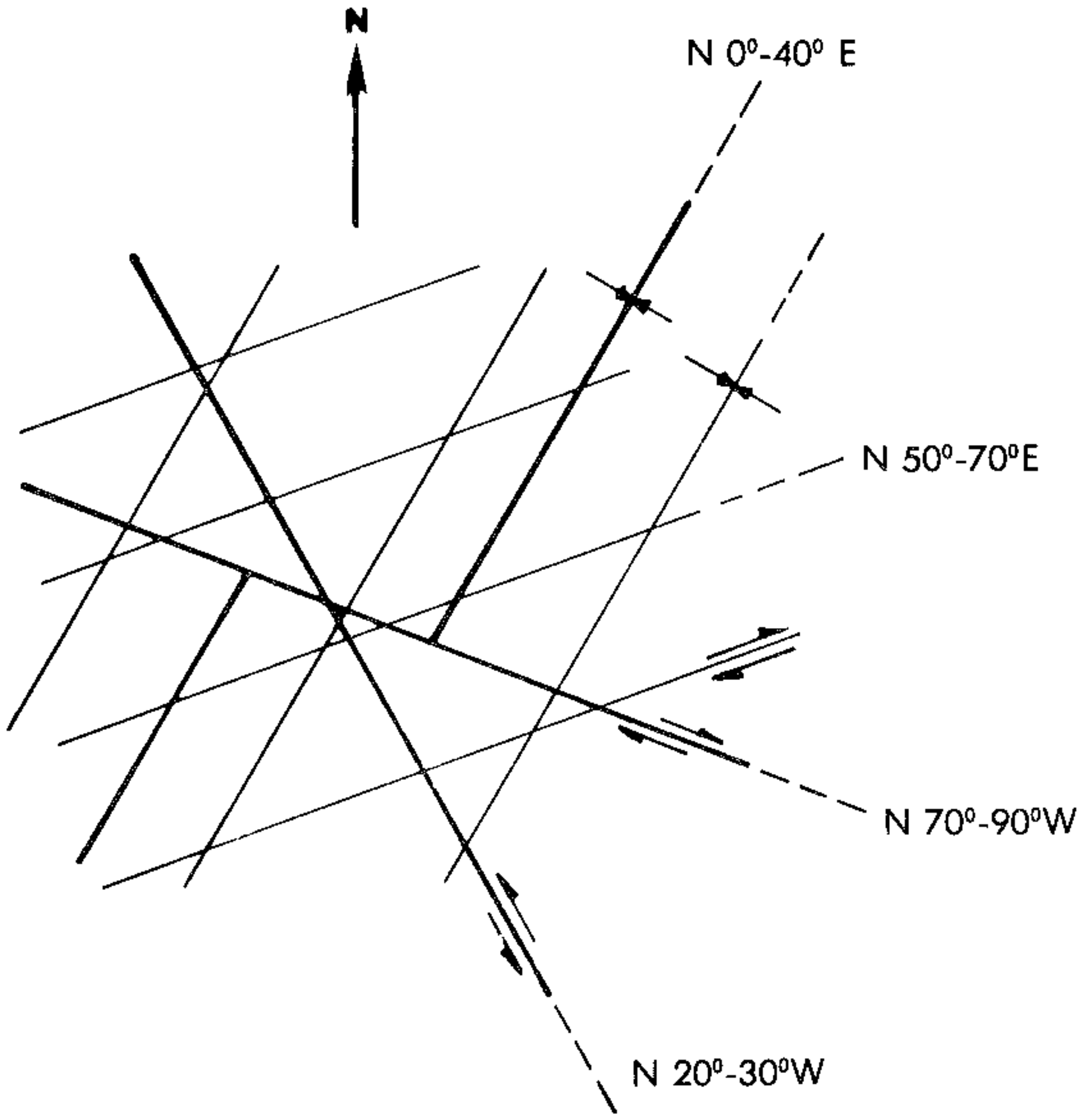

Fig. C-2.
Main orientations of surface fractures (after Drogue and Grillot, Univ. of Montpellier).

TABLE C-I

DATA FROM HYDRAULIC FRACTURING TEST AT LE MAYET DE MONTAGNE TEST SITE
(25 km SE of Vichy, in the center of France)

Depth (m)	Breakdown Pressure (MPa)	Reopening[a] Pressure (MPa)	Shut-In Pressure (MPa)	Injected Volume (m^3)	Recovered Volume (m^3)	Pumping Rate (ℓ/min)	Orientation at Wellbore[b]	
							Dip	Strike
27	233/333	-	-	-	-	60	Multiple fractures	
42	Fracture by packer	5.4	2.1	4.88	0.4	60	Multiple fractures	
54	Fracture by packer	5.9	4.2	1.19	0.24	60	82°	N60°E
65	Fracture by packer	-	3.2	4.58	0.12	60	80°	N46°E
84	10	8.5	4.6	2.54	0.26	60	-	-
90	34.7	5.1	4.4	3.59	0.14	60	80°	N20°W
174	15.1	-	5.6	0.02	?	1	82°	N59°E
186	29.5	-	5.4	13.0	2	320	80°	N57°E

[a] Pressure required to reopen the fracture generated during the first injection (measured after the pore pressure has dropped back to its original value).

[b] Orientation at wellbores was determined with a borehole TV camera.

One clear signal (maximum energy around 200 Hz) was recorded on five hydrophones located at distances smaller than 100 m from the packer (no signal on the seismometers) when the breakdown pressure occurred for the 90-m-deep fracture. No further high-frequency signals were observed afterwards. No recording was done for the 27-m-deep fracture. At 42-, 54-, and 65-m depth, fracture developed at the packer level because the packer inflation pressures (280 b) were too high. No signals were observed for the 186-m-deep fracture despite a clear breakdown pressure reading but with heavy surface noise in a broad frequency range (at least up to 600 Hz) due to pumping units.

Multiple low-frequency signals (∽30 Hz) were recorded on the seismometers at the end of the pumping phase and for at least half an hour after pumping had stopped for the 90- and 85-m-deep fractures (upper fractures have not been investigated). No signals were visible for the 186-m-deep fracture. Arrival times of the signals indicate they were transmitted through the upper soil layer (velocities less than 1000 m/s). Although these signals cannot be associated with full confidence to induced seismicity, they do not seem to have been caused by human activities on the surface. More work on this problem is currently under way.

