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GEOTHERMAL ENERGY: A NEW APPLICATION OF ROCK MECHANICS?

GÉOTHERMIQUE L'ÉNERGIE: NOUVELLE L'APPLICATION DE LA MÉCANIQUES DES ROCHES?

GEOTHERMISCHE ENERGIE: EINE NEUE ANWENDUNGSMETHODE AUF DEM GEBIETE DER FELS-MECHANIK?

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SUMMARY

A small group of scientists from the Los Alamos Scientific Laboratory has been working for the past 2 years in developing a new energy source based on the earth's heat. Their concept, the extraction of thermal energy from the numerous regions of the earth's crust containing hot--but essentially dry--rock at moderate depths, may offer a solution to the developing world energy crisis.

A deep exploratory hole has already been drilled into basement crystalline rock in north-central New Mexico, and tested at various horizons. These experiments have demonstrated, at least in this one specific region, that a large vertical fracture system can be created in granitic rocks using conventional-hydraulic-fracturing techniques. Of more importance relative to the Los Alamos convective energy extraction concept, an open pressurized fracture system has been maintained in these crystalline rocks for many hours with only negligible fluid leak off. Further, an analysis of seismic signals resulting from the hydraulic fracturing process indicates that a method may be available to determine both the orientation and vertical extent of the resulting fracture system.

In conjunction with the <u>in situ</u> tests, theoretical and laboratory studies have been undertaken in order to fully understand the different features observed in the field fracturing experiments. Permeability tests under various stress conditions have revealed the importance of this factor, and have drastically changed the procedure for measuring stress at great depths using the hydraulic fracturing technique.

Geochemical problems associated with the dissolution of certain minerals are also being investigated. The variation in concentration of the materials contained in a closed-loop fracture circulation system could be an indicator of the fracture extension rate due to thermal contraction of the reservoir rock as energy is withdrawn from it. This concept, however, must be tested and will be investigated in a subsequent field experiment.

SOMMAIRE

Dans le cadre des travaux réalisés, depuis deux ans, au Laboratoire Scientifique de Los Alamos, une étude relative au développement d'une nouvelle source d'énergie - ayant comme origine la chaleur contenue à l'intérieur de l'écorce terrestre - a été entreprise par un groupe de chercheurs. Leur concept consiste à extraire de l'énergie thermique de régions contenant des roches chaudes, mais surtout sèches, se trouvant à des profondeurs modérées. Si cette technique s'avère efficace, elle présenterait une finalité pratique à la crise énergétique mondiale.

Un forage exploratoire atteignant la roche crystalline a déja été réalisé au Nord du Nouveau-Mexique et plusieurs expériences y furent conduites à diverses profondeurs. Elles démontrèrent que, dans une région au moins il fut possible de créer une fracture verticale dans la roche granitique en utilisant les techniques conventionnelles de fracturation hydraulique. Cette série de tests a aussi mis en évidence le fait que le système pouvait être maintenu sous pression pendant plusieurs heures, sans pour autant enregistrer des pertes de fluide considérables. Une analyse complémentaire des signaux séismiques, provenant de la fracturation hydraulique proprement dite, indiqua la possibilité d'utiliser cette technique afin de déterminer l'orientation et la géométrie spatiale du système de fractures.

Parallèlement aux essais sur champs, un programme d'études théoriques et d'expériences en laboratoire fut conduit afin de mieux justifier les résultats obtenus lors des essais in-situ. Des essais de perméabilité radiale sous contraintes révélèrent l'importance de ce facteur au point de modifier le procédé à suivre lors de la détermination des contraintes existant à grande profondeur au moyen de la fracturation hydraulique.

Des recherches ont également été entreprises concernant les problèmes géochimiques associés à la dissolution de certains minéraux contenus dans la formation rocheuse. On a observé que la variation en concentration de certains d'entre-eux pourrait indiquer, quantitativement, la vitesse d'extension du système de fracturations due à la contraction thermique du réservoir, au fur et à mesure que l'énergie en est extraite. Ce concept se doit toutefois d'être testé lors d'expériences futures sur champs.

