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Progress Report

Nov. 1, 1975 - Aug. 30, 1976

Relationship of Rock Physics and Petrology to
Geothermal Energy Technology

Grant E (04 - 3) - 34
Earth Resources Development Administration

Principal Investigator
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Report By
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PROGRESS REPORT

The general framework of our research under ERDA contract E(04-3)34 is well summarized by the four questions stated in our mid-year report. Our objectives are focused on the problem of the control of bulk rock properties by rock structures. We are particularly interested in looking at how acoustic properties can be used to measure or monitor the volume averaged structural state of a rock, and so be used to help interpret grain boundary, crack and pore conditions and their changes due to actions of hot solutions and brines. The pertinent questions are:

1. How are acoustic properties correlated to rock structure?
2. What are the rock structures controlling permeability? How are these structures dependent on geothermal fluid interactions with the rock?
3. What are the grain boundary and fracture conditions at depth? What are the chemical control effects on crack growth and grain boundary and fracture healing at in situ pressures and temperatures?
4. Can seismic methods be used to measure and monitor these conditions?

Research results have been obtained on parts of questions 1 and 2. Results concerning question 1, were presented at the S.F. A.G.U. Fall Meeting, December, 1975, and the conference, "The Nature and Physical Properties of the Earth's Crust," August 1976, sponsored by the Office of Naval Research and the Colorado School of Mines. Earlier results are published in the Proceedings of the Sixth Lunar Science Conference, December, 1975. The ONR paper will be published in a monograph.

Results concerning question 2 are being written in a ERDA report, August 1976, with a published version planned for later this Fall. A summary of the ERDA report is attached, as well as the abstracts from the ONR paper and the Fall A.G.U.

PROGRESS REPORT
(continued)

Parts of this July and August were spent at LASL, at Q-21. During this time, our effort has been three-fold. First, we have begun to study the results of in situ measurements (acoustic logging and permeability logging), and the general characteristics of the GT-2/EE-1 hydrofracture system. This is forming the basis for considering questions 3 and 4 concerning in situ conditions and the application of our laboratory results to in situ problems.

Second, we have worked on the general problem of correlating laboratory ultrasonic measurements and permeability using the work of J. Balagna and J. Potter (CNC-11). Some of our preliminary results are discussed in the report (Trice and Warren, 1976) cited above, and in the report summary enclosed here.

Third, we have designed some experiments on permeability and crack growth for which a proposal has been written (for GTE funding) and which, if funded, will be conducted as a one year effort using recently acquired permeameter equipment which we will be setting up at UCLA this Fall.

Furthermore, at UCLA this Spring we have constructed an environmental chamber to be used in stress corrosion studies which will bear on question 3, and on the interpretation of the results of the proposed permeameter experiments.

SYSTEMATICS OF ROCK ELASTIC MODULI-PRESSURE RELATIONS

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Abstract

The pressure dependence of the moduli controlling compressional and shear wave velocities of suites of rocks show systematics which can be correlated with petrographic classification and description of structure and texture. Correlations have been found for suites of lunar samples (crystalline, and polymict breccias), soils, and sandstones. 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. Between these bounding curves, rock moduli data plot with curve shapes which correlate with petrographic descriptions involving metamorphic grade, texture, and fracture relations. There is also a strong indication of a correlation between the dynamic and static bulk moduli as a function of gross lithification. The systematics are partially quantified and interpreted using a numerical rock modeling program.

CORRELATION OF ELASTIC MODULI SYSTEMATICS WITH
TEXTURE IN LUNAR MATERIALS

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Abstract

Data on the elastic properties of a suite of lunar samples, including fines, breccias, and crystalline rocks, show systematic characteristics when plotted on log-log diagrams of elastic moduli versus pressure. Plots of dynamic moduli with pressure exhibit curve shapes ranging from those which are nearly flat (independent of pressure) to those typical of strong power laws. The static moduli show a correlation with the dynamic moduli as a function of gross lithification. New data on breccia 66055 and soil 69941 are presented. The systematics of the dynamic and static moduli data indicate that the moduli-pressure relations can be correlated with textural parameters; therefore, samples which have undergone disaggregation can be partially distinguished from those which have undergone lithification. Further confirmation of these systematics is provided by rock modeling.