Electrical mapping provided significant results (15 to 20% relative variation of potential) for the 65- and 42-m salty water injections. The 64-m electrical measurements showed an extension oriented about N40°W (Fig. C-3). Analysis of the conductivity anomaly for the 64-m test yields a depth of approximately 40 m, which would indicate that water has migrated about 25 m upward (Vasseur 1979). This suggests that measurements conducted for the 42-m-deep injection may have been influenced by the 64-m test. No measurements were made for the 90-m-deep injection, and artifacts seem to have hampered measurements conducted for the 186-m-deep fracture.

4. TENTATIVE INTERPRETATION OF FIELD RESULTS

A. Breakdown Pressure Measurements: Fracture Initiation

For the 27-m fracture, a first breakdown pressure was measured immediately after permeability tests had been conducted (pore pressure was not allowed to return to its original value); after 200 ℓ had been injected, the well was left open so as to bring the pore pressure back to its original value. Pumping was started again, and higher breakdown pressure than the first one occurred. Impressions taken with a packer after the test revealed

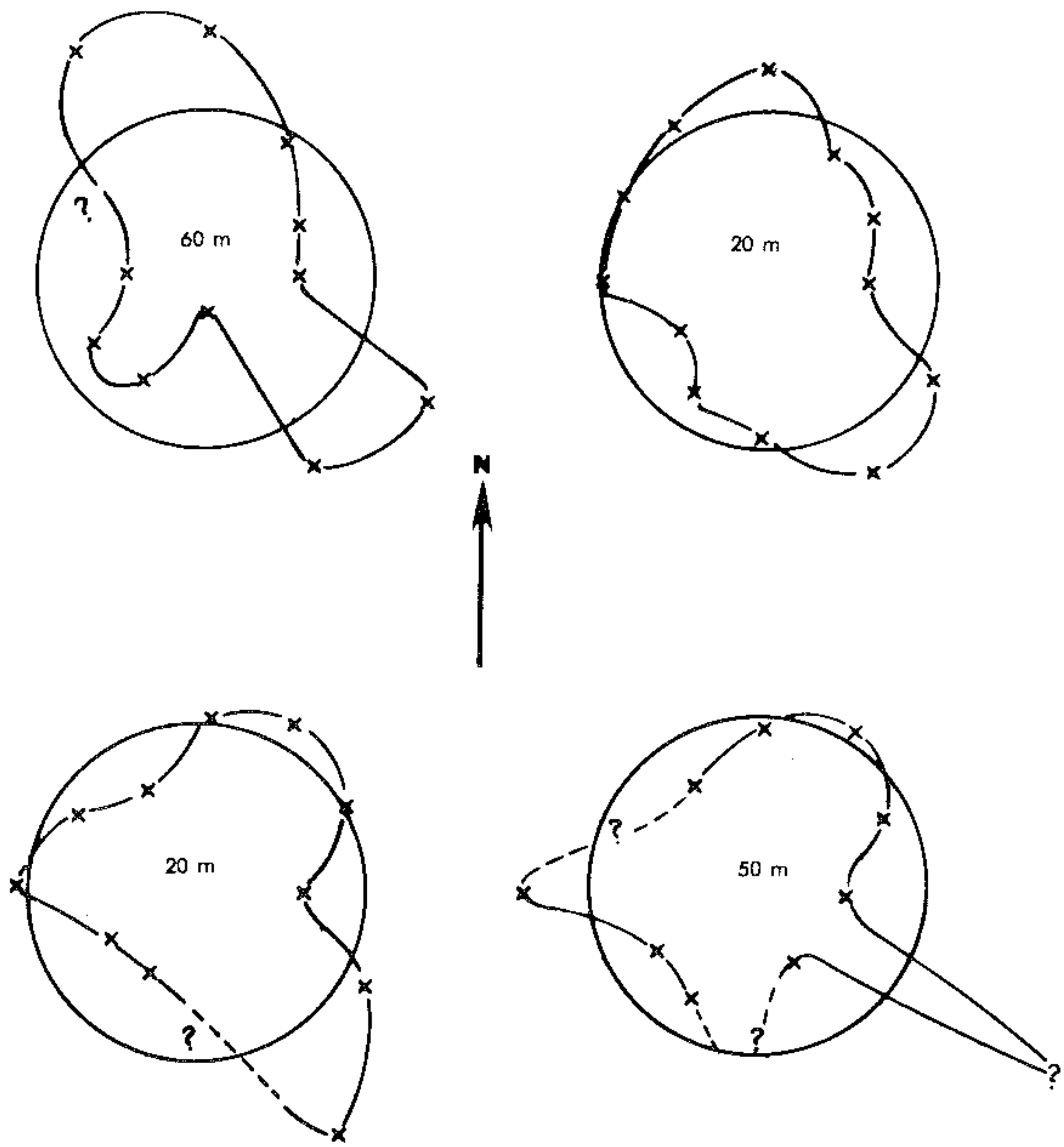

Fig. C-3.
Mapping of surface electrical potentials for the 65-m-deep injection distance between points of measurement and wellbore; curves correspond to relative change of potential (circle corresponds to no change.)

two vertical fractures. This effect is interpreted in a manner similar to that obtained in the laboratory experiments. Buildup of gradual pore pressure during the first injection allowed a pre-existing fissure to be reopened whereas a new crack developed during the second injection due to the high rate of flow.

Although the 174- and 186-m-deep injection tests were conducted on similar rocks, the test conducted at a 1-ℓ/min flow rate yielded a much lower breakdown pressure than that conducted at a 320-ℓ/min rate. For the 42-, 54-, and 65-m injections fracturing occurred at packer level. Packers had been inflated to approximately 250 bars about 1/2 hour before hydraulic fracturing took place, and it is assumed that they fractured the rock since no breakdown pressure was recorded. These results indicate that the apparent tensile strength of the rock is strongly dependent on the rate of injection (Haimson 1968).

It is concluded that fracture initiation in granite is strongly dependent on flow rate and pore pressure, which influence breakdown pressure and fracture direction.

B. Fracture Propagation Away from the Wellbore

For the 65-m fracture it was found that the fracture initiated in the N46°E direction (Table C-I). However, electrical measurements show an extension N40°W (60 m to the north, 50 m to the south, 35 m upwards). If one assumes the same mechanics to govern the 90-m-deep fracture (which was formed before that at 65 m), then it must have reached the 55-m level. Projection of the fracture surface shows that it was probably 5 m away from the borehole at this depth. It seems likely that this pre-existing fracture has governed extension of the 65-m fracture. (This mechanism has been obtained qualitatively with the numerical model, which would suggest that pre-existing fractures may influence significantly crack path away from the wellbore.) This influence must depend strongly on fluid viscosity and flow rate.