ZUSAMMENFASSUNG

Wissenschaftler des Los Alamos Scientific Laboratory haben in den letzten zwei Jahren eine neue Energiequelle entwickelt, die die hohen inneren Temparaturen unserer Erde ausnuezt. Die Methode, die die Nutzung thermaler Energy in vielen Gebieten vorsieht, in denen die Erdkruste in geringer Tiefe aus heissem--hauptsaechlich trockenem --Gestein besteht, koennte die drohende Weltenergiekrise vermeiden.

Ein tiefes Bohrloch ist bereits zu Forschungszwecken in kristallinisches Grundgestein des noerdlichen, zentralen New Mexico gesenkt worden. Der Versuch hat erwiesen, dass, zumindest in diesem Gebiet, ein ausgedehntes System von Bruchrissen in Granit mit konventionellen hydraulischen Druckmethoden erzeugt werden kann. Von besonderer Bedeutung fuer das Los Alamos Konzept konvektieven Energieentzuges ist die Tatsache, dass das Bruchsystem in kristallinischem Gestein viele Stunden lang ohne nenneswerten Fluessigkeitsverlust unter Druck offen gehalten werden konnte. Auswertung der seismischen Signale, die von dem entstehendem Bruchsystem ausgingen, hat ausserdem ergeben, dass die Signale sowohl die Ausrichtung als auch die Tiefe der Bruchrisse anzeigen koennten.

Gleichzeitig mit dem in situ Test wurden theoretische und Laborversuche durchgefuehrt, um die verschiedentlichen waehrend des Tests beobachteten Merkmale zu erklaeren. Durchlaessigkeitsversuche unter verschiedenen Druckverhaeltnissen haben die Wichtigkeit dieses Faktors erwiesen und haben die Methode drastisch geaendert, mit der der hydraulisch erzeugte Druck in grosser Tiefe gemessen wird.

Geochemische Probleme, die mit der Loeslichkeit gewisser Minerale verbunden sind, werden auch untersucht. Die Konzentrationsschwankungen von Stoffen im geschlossenen Zirkulationssystem der Bruchrisse koennten anzeigen, wie rasch sich die Risse wegen thermaler Zusammenziehung ausweiten, wenn Energie aus dem Gesteinsreservoir entzogen wird. Diese Moeglichkeit wird in kommenden Gelaendeversuchen untersucht werden.

Introduction

Due to the energy crisis that the world is facing, the development of new resources--other than fossil fuel--is of great value and interest. Considering the amount of heat contained in the earth's crust, it is quite obvious that geothermal energy represents, theoretically, the largest energy reserve available to man. So far, this supply of usable energy has been generally ignored, except for a few natural hydrothermal regions, such as those located at Larderello, Italy; Cierro Prieto, Mexico; and The Geysers in California. Geothermal energy does not have the disadvantages associated with the use of the fossil resources. This energy already exists in the form of clean heat; and pollution--other than thermal--is avoided.

In nature, connecting water circulation channels in combination with overlying impermeable rock layers have produced natural steam reservoirs. However, this represents only a small portion of the very large energy resource available from "hot dry rock." The logical approach in developing a method to use this energy would be to create the circulation system in hot dry rocks that nature has failed to provide.

Technologically, it would appear that man-made geothermal systems are possible and that one could economically develop a method to extract this form of energy in the near future (Smith, 1973). Both the ideas and the tools to develop this resource are under active investigation at the Los Alamos Scientific Laboratory. If the system works, it will provide mankind with a significant new energy source, the extraction of which will not deteriorate our environment.

Potential of This Energy Resource

The largest part of the heat that is available underground is not yet accessible with today's existing technology. The magnitude of the usable geothermal resources will, consequently, increase with the degree to which any of these technological advancements can be achieved. Improvements need to be made in the following areas:

- Techniques of prospecting.
- Improvements in high temperature drilling technology.
- Detection of induced underground fracture systems from downhole measurements.
- Chemical and mechanical behavior of hot dry reservoirs.
- Heat transfer mechanisms in rock.

