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Progress Report

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"Relationship of Rock Physics and Petrology
to Geothermal Energy Technology"

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Earth Resources Development Administration

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PROGRESS REPORT

The original proposal from the Institute of Geophysics and Planetary Physics at the University of California at Los Angeles to ERDA was designed to obtain support for a two-year research effort, and included the following objectives:

- A. Petrographic and petrologic characterization of rock cores obtained from Los Alamos Scientific Laboratory (LASL) geothermal test holes. This study was to include modal analysis, chemical analysis by the electron microprobe, and fabric and textural analysis.
- B. The determination of the sound velocity of rocks from the rock cores, and associated rocks. This was to include an attempt to determine the effect of several important parameters on velocity: cracks and inclusions, mineral composition, pore fluid, and grain boundaries.
- C. Further development of a theory which would allow predictive computation of sound velocity in basement rocks from a petrographic examination of core samples.
- D. The integration of petrography and sound velocity theory of drill cores and associated rocks with the Geothermal Energy Program at LASL.

During the period covered by this report (November 1974 through August 1975), we have concentrated on elements of Objectives A, B, and C. Detailed petrographic characterizations have been made of drill core samples. Correlations between rock texture and bulk elastic properties have been studied. Theory of texture effects on elastic moduli has been extended, and a rock-modeling code has been further developed and tested. A theoretical study of possible applications of stress corrosion

cracking to geothermal technology was made.

Ten papers and reports which bear on these problems are listed in the attached bibliography.

General Program

Objective A

Petrographic Characterization of Rock Cores Obtained from LASL Geothermal Test Holes

Detailed petrographic descriptions have been prepared for the samples of the GT-1 drill core which were described in the report "Petrography of Some Rock Types of the Precambrian Basement near the Los Alamos Scientific Laboratory Geothermal Test Site," by Priscilla Perkins.¹ These descriptions are enclosed with the attached papers to this report.

Microprobe analyses of plagioclase, biotite, hornblende, magnetite, microcline, and chlorite for selected samples of the GT-1 core will be published in a report "Electron Microprobe Analyses of Minerals in Precambrian Rocks at the Los Alamos Scientific Laboratory Geothermal Test Site, Jemez Mountains, New Mexico," by Priscilla C. Perkins and Stephen N. Ehrenberg.² This report will be published in the Los Alamos Scientific Laboratory Technical Report Series, and will appear either in late 1975 or early 1976.

Petrography and electron microprobe analyses of the GT-2 core are presently being carried out by the staff at LASL.

Work has begun on the characterization of GT-1 samples which have been exposed to an artificial hydrothermal system in the LASL Laboratory of John Balagna. Results of this preliminary study will appear in the report "Solution Channels Produced by Exposure of a Granite to an Artificial Hydrothermal System," by Stephen N. Ehrenberg, Priscilla C. Perkins, and John Balagna.³ This report will be published as a Los Alamos

Scientific Laboratory Technical Report. An illustration from this report (Figure 10 in Ehrenberg, Perkins, and Balagna) is reproduced in Appendix 1. In this figure, photomicrographs of quartz with solution channels are shown. As indicated in the grant proposal, one of the conditions required for successful dry geothermal energy extraction, according to the method proposed by LASL, is the control of water geochemistry to minimize deposition of dissolved mineral constituents during the cool return flow in the circulating system. Solution of quartz and takeup of silica by the circulating fluid have been observed in Balagna's hydrothermal experiments. The report by Ehrenberg, Perkins, and Balagna also presents illustrations of solution of feldspar crystals in the granite.

A detailed map of a thin section of granite exposed to the solutions in Balagna's hydrothermal experiments has been prepared and is reproduced as Appendix 2 of this progress report. In the first figure, all the mineral grains of the section are identified and mapped, and in the second, through-going cracks are shown, and alteration areas of quartz and feldspar crystals are isolated for clarity.

Stress Corrosion Cracking and Geothermal Technology

As stated in the grant proposal, successful extraction of geothermal energy by the LASL hot dry rock method involves the creation of a closed loop. A circulation system between two holes across hydrofractured rock will create appropriate conditions for a large heat transfer from the hot rock to the circulating water. The process of cracking rock, (in particular hot rock with fluid) is therefore a very important factor controlling the success of the geothermal experiment, and a clear understanding of the process is essential to the development of geothermal technology. During the course of research under this grant, we have investigated the possible role which stress-corrosion cracking may play in the operation of a dry hot rock geothermal system.