C. In Situ Stress Determination

In situ state of stress is supposed to be the superposition of gravity effect and a horizontal tectonic stress field,

$$(\sigma) = \begin{pmatrix} \sigma_1 + \alpha\rho gh & 0 & 0 \\ 0 & \sigma_2 + \alpha\rho gh & 0 \\ 0 & 0 & \rho gh \end{pmatrix} , \qquad \text{(C-1)}$$

where σ_1 and σ_2 are the principal components of the tectonic stress field,

h = depth of measurement

ρg = gravity stress gradient

α = an unknown constant ≤ 1.

Four unknowns have to be determined: σ_1, σ_2, α, and y (orientation of σ_1).

If the shut-in pressure is interpreted as being equal to the normal component of the stress that acts on the fracture,

$$P_F = \sigma \underline{n} . \underline{n} \quad , \tag{C-2}$$

where n is the normal to the fracture. Three fracture orientations with different orientations and two fractures in the same orientation, but at different depths, provide enough information for solving the nonlinear system,

$$(\sigma_1 + \sigma_2) + (\sigma_1 - \sigma_2) \cos 2 (\beta_i - y) = \frac{2 P_{F_i} - \rho g h_i [n_3^{i^2} + \alpha(1 - n_3^{i^2})]}{1 - n_3^{i^2}} ; \tag{C-3}$$

i refers to the i^{th} fracture where β is the orientation of the projection of $\underline{n}$ in the horizontal plane, and n_3^i is the cosine of $\underline{n}$ with respect to the vertical direction.

For subvertical fractures, measurement of reopening pressure P_0 provides another equation,

$$(\sigma_1 + \sigma_2) + 2(\sigma_1 - \sigma_2) \cos 2 (\beta - y) = P_0 - 2\alpha\rho g h \quad , \tag{C-4}$$

which provides the useful result for fast-field checking,

$$\sigma_1 + \sigma_2 = 4P_S - P_F - 2\alpha\rho g h \quad . \tag{C-5}$$

Least squares can be used to find the best fit for more than three fractures. In the case of data from the fractures at 54, 65, 84, 90, 174, and 186 m, maximum error was 3 bars (α = 0.43, σ_2 = 14b, σ_1 = 67b, y = 17°E).

This new technique does not require any breakdown pressure measurement; it can be applied to fractured material, and it allows for error estimation. It necessitates that fissures in at least three orientations be injected if re-opening pressures cannot be accurately measured. (This last measurement implies that fast flow rates are used to prevent fluid penetration.)

In conclusion, if the stress determination is correct, none of the fractures was aligned with the σ_1 direction although clear breakdown pressures were measured at 90, 174, and 186 m. If one assumes the 84-m fracture to be subvertical, then it strikes N58°E. This direction (N58°E) coincides with the orientation of a fracture set mapped on the surface. This granite exhibits a strong anisotropy that significantly influences hydraulic fracture orientations. If the influence of depth follows that proposed in our model, the effect of anisotropy can be significant even at great depth.

ACKNOWLEDGMENT

The field work was supported by E.E.C. contract 100-76 EGF and I.N.A.G., A.T.P. Geodynamique. Laboratory work was conducted at the University of Minnesota under NSF Grant GK-41220.

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APPENDIX D

THE HYDROGEOLOGY OF CRYSTALLINE ROCKS: PROPOSED WORK WITHIN THE UK RADIOACTIVE WASTE DISPOSAL PROGRAM (J. H. Black)

The Institute of Geological Sciences is the main contractor to the UK government concerning the geological aspects of the disposal of highly radioactive waste. At the present time the work is almost wholly devoted to the potential of crystalline rocks at depths between 500 and 1000 m below surface as possible host rocks for a radioactive waste respository.

Within the field of hydrogeology the aim is to characterize a potential repository site, so that volumes in the order of 5 x 5 x 1 km deep are being considered. The characterization is required as a starting point for modeling the likely effects of the perturbations involved in the construction of a radioactive waste repository and its subsequent backfilling and sealing. There are two interrelated tasks to be carried out, namely, to measure the relevant hydrogeological parameters at a potential site and to devise new or more reliable methods of measurements.

After a preliminary appraisal it was apparent that there are few if any hydrogeological test methods that are readily usable in low permeability crystalline rocks and that to attempt to measure the parameters of a potential site at a density likely to be required by a nuclide transport model would be almost impossible. Therefore our intention is to define carefully small geological environments, measure their hydrogeology as precisely as possible, and then use this information to interpolate between measurement points at the scale of a repository volume.

A nuclide transport model will require, amongst other parameters, the measurement of hydraulic conductivity, hydraulic potential, and porosity. Within these general parameters are such subdivisions as the variation of hydraulic conductivity with direction giving rise to dispersion and the type, disposition, and pressure dependence of porosity.

The major aim of the proposed research is the three-dimensional description of the hydrogeology of a fractured crystalline rock. This objective requires an extension of the one-dimensional approach of single borehole tests and indeed of classical line-source aquifer testing. The intended work centers on the use of a newly devised sinusoidal pressure technique. It involves an excitation borehole in which sinusoidally varying pressure is applied in a small length of open borehole at a relatively large depth below free water surface. The pressure variation should be detectable (depending on excitation amplitude, hydraulic conductivity, specific storage, and pressure wave frequency) at distances up to about 100 m from the excitation borehole. Measurements of the attenuation of the signal between the source and observation points should yield values of hydraulic diffusivity that are orientated in the relevant direction. Observations will be made using a packer system measuring a limited length of observation borehole. All being well and depending on the number of closely spaced boreholes, a skeleton of the vector space of the hydraulic diffusivity would be built up, which should reflect the fracture system.

It is also intended to try to extend this vector space approach to the use of interborehole geophysical techniques involving measurements of seismic velocity and electrical resistance. The successful combination of these techniques will probably be dependent on a detailed knowledge of the fracture systems and the magnitude and disposition of earth stresses.

Hydraulic diffusivity (hydraulic conductivity/specific storage) is only one part of a solute transport system, the others being hydraulic potential and porosity. As far as porosity is concerned, it is hoped that borehole geophysics can indicate, down to the required measurement limits, the appropriate magnitude and disposition of fissure type porosity. Of the methods available, those that measure it by default (nuclear density) appear to offer the most promise. New methods are almost constantly being invented and a recently proposed method based on high-frequency hydraulic pulses is an example of one of the more abstract methods that might prove useful. It is also intended to perform a limited amount of laboratory work on the disposition of intergranular porosity in core material in order to give an insight into the variation of diffusion paths and their dependence on rock type. Despite the amount of work done in this field, the present measurements of intergranular interconnected porosity in crystalline rocks vary widely dependent on test method.