However, the relatively small amount of geothermal heat now available to man from hot dry rocks, and which could be extracted with present technology, is sufficient to satisfy the demand for several thousands of years.

If one considers, for example, a volume of granite of about 160 km^3, the amount of energy which could be extracted by cooling it by 200°C is of the order of 1.7×10^{19} calories, a number which corresponds to the total energy used in the United States in 1970. This volume of rock represents an infinitesimal quantity (5 km by 4 km by 8 km) of the total rock reservoir available for such purposes.

Site Selection

It was necessary that the dry hot rock geothermal demonstration be undertaken in a region where relatively impermeable rock at a usefully high temperature could be reached at reasonable cost. Somewhat arbitrarily, 200°C had been set as a minimum useful temperature and 10^{-17} m^2 was the permeability limit. In addition, the maximum depth to be considered, at least initially, was about 3500 m.

The site chosen for the project is situated in the Jemez Mountains in north-central New Mexico about 50 km from the Los Alamos Scientific Laboratory. The Jemez Mountains are part of the Southern Rockies and are located at the northern limit of the Rio Grande depression.

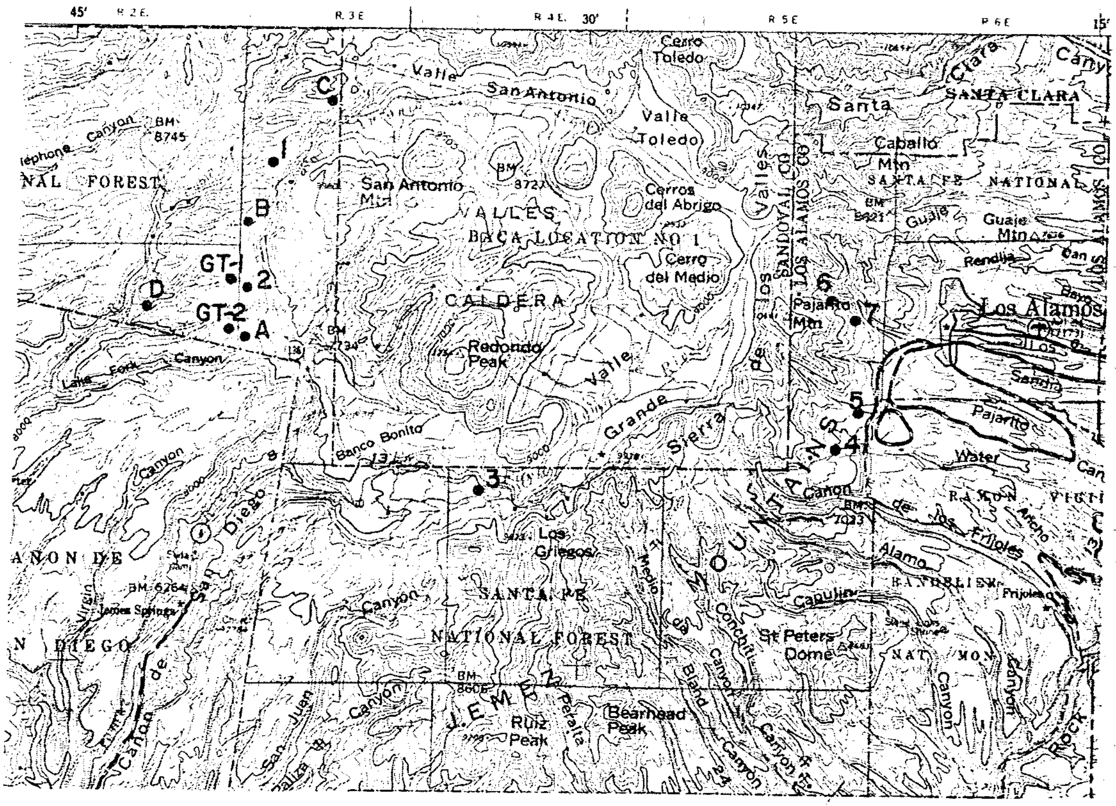

Figure 1 Regional map of the Valles Caldera (U.S.G.S. Map NI13-1; scale 1:250000; contour intervals: 200 ft).