Stress-corrosion cracking has been well studied in metals, glasses, and certain ceramics, but it has not received much attention in the geological literature, and experimental data on stress-corrosion cracking in rocks and minerals are sorely lacking. The article by Anderson and Perkins "Stress Corrosion Theory of Crack Propagation with Applications to Geophysics"⁴ presents a review of stress corrosion and an extension of what is known about stress corrosion in non-geological materials in relation to its possible role in geological and geophysical phenomena. As an extension of this work, Harold H. Demarest, Jr., has considered the particular applications of stress corrosion to hot dry rock geothermal systems. In an informal report "Application of Stress Corrosion to Geothermal Reservoirs,"⁵ a method is suggested for the estimation of stress intensity factors which will be sufficiently low to ensure that slow crack propagation will not destroy a geothermal well. Using certain assumptions, Demarest obtains the result that "the stress which can safely be contained in a geothermal reservoir is only slightly lower than the stress which causes hydrofracturing" or that stress corrosion cracking may not destroy an artificial geothermal system if the pressures of fluid in the rocks are not excessive. However, there is still a great deal of uncertainty in the estimates because of the lack of appropriate experimental data on stress corrosion cracking in rock materials.

Petrology and Subterrene Technology for Dry Hot Rock Geothermal Drilling

The rock-melting drill, called the Subterrene, which has been developed by LASL may be used in the future to drill holes in crystalline basement prior to the creation of an artificial circulating hot water system. However, the Subterrene is presently in a rather early stage of development, and information is still needed about the interaction of the penetrator and the invaded rock. The paper by Ehrenberg, Perkins, and Krupka⁶ is the first petrographic and electron microprobe study of the effect of the penetrator on a variety of rock types. For this study, samples were provided by the LASL team, and this included basalt, rhyolite tuff, shale, alluvium, siliceous limestone, and granitic rocks which had been penetrated by the Subterrene. Petrographic examination and microprobe analyses of samples revealed a gradation in textural, mineralogical, and chemical effects from the penetrator face outward into the unaltered rock. In volcanic and sedimentary samples, finer grained matrix material melts most readily, leaving larger residual grains immersed in a highly inhomogeneous, inclusion-rich glass. Spherulitic crystals, interpreted to have grown during sample quenching, are abundant in the fused zones of most specimens.

In the extensive drilling by Subterrene for long time periods in granitic basement which is proposed for eventual development of future dry hot rock geothermal systems, viscosity of the melted zone and the identity and shape of residual crystals will be major factors determining the rate of penetration and degrees of chemical corrosion and abrasion of the metallic penetrators. The study by Ehrenberg et al.⁶ is a preliminary one in that it attempts to (1) show the type of information which can be obtained from standard petrographic and petrologic examination of partially fused rocks, and (2) to illustrate that rocks of different composition and texture have diverse responses to penetration.

Petrographic analyses can provide data on the identity, volume percent, size distribution, and angularity of relict unmelted crystals and quench products in the fused zone of Subterrene samples. Estimates of the degree of abrasion to be anticipated in various rocks types could be made following systematic studies. Penetration rate is inhibited by high viscosity, particularly in highly siliceous melts. Effective viscosity measurements coupled with determination of temperature gradients in the samples, can be correlated with petrographic data in order to investigate possible ways to reduce the viscosity of the mixtures of liquid and crystals in the fused zone.

In the geothermal energy technology of the future, drilling by the Subterrene may play an important role, and this preliminary study points the way for future work to enable prediction of the Subterrene drill behavior in crystalline terrains.

Preferred Orientation in Rocks and Geothermal Technology

Preferred orientation is the nonrandom alignment of mineral grains, joints, or cracks. Geothermal technology must allow for the effects of preferred orientation in several ways. For example, if there are nonrandom systems of joints in a basement drilled for dry hot rock geothermal energy, the preferred orientation must be taken into account when planning hydrofracture experiments. If slow cracking in rocks proceeds by stress corrosion, then the existence of preferred orientation in mineral grains of a rock can cause greater ease of cracking in certain directions. Preferred orientation in metallic alloys is known to enhance stress corrosion crack-growth rates in certain directions.