The measurement of hydraulic potentials poses a major problem in low-permeability, low-porosity rocks since the drilling of the borehole destroys or overwhelms the environment to which it provides access. We hope to overcome both the problems of reliable water sampling and potential measurement by allowing for long-term pressure measurements within high-integrity packers. Some consideration is being given to the possibilities of measuring pressures during drilling, setting temporary bridge plugs immediately after drilling, or only completing boreholes as piezometers. The second two methods are cumbersome and expensive but also serve to prevent the mixing of ground waters from separate fracture systems.

Underlying the hydraulic approach to crystalline rock hydrogeology are the methods based on geochemistry and water chemistry. It is felt that water chemistry has great advantages in that results are an independent check on conclusions based on hydraulic models and that they are representative of large volumes of rock. Additionally, water dating results (where long time spans are indicated) have much greater credibility than model predictions over long periods of time in the future. Therefore much reliance is being placed on chemical methods and no hydraulic testing procedures are planned that may compromise the value of potential water samples. Apart from normal interpretation methods based on major element rock/water chemistry, certain trace elements are also being measured. Many isotope methods are being proposed or developed including the hydrogen, carbon, oxygen, uranium, thorium, and strontium isotopes. The $^{234}U/^{238}U$, $^{230}Th/^{234}U$, and $^{230}Th/^{232}Th$ isotope methods are being developed by the UKAEA while helium measurements will be undertaken at the University of Bath.

It is intended that all this information will be incorporated within an overall nuclide transport model, which would include information on effects such as the relationships of heating to permeability and rock/water interactions. Tracer studies either to measure parameters or to validate the model are not proposed for the immediate future because of the emphasis placed on original water chemistry and the need to know a good deal of background hydrogeology in order to interpret a tracer test.

Naturally there are other hydrogeological aspects being undertaken within the program but the approach outlined above represents broadly the methodology currently being proposed by the Institute within the UK radioactive waste geological disposal program.

APPENDIX E

DEPTH-DEPENDENT HYDROLOGIC CHARACTERISTICS OF DENSE BEDROCK: THE 0- TO 500-M INTERVAL (S. N. Davis)

1. ABSTRACT

Several hydrodynamic and hydrochemical characteristics of dense basement rock change significantly as a function of depth. These changes are distinctive in the first 200 or 300 m of depth but become difficult to define in the deeper water-bearing zones for which data have been reported. Porosity changes near the surface are defined the best. In areas of slow erosion, residual soil at the surface may have porosities in excess of 50%. This high porosity will persist to the base of intense weathering, which may be at depths of from 5 to 50 m, depending on geologic and climatological factors. At the base of weathering, porosity will decrease rapidly to values of less than 5%. Deeper zones will generally have effective porosities ranging from 1 to less than 0.1%. Once unweathered rock is reached, further decreases of porosity with depth are difficult to measure, but minor changes undoubtedly take place.

Changes of permeability with depth in bedrock are also well documented. Where intensely weathered residual soil mantles the surface, the permeability of this soil may actually be less than underlying partially weathered rock at depths of 5 to 15 m. Below the zone of partial weathering, permeability decreases significantly until depths of about 300 m are reached. Although intuitively one would assume a continued decrease of permeability with depth, available data are not sufficient to determine these trends with confidence. The statistical distribution of zones of differing permeability in space and the nature of the interconnections among these zones will help determine the nature of hydrodynamic dispersion in the rock. Although reliable data for a large number of field tests are completely lacking, one might assume that dispersivity will increase with depth. The rate of this increase should be particularly marked in the transition zone from completely weathered rock into unweathered material.

In a given region, the chemistry of water from dense bedrock will also change as a function of depth. Generally, total dissolved solids, pH, Na^+, HCO_3^-, and Cl^- will increase significantly with depth. In nongeothermal areas, SiO_2, NO_3^-, NH_4^+, Ca^{++}, Mg^{++}, and $SO_4^=$ may not change very much with depth.

Almost everywhere, dissolved O_2 will decrease with depth with most of this decrease taking place in the upper 30 m of the rock.

2. INTRODUCTION

The purpose of this paper is to give a brief review of depth-dependent hydrologic changes in dense bedrock that have been measured at depths of less than 500 m. Although the general topic of our workshop focuses on much deeper zones, data in the deeper zones are sparce. Hopefully, this review may provide some information that can be also applied to deeper zones.

The term "bedrock" has been chosen to include all plutonic igneous and metamorphic rocks. Although most tests discussed in my review have been made in granitic and closely related rocks, numerous metamorphic rock types are included also. In a broad sense, the rock type has only a secondary influence on hydrologic properties at depths of less than 300 m (Davis and Turk 1964). Rate of surface erosion, degree of weathering, surface topography, and most importantly, structural history of the rock appear to be the dominant variables (LeGrand 1967). Serpentine and narrow dikes and veins are probably exceptions to the above generalizations concerning the secondary importance of lithology. Serpentine, where it is highly sheared, appears to behave in an almost plastic manner and both porosity and permeability decrease rapidly with depth. Dikes and veins commonly form local discontinuities in the mechanical properties of the rocks and may tend to fracture to a greater extent than the more homogeneous surrounding rocks.

3. POROSITY

Highest porosities in dense bedrock are associated with zones of weathering (Fig. E-1). In some rock types, the transition from residual weathered material to fresh rock is rather sharp and occurs at an almost constant depth. More commonly in deeply jointed rock, the penetration of weathering is highly irregular and may even leave residual blocks of fresh rock completely surrounded by weathered rock. Such was the situation at Folsom Dam in California where the inability to predict total depth of weathering cost several million dollars in renegotiated foundation-preparation contracts. The scatter of data shown in Fig. E-2 reflects this uneven transition from weathered to fresh rock. Despite this uneven transition, it still generally takes place within a vertical distance of only 20 m or less.