This region had been tectonically active during most of geologic time and has, in recent time, been the site of large scale volcanic eruptions. As lavas and ashes accumulated, the eruptions were less frequent but more violent. The last one, the largest, produced a local tuff layer of about 300 m thick. The volcanic center later collapsed to form what is believed to be one of the largest calderas in the world (Purtymun, 1973; West, 1973). The Valle Grande, a valley nearly 12 km across, lies in this caldera.

The latest geothermal experimental site, referred to as GT-2, lies on the western outside slope of the caldera, at a distance of about 13 km from the center of it. Several exploratory boreholes were drilled around the edge of the caldera prior to this selection, and are indicated on the region map (Fig. 1).

In this particular locality, the heat flow measured in situ gives a value of about 5 cal/cm^2-sec (which is sufficient for the projected experiment) as compared to an average value of 1.5 cal/cm^2-sec for the total area of the earth's crust.

Extraction Techniques

The experiment involves drilling two holes of unequal depth (Fig. 2) into the hot basement rock, connecting them by means of a large crack that will furnish enough surface area to effectively transfer the heat from the rock to the circulation fluid (Brown et al, 1973; Smith, 1973a). The loop will be closed by means of a heat exchanger at the surface.

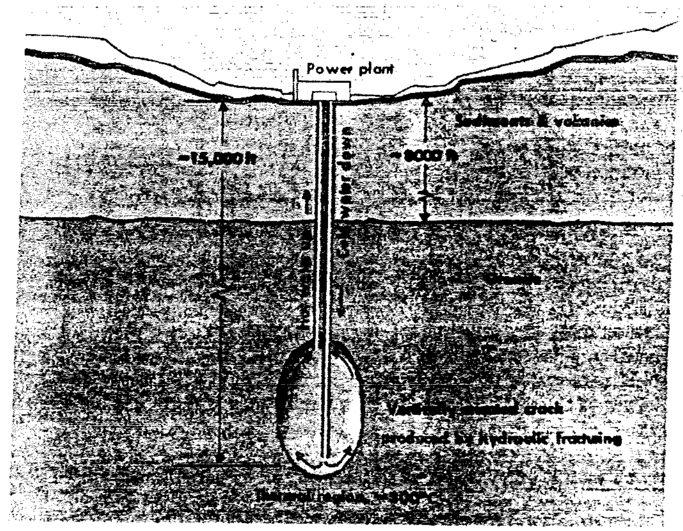

Figure 2 Proposed hot-dry rock extraction scheme.

The creation of the connecting fracture is based on the hydraulic fracturing technique that has been used for about 30 years in the oil industry. However, very few hydraulic fracture experiments have been carried out in crystalline formations, and the technique had to be adapted to the granitic basement rock in the experimental area (Roegiers et al, 1973; Roegiers, 1974).

Basically, the technique consists of drilling a borehole to the appropriate depth. A section of hole is then sealed off by means of packers and the pressure in the so-formed cavity is increased until a vertical fracture occurs. The breakdown of the borehole wall occurs as soon as the local stress concentration plus the tensile strength of the formation is overcome (Fairhurst, 1964). This is referred to as the intiation pressure, P_i. The fracture is then extended at a somewhat lower pressure, the propagating pressure, P_p; the value of which is very much dependent on the viscosity of the fluid and the pumping rate. At this stage, proppants may be added to keep the crack open after the pressure is released. Finally, when the fracture is sufficiently extended, pumping is stopped and the pressure rapidly drops to a lower value, the instantaneous shut-in pressure, P_{ISIP}, which is a very good approximation for the least *in situ* principal stress. It is worthwhile noting that the difference between the values of P_p and P_{ISIP} depends on the fracture extent--it is almost negligible for a very large fracture. (Experimental work has recently been done in the U.S.S.R. where a hydraulic fracture has been continuously pumped for 24 consecutive hours and has proven that statement.)