Although there have been many studies of preferred orientation of mineral grains in rocks, little rigorous statistical treatment has been presented, particularly in the earth sciences literature, for determining with certainty whether mineral grains in a rock sample, or joints and cracks crossed

by a drill hole, are randomly oriented or whether they have preferred orientation. Of course, if orientation is strong, no statistical tests are really necessary, as the nonrandom character is evident from inspection. However, in rocks with weak preferred orientation, visual estimation and even some previous tests in the geological literature, are insufficient to determine whether an orientation is preferred or nonrandom.

An additional complication arises from the fact that some elements (crystals with a flat habit, such as mica flakes, cracks, and joints) offer special problems in measurement and testing. For example, in what is generally called a "Schnitteffekt" or cut effect, the set of grains encountered by a thin section may be unrepresentative of the total specimen because grain shapes and cleavages or optic axes are related, and the probability that a plane section encounters inequant grains (e.g., biotite flakes) varies with their angles of inclination. For rock joints intersected by a drill hole there is also a "Schnitteffekt."

In the paper by Dudley, Perkins, and Gine, "Statistical Tests for Preferred Orientation"⁷ the previously proposed tests for preferred orientation in fabric diagrams have been critically reviewed. New tests are presented for maxima and girdles, with a simple "Schnitteffekt" correction procedure for applications to inequant grains such as mica flakes or to planar elements such as rock joints and cracks. The tables and formulae in the paper evaluate the significance of the results of the tests for any number of grain points. The tests may be applied to many different types of orientation measurements, such as those for crystal orientation in a rock, orientation of cracks in a thin section, and orientation of joints and cracks in a crystalline basement penetrated by drill holes.

Objectives B and C

During the period covered by this progress report, we have made general studies relating rock structure and texture to elastic properties, and we have developed a predictive modeling theory of rock elastic moduli as functions of pressure.

The work was done, in part, in conjunction with studies on lunar and analogue lunar samples, based both on our own and on published data.

The lunar samples bear on the problem here since as a group they have been well characterized petrographically and acoustically by a number of investigators. The samples thus constitute one of the most completely characterized groups of rocks described in the literature.

During the first year of the research grant, we have not had access to ERDA samples for acoustic measurement, although petrographic characterization studies have been made.

Systematics of Rock Moduli-Pressure Relations

As part of a study of lithification (grain welding) and disaggregation (crack damage) effects on the elastic moduli of rocks, we have looked for systematics in the moduli-pressure relation of a large suite of petrographically described lunar rocks. The sample classes grade from soils through uncrystallized and partially crystallized breccias to fully crystallized rock.

We have found important systematics and correlation with texture, which are described in "Correlation of Elastic Moduli Systematics with Texture in Lunar Materials," by Nick Warren and R. Trice⁸. Moduli-pressure curves for various classes of rock grade from power-law curves (grain-asperity contacts dominate) to pressure-independent curves controlled almost solely by rock mineralogy. The general characteristics of classes of curves have been correlated with general petrographic descriptions of metamorphic grade, cooling rate, and damage (e.g. shock damage) level. Details of the moduli-

pressure curves are controlled by the spectrum of voids, cracks, and grain boundary conditions which are pressure-sensitive.

Moduli Modeling

Rock modeling substantiates interpretation of texture control of moduli systematics. The theory of the modeling method is discussed in "Theoretical Calculations of Compliances of a Porous Medium," by N. Warren and R. Nashner, to appear (1976)⁹, abstracted below:

"A method is presented in this paper for calculation of the components of the compliance tensor of porous media. The theory extends from previous work on the relative compressibility based on stress and strain concentrations. The operational equations for the compliances are very general and are valid over the entire porosity domain. In this paper, the theory is restricted to rock-like materials. Upper-bound and averaged self-consistent isothermal static or long-wavelength elastic moduli are presented. The theory also can be extended to allow calculation of elastic properties as functions of pressure. Predicted and experimental results are presented for a rock to 2kb. For rock-like media, the input parameters are mineralogy, partial porosities, and pore geometries. Ideally, petrographic and mineralogic observations of samples provide sufficient characterization to allow prediction of elastic properties of rock under a wide range of geological conditions."