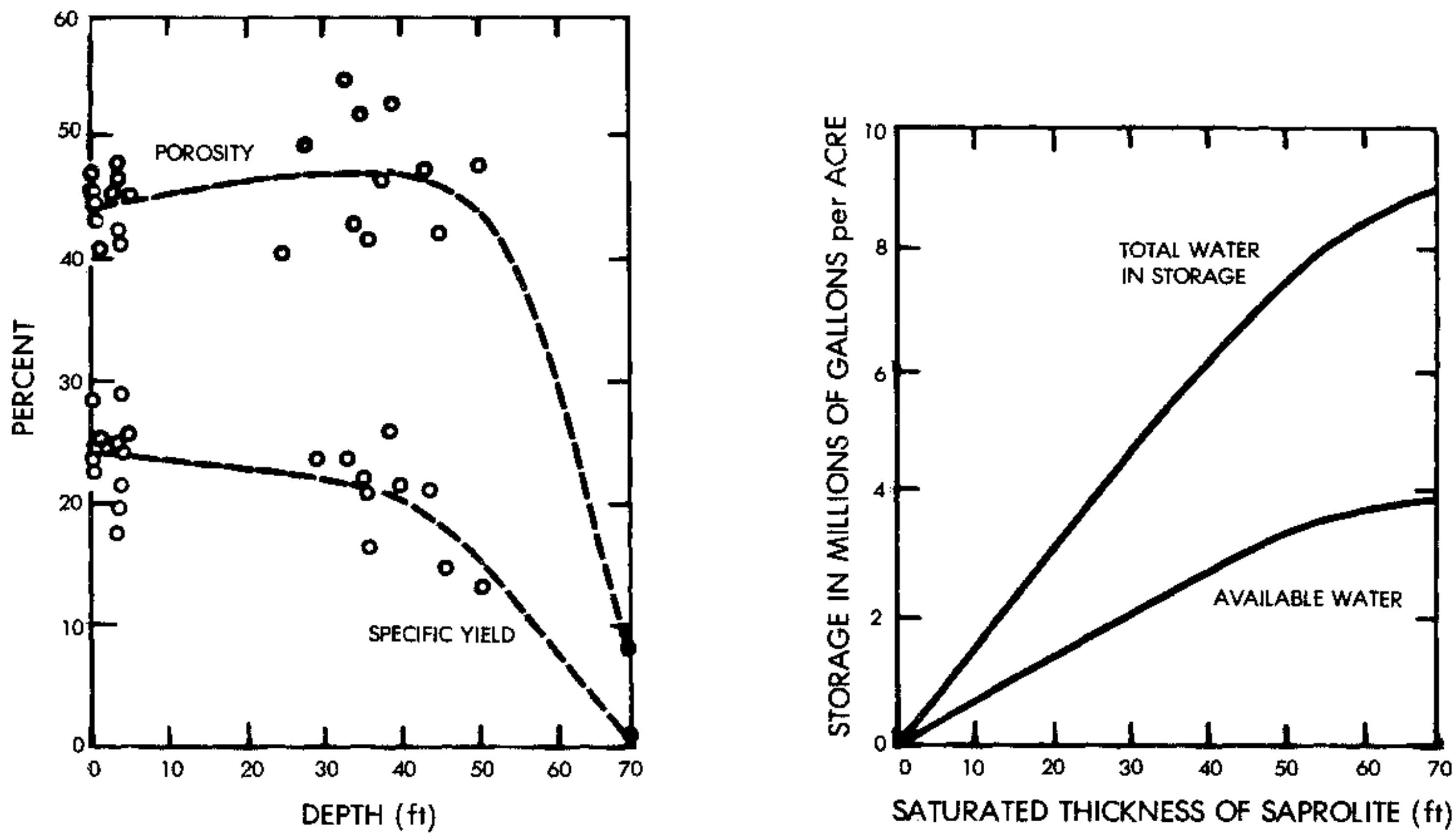

Fig. E-1

Results of laboratory tests on core samples of highly weathered metamorphic rocks from the Georgia Nuclear Laboratory area north-northeast of Atlanta, Georgia. (Stewart, 1962)

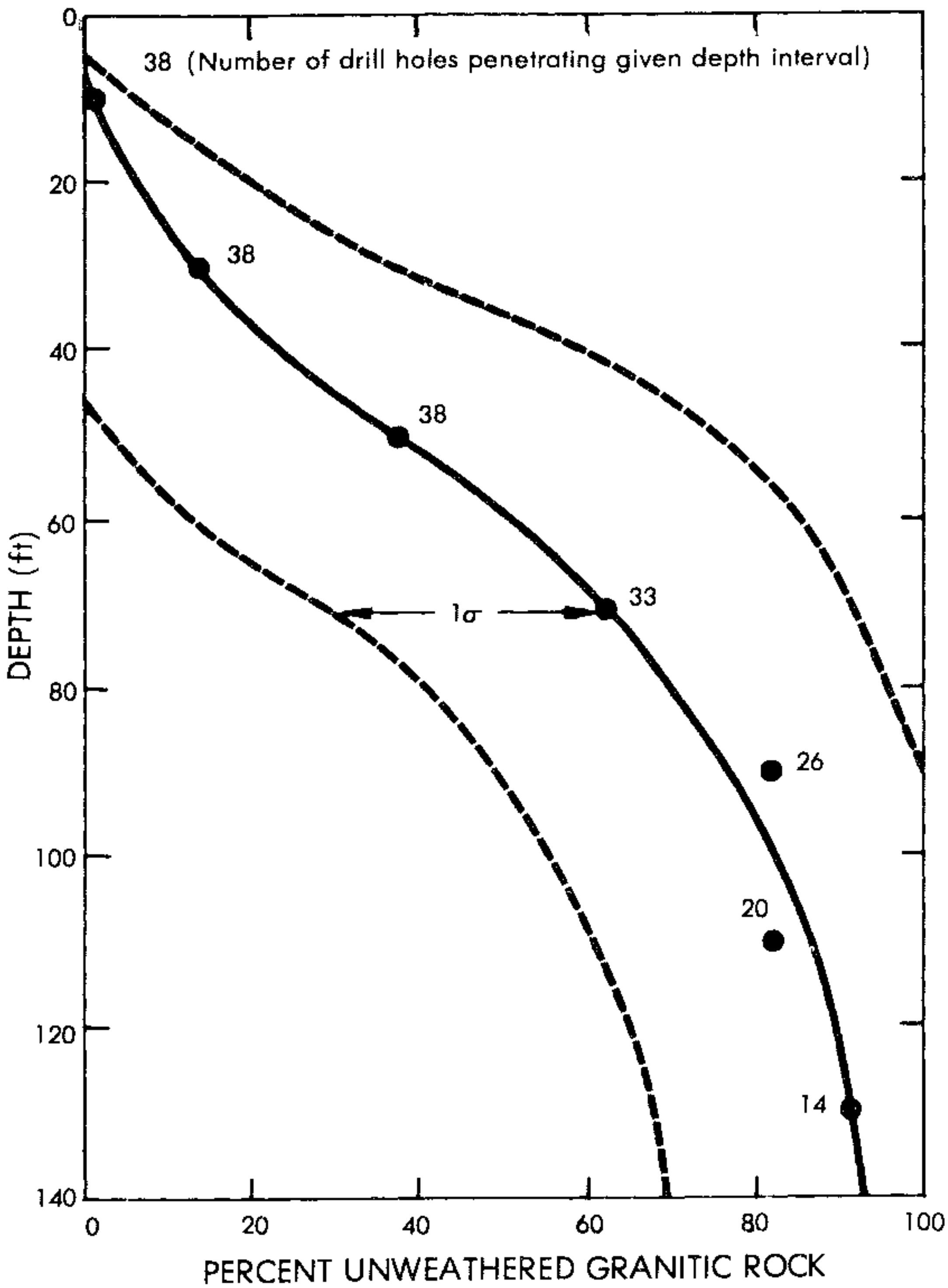

Fig. E-2.