From the spatial geometry of an induced fracture, one can determine the orientation of the stress vector since the propagation of the crack occurs in a direction perpendicular to the least principal compressive stress.

We, consequently, propose to drill a borehole of 2750 m depth in order to attain a temperature of about 250°C in the basement granite rock. After having induced a fracture of more than a 500 m radius, a second shallower borehole will be drilled to intersect the fracture plane. The deepest borehole will be used to inject the fluid, which will travel through the fracture, absorb heat and be returned to the surface. Additional fluid will be added as required to make up for permeability losses and for rock shrinkage due to cooling.

Due to the density differences between the injected relatively cool fluid and the heat effluent, a spontaneous circulation may develop and no pumping facility will be needed. The system will be operated under pressure to avoid the production of steam.

The system described above is believed to be capable of producing about 100 MW of power (corresponding to 20 MW electrical). However, if the fracture network propagates further as the rock cools off, the lifetime of the system and the power generated could very well increase.

As will be seen, the development of the dry geothermal energy concept involves several rock mechanics problems which are at the present time under investigation, both in the field and on laboratory scale.

Field Testing

Prior to drilling the present test hole, several exploratory holes were drilled to determine the area of highest temperature gradient and the simplest geology. The holes had an average depth of 200 m and were located in an arc around the west side of the caldera. This preliminary investigation showed that the temperature gradient rapidly decreases as one goes away from the center of the caldera (Smith, 1973b).

A first deep borehole, designated as GT-1, was then drilled to a depth of 760 m, the last 120 m being in the Precambrian granite rock. The rock formation at that depth varied between a granitic gneiss and an amphibolite. Several vertical hydraulic fractures were then induced at surface pressures between 8.1 x 10^6 and 15.7 x 10^6 Pa. The general orientation of the fractures was NW/SE. The temperature at the bottom of the borehole stabilized at 100.4°C, which indicated that the heat gradient interpolations made from the previous exploratory holes were reasonable. The cores obtained from near the bottom of the hole indicated a very competent rock; *in situ* tests verified that fractures could be maintained open at fluid pressures of 6 x 10^6 Pa.

The following table summarizes the various hydraulic fracturing tests which were undertaken in GT-1. The pressures were measured at the surface; σ_3 referring to the smallest *in situ* principal compressive stress.

TABLE I

RESULTS OF HYDRAULIC FRACTURING TESTS PERFORMED ON GT-1

Date	Depth (m)	Pressures Breakdown (10^6)	ISIP (Pa)	σ_3 (10^6 Pa)
7/3	761	9.10	7.94	15.55
14/3	730	15.66	13.38	20.67
21/3	751	9.52	8.05	15.56
23/3	776	9.10	--	--
24/3	740	8.07	6.99	14.39
27/3	748	11.74	8.96	16.44
28/3	745	10.41	7.41	14.86

Making the usual assumptions of elasticity would allow us to compute the value of the second horizontal principal stress, this can however be of very dubious value as we will see later.

Another approach to compute the stresses is to use energy considerations (Aamodt, 1974). By successively inducing a fracture, letting it collapse and repressurizing it, we were able to compare the energies involved. Knowing the specific fracturing energy (α), Young's modulus (E), and Poisson's ratio (ν), an equation of energy balance can be written as follows.

$$\left.\begin{array}{l}\text{Work to extend fracture}\\ \text{Work to reopen pre-existing fracture}\end{array}\right\} \; 2\pi\,\alpha R^2$$

Where R is the crack radius.

Introducing then Sneddon's and Sack's equations, we end up with a system of three equations between the three unknowns $(P - \sigma_3)$, α and R. The value of the least compressive stress, σ_3, is finally computed knowing that the work needed to reopen a pre-existing fracture of volume, V, is given by

$$U_r = \frac{(P + \sigma_3)V}{2} .$$

By applying this technique to the test performed in GT-1, we obtained

$$\sigma_3 = 14.7 \times 10^6 \text{ Pa.}$$

The value of σ_3 compares very well with the one obtained from the pressure curve.