Detail and discussions of the computational equations and modeling code are presented in "Displacements and Stresses about an Arbitrarily Loaded Spheroidal Inclusion"-by R. Nashner and N. Warren¹⁰ to appear in the Los Alamos Scientific Laboratory Technical Report Series. This paper is intended as a supplement to the paper by Warren and Nashner dealing with porous medium compliances. The expressions in the code are based on the theoretical results of Edwards (1951)¹¹

an arbitrary external load applied. In Nashner and Warren, general descriptions of the solutions of Edwards are presented and applied to some specific loading configurations. Specific superposition solutions for certain load types and pore orientations along with some numeric results are given. Basic program flow diagrams for computing the results of loading configurations are also given.

We have been testing the code by generating hypothetical rocks with structures ranging from almost soil-like (high porosity granular) to cracked and uncracked (granite-like).

Examples of moduli systematics and modeling results are presented in Appendix 3.

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Appendix 1

A

B

C

D

Fig. 10. (A) and (C) Beam-scan photographs of silicon abundances in quartz crystals containing solution channels. (B) and (D) Photomicrographs showing locations of areas scanned in (A) and (C), respectively.

GRANITE
SAMPLE PD-2-4 RUN 9

KEY

- ab ALBITE
- ap APATITE
- bi BIOTITE
- cc CALCITE
- ch CHLORITE
- mi MICROCLINE
- mt MAGNETITE
- mu MUSCOVITE
- mv ~~MUSCOVITE~~ -
SERICITE MIXTURE
- my MYRMEXITE
- q QUARTZ
- pl PLAGIOCLASE
- v VOID
- z ZIRCON

0 0.5 1.0
ONE MILLIMETER

GRANITE
SAMPLE PD-2-4 RUN 9

KEY

- bi BIOTITE
- mi MICROCLINE
- mt MAGNETITE
- q QUARTZ
- pl PLAGIOCLASE
- Voids and CRACKS
- ▨ ETCHED QUARTZ
- ▧ ALTERED FELDSPAR

0 0.5 1.0
ONE MILLIMETER

Appendix 3

SYSTEMATICS

Systematics in the elastic moduli-pressure relations of rock are brought out by comparing log-log plots of the data for various rocks. Data plotted in this way are bounded by power-law curves typical of soils, and by nearly pressure-independent flat curves typical of good quality polycrystalline aggregates.

Data from lunar samples (crystalline, breccias, and soils) show definite correlation of curve character with petrographic descriptions of rock texture. Figure 1 illustrates some key characteristics. The compressional wave modulus C is used,

$$C \equiv V_p^2 \rho$$

where ρ is bulk density and V_p is the compressional wave velocity.

Sample 14311 (curve 1) is a fully recrystallized breccia. Its curve is characteristic of that for a very good polycrystalline material.

Low to moderate levels of crack damage in a good rock lower the low pressure values of the elastic moduli and the curve becomes "s-shaped" or monoclinic. This is typified by data for KREEP basalt 14310 (curve 2).

Induration and partial or mechanical welding of loose grains raises the low pressure values of the elastic moduli, as indicated by comparison of data for 14313 (a regolith breccia, curve 5) to data for soil sample 72161 (curve 6).

The data curves for low to unshocked vesicular basalts (e.g., 10057, curve 3) have characteristics somewhat similar to moderate grade unrecrystallized breccias (e.g., 14318, curve 4).

The effects of cracks can be quantitatively predicted by modeling cracks as flat flaws with subparallel faces which close at finite hydrostatic pressures.

Power law curves, as observed for soils, are predicted

by Hertzian theory of grain contacts. Although the texture parameters controlling the elastic properties of partially indurated rock and glassy breccias have not yet been directly established, we postulate that asperities are important. Grain bonding at asperities in low-grade breccias has been shown by Christie et al. (1975) and Heuer et al. (1974). Asperities are also postulated to be important in controlling the elastic moduli of vesicular basalts. Asperity contacts at grain boundaries rather than continuous bonding over the dimensions of the grains could result from rapid cooling and outgassing.