Percent unweathered granitic rock as function of depth Folsom Dam, California. (U.S. Corps of Engineers, unpublished data).

Interconnected porosity, or effective porosity, at depths of 100 m or more is almost exclusively produced by fractures that probably range from about 1 to 100 microns in width (aperture) (Snow 1970). The precise measurement of the geometry of these fractures as they exist in their undisturbed state is still an elusive task. Present estimates are based on: (1) direct observations including borehole photography; (2) measuring the geometry of cement and other grout-like mixtures injected into cracks; (3) hydrodynamic testing using fluid injection and tracer transport, then the application of theoretical equations to calculate fracture apertures; (4) measuring the dynamic response of fractured rocks to various induced stresses; and (5) various indirect geophysical methods, many of which do not distinguish between effective porosity and total porosity.

Actual porosity values observed in residual soils may commonly exceed 50% (Fig. E-1). Porosity drops to around 5% in the transition zone between unweathered and weathered rocks. In fresh, unweathered rock, the effective porosities may commonly be less than 0.1%; although total porosities are considerably larger (Norton and Knapp 1977). Because of the very small porosity values, precise measurements of effective porosity, and to some extent total porosity, are difficult to make. I have not found convincing data on the changes of effective porosity as a function of depth within unweathered bedrock. In general, one might expect to find a very gradual decrease in effective porosity with depth (say, perhaps, from an average of 0.2% at 50 m to about 0.1% at 200 m) to maybe less than 0.05% at 500 m.

4. PERMEABILITY

Most permeability data for bedrock deeper than 100 m come from the interpretation of packer tests in drill holes (Snow 1968; Lindblon 1977). A small number of aquifer tests using data from flowing or pumping wells in deep bedrock have also been completed (Marine 1967). For depths less than 100 m, abundant data from both water wells and exploratory test holes are available (Davis 1969; Landers and Turk 1973; Mundi and Wallace 1973; Stewart 1962; Uhl 1976).

The fact that the specific capacity per depth of saturated rock penetrated by a water well decreases rapidly with depth has been noted by hydrogeologists for almost 100 years. Typical data are shown by graphs of different types in Figs. E-3 and E-4. Two possible explanations for these trends exist.

First, and most obvious, the permeability decreases with depth. Second, the data may be only an artifact of the way in which water wells are drilled and may only indicate lateral variations of permeability. Specifically, where permeable rocks are encountered, drilling stops at a shallow depth and a high near-surface permeability is suggested, and where rocks of low permeability exist, wells are drilled deeper in search of water and the apparent overall permeability of the rocks is low.

Although the type of data bias suggested above may have some effect, Davis and Turk (1964) and many later investigators have looked at dam and tunnel exploration data, some of which have a bias in the opposite direction. Specifically, many deep holes have been drilled in order to intersect permeable zones. Hence, data from a large number of drill holes, unless the intent of the engineering geologist could be taken into account, would probably have a bias in favor of greater permeability at depth. However, the location of the dam or tunnel most commonly favors areas of sound rock, so permeabilities of the area in general would tend to be lower than adjacent areas. The general conclusion is that test-hole data show a decrease of permeability with depth that is very similar to water-well data (Figs. E-5 and E-6).

Recent interest in deep-bedrock repositories for nuclear waste as well as "dry rock" geothermal resources have stimulated deep drilling and testing in Canada, Sweden, France, United States, and other countries. Some data from Sweden are shown in Fig. E-7. The data are from drill holes in four different regions that represent different geologic settings. At least one of the holes was reported to have been drilled with the purpose of intersecting permeable zones at depth. Despite these limitations, a general decrease of permeability with depth is evident.

Numerous interrelated reasons exist for the decreases of permeability with depth. These are noted briefly below:

(1) decrease of weathering with depth,

(2) increase of spacing between all joints and particularly sheet joints with depth (Crosby 1881; Jahns 1943; Schaeffer 1978),

(3) increase of lithostatic pressures with depth that tends to close fractures at great depths,

(4) decrease with depth of the abundance of fractures related to surficial mass wasting, and

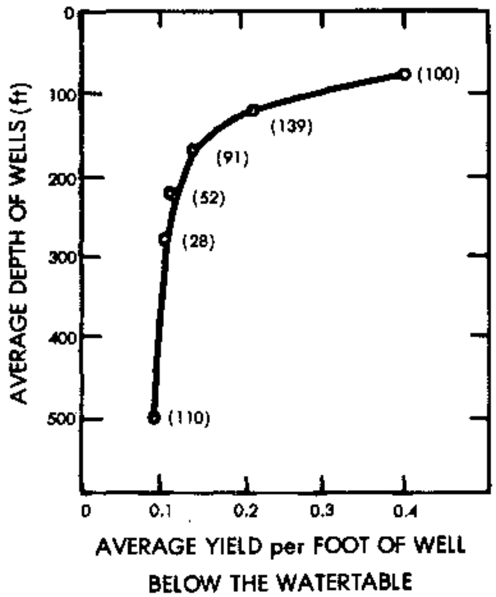

Fig. E-3.
Decrease in yield of wells with depth in crystalline rocks of the Statesville area, North Carolina. Numbers near points on curve indicate the number of wells used for each average shown (Le Grand 1954).