Seismic Detection of Fracturing Events

One of the most significant results obtained from the recent series of rock mechanics experiments performed in GT-1 was the seismic detection, at the surface, of downhole fracturing events (Potter et al, 1974). Although no seismic signals were detected at the surface during the extensive series of small-scale (about 3 m high) hydraulic fracturing experiments, seismic signals were obtained both during and following the formation of the final large (about 34 m high) hydraulic fracture.

Of particular note was a large seismic event that occurred some 6 sec after the termination of pumping on the final large hydraulic fracture. This event, as shown in Fig. 3, was preceded by a large damped pressure oscillation with an initial peak-to-peak variation of 5×10^6 Pa. It is postulated that this seismic event was related to the preceding shut-in-induced large-scale pressure oscillation, which may have resulted in the broaching of the lower packer. The significant shear component recorded by the vertical seismometer channel would support this hypothesis, for a suddenly extending fracture in an inclined borehole.

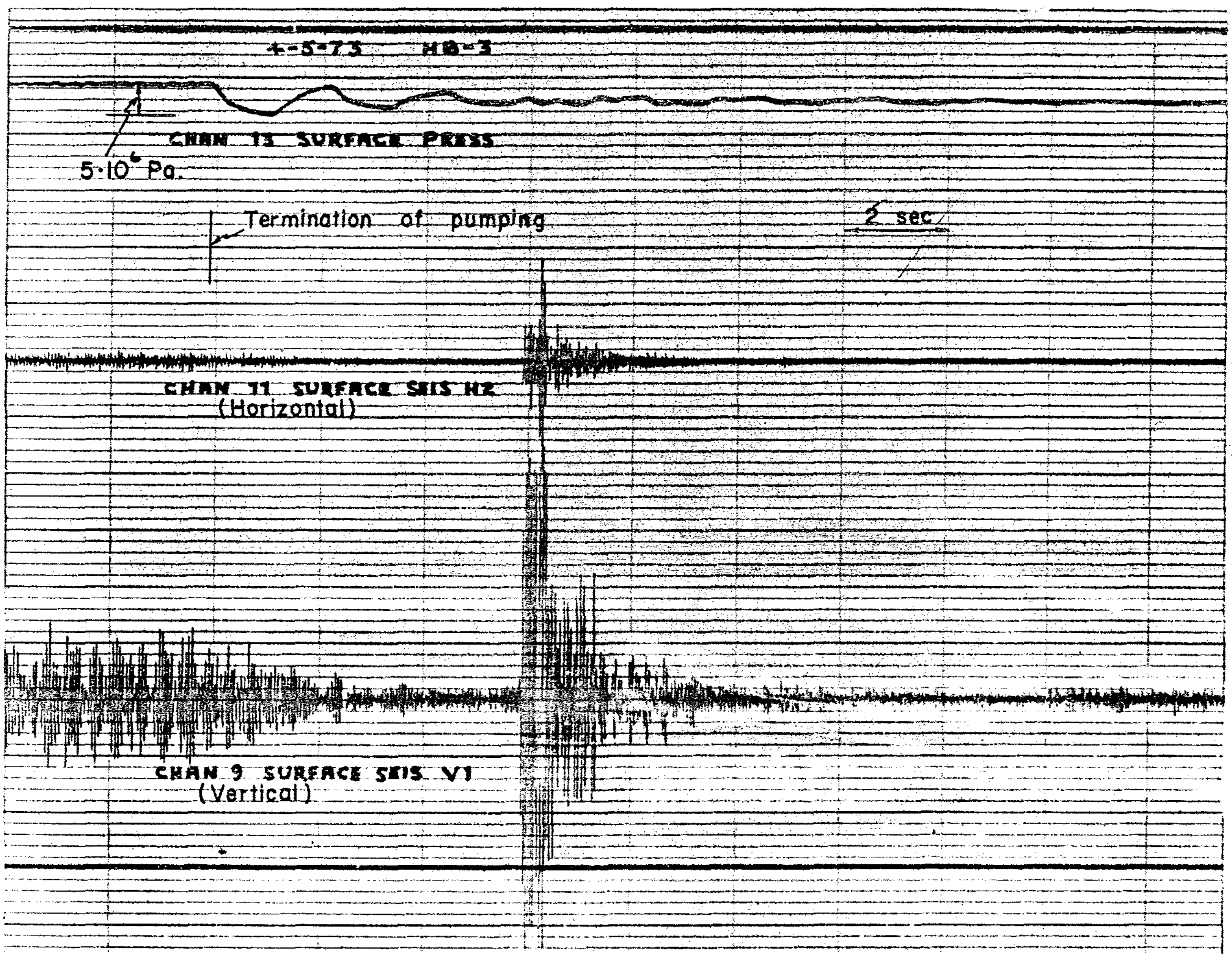

Figure 3 Seismic surface recordings during a typical hydraulic fracturing test in GT-1.

Figure 4 Close up of cross-section of granite specimen. (Note the arrowhead fluid penetration surrounding a fracture which has been propagated and stopped halfway through the specimen).