The sandstone data (Figure 2) have trends with characteristics which are different than those of the breccia or crystalline groups, even though they also represent a lithification sequence from soils to competent sandstones.

The Berea sandstone data, plotted in Figure 2, has a porosity of about 20 percent. The Caplen Dome sandstone has a porosity of about 3 to 5 percent. Porosities for the other samples were not published. Even though the sandstones have high porosities, the $\log C/\rho$ - $\log P$ trends for these sandstones are remarkably linear over the entire pressure range and are similar to good crystalline rocks. The curves do not show the definite concave shape or strong pressure-dependence of medium grade breccias.

There appears to be a definite correlation between the pressure dependence of dynamic and static bulk moduli as a function of lithification. The correlation is based solely on the lunar samples for which we have sufficient data.

Rock modeling substantiates these interpretations of the textural control on moduli systematics, and it provides a reasonable framework for understanding the relation between the static and the dynamic moduli. Details of the modeling method are discussed in Warren and Nashner.⁹

Average elastic moduli can be calculated as functions

of pressure for materials consisting of a welded matrix and spheroidal pores or inclusions. High and low estimates of the moduli can be made by neglecting effects of pore interactions (the non-self-consistent or "upper bound" calculation) or by including them (self-consistent calculations).

Asperities are qualitatively modeled by making the quasi-spherical pore density so high that the matrix essentially consists only of small grains connected by asperities.

Some results of the modeling are shown in Figure 3, in which the calculated moduli are plotted versus pressure for a sequence of model materials with assumed pore shapes and porosity distributions. First, the general character of the dynamic moduli curves is generated by assuming minimum pore interaction effects. Significantly, both the experimental results and the model data show characteristic local irregularities in the curves. In the modeling, these kinks can be generated by the assumption that populations of cracks are closing with increased pressure.

Second, the non-self-consistent and the self-consistent moduli in the models are related in a manner similar to that of the dynamic and static moduli. This suggests that the observed difference between the experimental moduli is related to pore interactions in the tested samples.

Figure 4 shows modeled self-consistent and non-self-consistent moduli for a 13 percent porosity "sandstone." K and V^2 denote the self-consistent bulk modulus and the compressional wave modulus; KN and VN^2 denote the non-self-consistent results. Partial porosities are given by decimal fractions. Pore aspect ratios are given by integers. Comparison of these graphs to Figures 5a, b, and 6a, b, show the effect of quasi-spherical pores on the moduli-pressure relation relative to the effect of flat cracks.

Figures 5 and 6 show computer models of the pressure dependence of the elastic moduli of Westerly granite and of lunar sample 14310.

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For 14310, inputs were the VRH (averaged) polycrystalline aggregate moduli based on mineralogy (Warren et al., 1973) and three crack populations based on approximate pore-closing pressures and porosities obtained from linear strain data. Non-self-consistent models were calculated for comparison to the dynamic experimental moduli. No definite attempt to fit the experimental data was made, other than to assure approximate agreement with the dynamic K at zero pressure.

- In the first model (the solid curve in Figure 5,a), the partial porosity existing above 1.5 kb was considered to consist of spherical pores. In the second model (the dotted curve in Figure 5,a), the partial porosity was assumed to be due to oblate spheroidal pores with aspect ratios of 20 to 1. Self-consistent models for the bulk modulus were calculated using the same input parameters. In Figure 5,b, the self-consistent calculations (curves B and C) are plotted for comparison with the experimental static moduli data (curve A).

Westerly granite was modeled by approximating the dynamic compressibility-pressure data by an inversion of our basic compressibility equation. Pore aspect ratios, closing pressures, and fractional porosities are obtained from the inversion. No attempt was made to fit zero-pressure data.

The log C and log G curves were then calculated as functions of pressure from those input parameters and mineralogy data. The dynamic moduli were modeled using non-self-consistent calculations. The self-consistent calculation for the bulk modulus was then made for comparison to the observed static data (Figure 6-b). The agreement is remarkable.

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Fig 1

$G=374.0$ $V=0.169$ w | α
 $G'=0.0$ $V'=0.0$ 0.1330 | 3.
0.0040 | 57.
0.0010 | 100.