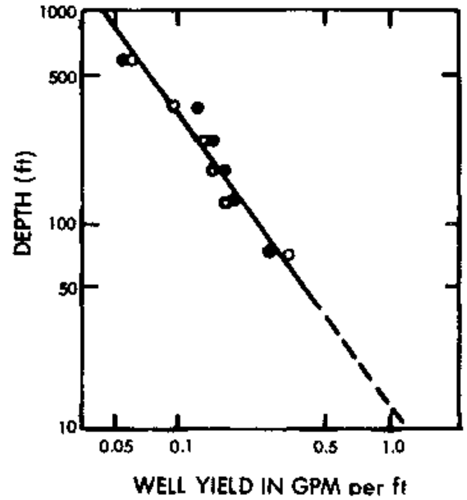

Fig. E-4.
Yields of wells in crystalline rock of eastern United States. Open circles represent mean yields of granitic rock based on a total record of 814 wells. Black dots represent mean yields of schist based on a total record of 1522 wells (Davis and Turk 1964).

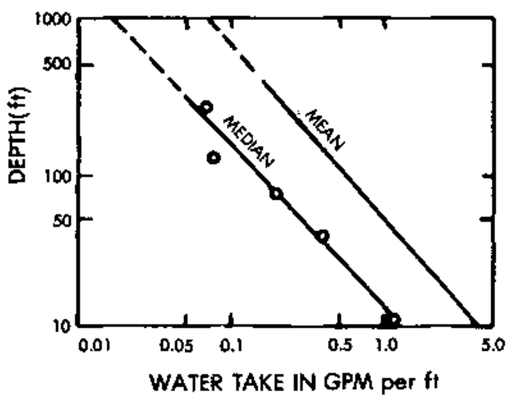

Fig. E-5.
Water-injection rates, or water take, related to depth in granitic rocks of California. Diagram based on data from 412 tests (Davis and Turk 1964).

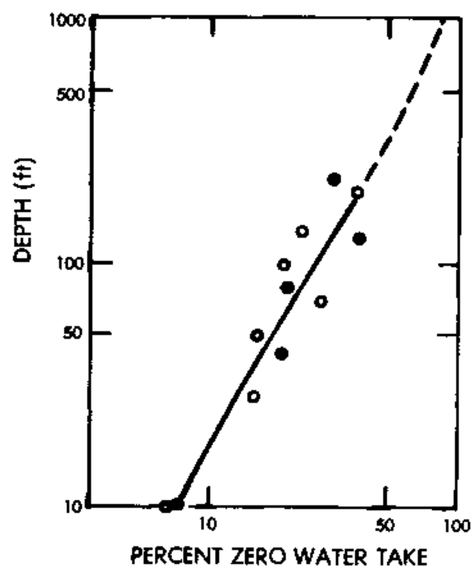

Fig. E-6.
Percent of tests having zero water take in granitic rocks, shown by black dots and miscellaneous rocks, shown by open circles (Davis and Turk 1964).

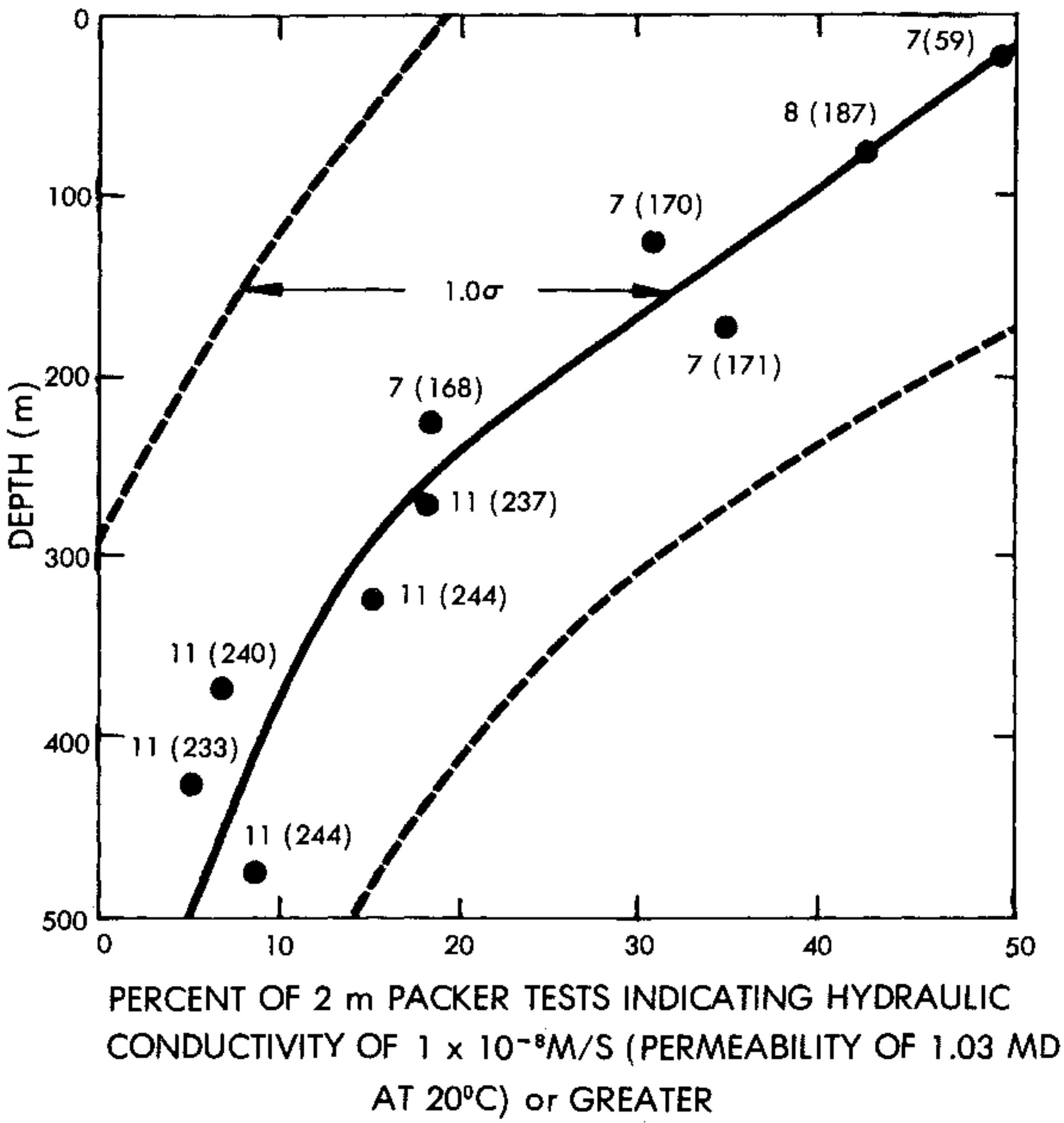

Fig. E-7.
Diagram showing variation in percent of 2-m packer tests indicating hydraulic conductivity of 1×10^{-8} m/s (permeability of 1.03 md at 20°C) or greater. Test conducted in crystalline basement rocks in Sweden. Upper number of each data point is the number of holes penetrating a given depth interval. Lower number is the total number of packer tests in the interval (from unpublished KBS reports).