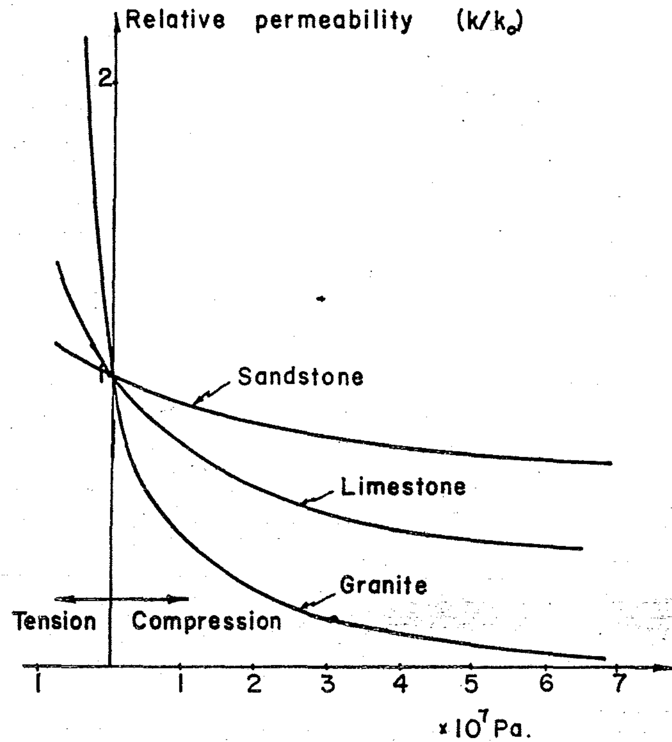

Figure 5 Schematic representation of relative permeability variations.

Laboratory Tests

Two laboratory research projects are in direct relationship with the Géothermal Energy Program. One concerns the effects of the stress field on the permeability coefficient and the other is associated with the induced fracture geometry.

In the Dry Hot Rock Geothermal Demonstration, a hydraulically induced fracture will provide the man-made circulation system. Although there seems to be no doubt that this fracture will propagate in a direction perpendicular to the least compressive stress (Haimson, 1968), many assumptions have to be made to compute the horizontal principal stress acting parallel to the plane of the crack. The accuracy of the usual analytical approach using elasticity theory is doubtful because laboratory tests have shown that various loading rates lead to different values of the breakdown pressure. The problem seems to be the unknown stress concentration around the borehole which has to be overcome if a fracture is to be created. This stress concentration is very dependent on the fluid percolation rate prior to fracture initiation. Consequently, the variation in permeability as a function of applied stress is a factor of major importance (Roegiers, 1974). If even a small amount of fluid percolates though microcracks, it will induce a body force which will influence the value of the breakdown pressure.