(5) decrease with depth of the effect of topography on those stress patterns that might help contribute to localized rock failure.

Despite the general decrease of permeability with depth, certain mechanisms potentially controlling bedrock permeability do not become less effective with depth. Experimental evidence suggests that if rocks approach failure under mechanical stress, they experience a dilatancy that produces microfractures (Brace and Paulding 1966; Zoback and Byerlee 1975) thus increasing to some extent the rock permeability. This effect can probably be important at all depths where rocks have a finite strength, and certainly down to depths of 10 km. Pressures of fluids contained in rock fractures are also important. In contrast with the limited depth of tensile failure possible in dry rock, high fluid pressures could help produce fracturing at depths of several kilometers. In view of the foregoing discussion, the general decrease of permeability with depth, which is evident from shallow drill cores, possibly cannot be extrapolated to depths of several kilometers.

At any depth interval in a given region, the statistical distributions of measured permeability values are strongly skewed to the right or to the higher values. Where enough data are present to test, the distributions of permeability appear to be log normal (Figs. E-8 and E-9). This conclusion corresponds with the well-known fact that most well yields in crystalline rocks, as well as other geologic media, have log-normal distributions (Davis 1969).

5. DISPERSIVITY

Inasmuch as dispersivity is some function of the geometry of the cracks in fractured bedrock and this geometry varies with depth, it is safe to assume that the dispersivity also varies with depth. Spacing between water-bearing fractures, on the average, probably increases with depth suggesting that dispersion also may increase. Unfortunately, reliable studies of dispersion in natural systems are difficult under the best field conditions, so sufficient multiple, systematic measurements in bedrock in any single location are not available to test the above speculative remarks.

6. HYDROCHEMISTRY

Studies of the chemistry of volcanic vapors, geothermal waters, various mineral springs and wells (Mack and Ferrell 1979) and fluid inclusions in minerals within bedrock (Rich 1979) have all suggested strongly that the

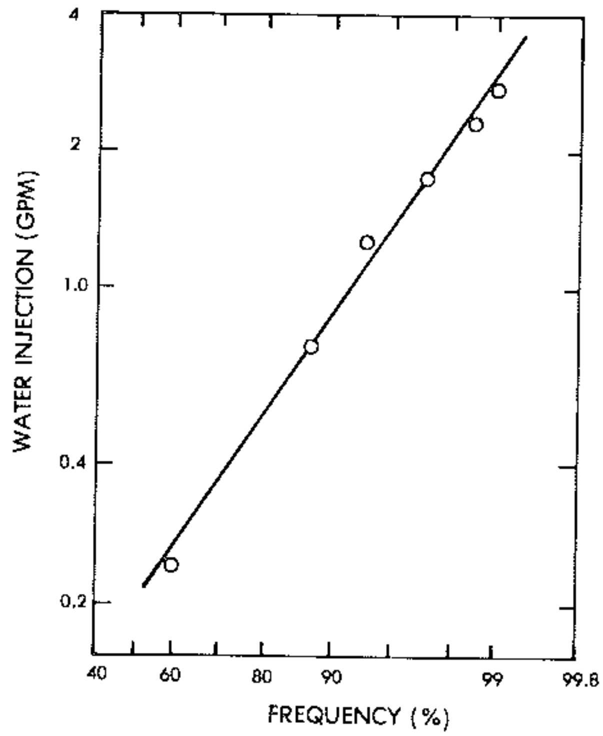

Fig. E-8.
Log-probability plot of frequency of water-injection rates in 62 tests at depths of 81 to 100 ft at the Oroville dam site, California (data from Davis and Turk 1964).

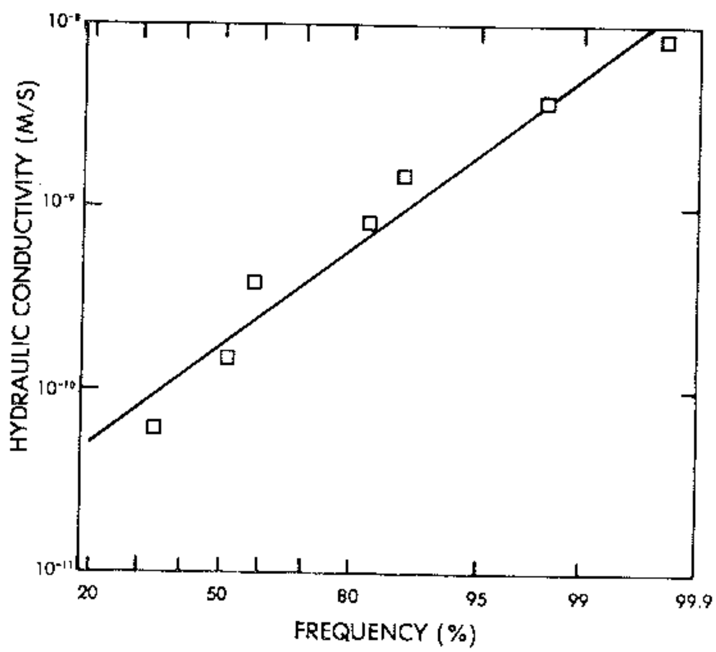

Fig. E-9.
Log-probability plot of calculated hydraulic conductivities from 500 to 600 m depth in the Karlshamn borehole (Ka 1), Sweden. A total of 59 packer tests were made in this interval (from unpublished KBS data).

initial composition of fluids saturating the micropores in newly formed rock is highly saline. Presumably then, as test holes penetrate to great depths in crystalline rocks, small amounts of saline water should be present owing to the very slow flushing by almost static fresh ground water in deep fractures and the even slower molecular diffusion in the cool to slightly warm bedrock. Scattered observations suggest that total dissolved solids, pH, Na^+, HCO_3^-, and Cl^- increase significantly between the depths of 50 and 500 m. In nongeothermal areas, SiO_2, NH_4^+, Ca^{++}, Mg^{++}, and $SO_4^=$ may increase only slightly with depth. In geothermal areas, K^+ and SiO_2 increase rapidly with depth, undoubtedly in response to an increase in water temperature (Fournier and Rowe 1966; Fournier and Truesdell 1973). Almost everywhere, NO_3^- and O_2 decrease to very low concentrations in the first 100 m as depth increases.

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