Up until now, granite has been generally considered impermeable (Fig. 4). Its permeability is probably very low indeed, but the relative change in permeability under compressive and tensile stresses is enormous compared to a limestone or a sandstone (Fig. 5). In a borehole, the granite is subjected to a circumferential tensile stress field prior to fracture initiation. Percolation occurs under these conditions and the breakdown pressure changes, which is contrary to what elasticity theory would predict. Nevertheless, the value of the breakdown pressure decreases as the permeability increases. For instance, on a saturated laboratory sample of granite, under tensile stress, the breakdown pressure can be decreased to as low as 5.10^6 Pa, as compared to the usual value of 1.5×10^7 Pa generally given in the literature (Fig. 6). The conclusion is that the assumed value of the breakdown pressure can only be used if preliminary laboratory tests have first been undertaken to determine if the percolation rate changes under the applied stress conditions.

An additional important problem is the detection of the fracture geometry at some distance from the borehole. The solution of this problem would have a tremendous impact in several ways. We would not only be able to detect variation in the orientation of the stress tensor from the side of the borehole, but the problem of trying to intersect the fracture by means of an additional borehole would be much easier.

Model studies using the first arrival refraction wave method have shown that acoustic detection can be used to determine the extent and the orientation of an induced fracture (Fig. 7). The compressional P waves refract at the tip of the crack and by placing an emitter and receiver on each side of the crack, the travel time to the tip of the crack and back can be determined. Two different measurements are sufficient

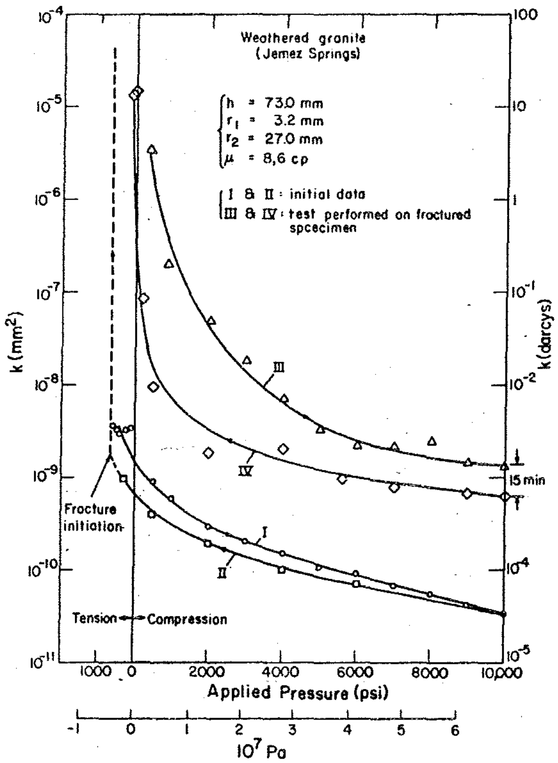

Figure 6 Permeability variation of granite specimen (intact and fractured).

to locate the crack tip. Several tests were also conducted with a water-filled crack and the fluid seems not to alter the method.

Conclusions

Although hydraulic fracturing is a well known technique, many refinements in measuring and calculating rock stresses are needed for future geothermal energy extraction experiments. Several additional research topics in rock mechanics definitely need to be developed to better utilize the natural heat of the earth. Another important need is the development of more efficient air drilling methods operable at temperatures reaching 400°C. Also, downhole measuring instruments will have to be produced which are heat and corrosion resistant.

In order to break away from the conventional natural steam systems used in the past, a better understanding of dry hot rock reservoir behavior will be required for the successful formation of artificial hot water systems. These problems offer many new challenges to the science of rock mechanics.

Acknowledgments

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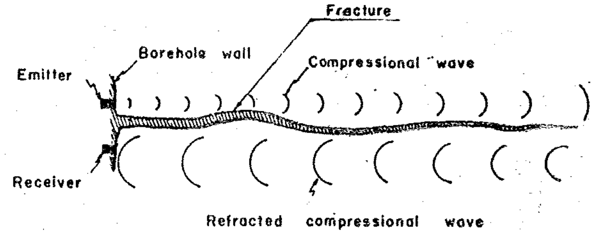

Figure 7 Schematic representation of the first refraction technique.

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