CHARACTERIZATION OF MODULI-PRESSURE SYSTEMATICS
OF ROCKS; DEPENDENCE ON MICROSTRUCTURE

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Abstract

Dynamic moduli-pressure (M-P) data for rock show important systematics and characteristics which are related to microstructure. Diagnostics characterizing the functional form of log M-log P data include average slope, elbows (sharp changes in slope), local inflections and relative behavior of the moduli with increasing pressure versus decreasing pressure. Characteristics are strikingly similar for rocks with similar petrographic or structural-texture descriptions. The forms of a number of the characteristics can be modeled by using theoretical expressions giving the dependence of the moduli on porosity and pore strains. The typical form of log M-log P data for microcracked rock can be modeled assuming cracks have linear strain dependence on pressure and that pore-pore interactions are minimal. Power laws are predicted for non-linear pore strains and for very strong dependence of pore strains on pore concentration. Theoretically, over-cracking a rock yields power law behavior typical of soils. Discrete distributions of crack closing pressures generate inflections in M-P curves. Conclusions are that M-P data exhibit systematics dependent on microstructure, that the effects of microstructure on moduli override mineralogical effects even at low porosities, and that velocity-pressure data can be inverted to give detailed characterization of volume averaged microstructure of rock.

SUMMARY OF REPORT IN PROGRESS:

The more detailed report is Titled;

"Preliminary study of a correlation of acoustic velocity and permeability in two granodiorites from the dry well GT-2 at Fenton Hill in the Valles Caldera, New Mexico.

Report by R. Trice and N. Warren"

August, 1976

Abstract

Acoustic velocity and strain data were obtained on two GT-2 samples as part of a study on using acoustic data to infer or characterize volume average rock microstructures. The pressure dependence of these data have been compared to the pressure dependence of permeability measured on adjacent samples in a preliminary effort to study the relation between the microstructure networks controlling these two bulk physical properties. For pressures below about one Kb, the permeability data agree well with a function involving the cubic power of the compressional velocity modulus. This relation is suggested from comparison of the Kozeny relation for permeability to the form of the functional dependence of elastic moduli on porosity and pore strains. Correlation suggests that in such rocks, crack strains are essentially linear with pressure and that the same network of cracks control both permeability and elastic properties.

Introduction:

The development of technology to feasibly extract energy from hot dry rock requires advances in methods of measuring and monitoring a number of rock physical and chemical properties, both in situ and in the laboratory. It is important to know and therefore to somehow characterize the rock structures controlling fluid flow, the growth of cracks and fractures, and the response of both of these to changes in stress or chemical reactions.

Acoustic and ultrasonic techniques provide a means of measuring volume average bulk physical properties both in laboratory size samples and in the vicinity of a bore hole. In particular, ultrasonic measurements are sensitive to network structures such as cracks, pores, and grain boundary conditions, which are also important in the control of other rock properties such as permeability and stress response.

The development of acoustic techniques applicable to the problems, of hot dry rock involves improving methods of interpreting acoustic data in terms of rock structure (cracks and fractures, rather than seismic layering) and improving understanding of the relations between structure networks which control various physical properties such as acoustics on one hand and permeability on the other.

In a recent paper Warren (1976) shows that the functional forms of the dependence of ultrasonic data on pressure provide indication of pore closure laws and crack closing pressure distributions. In this paper we consider in a preliminary fashion, the extension of these results to permeability. Primary concern is with igneous textured rocks, such as encountered in the hot dry rock wells at Fenton Hill in the Valles Caldera, New Mexico, being experimentally developed by ERDA.

The following two tables and five figures summarize the key results of this current research.

Tables 1 and 2 present model elastic moduli compared to measured data for Westerly granite (after Simmons and Brace, 1965 and Brace, 1965) and for ERDA GT-2 core sample 8581. The models were calculated assuming the crack model parameters given in the tables. The quantities a/b are crack aspect ratios (major to minor axes) and ω_0 are the zero pressure porosities of each of the crack populations. The moduli are

$$C = K + 4/3 G$$

K_s is the static bulk modulus

K_d is the dynamically determined bulk modulus

G is the shear modulus

N.S.C. indicates that pore-pore interactions are ignored in the model calculations and S.C. indicates a self consistent calculation (maximum pore-pore interaction).

Figures 1 and 2 show graphic comparisons of the Westerly granite data and model moduli (figure 1) and comparison of model porosity-pore aspect ratio distribution to observed data (Hadley, 1976). In figure 2 the shaded areas are measured data, and the heavy bars are model results.

The important point of these results is that fairly simple distributions of cracks which close linearly with pressure satisfy the elastic properties, and that the theoretical form used for the modeling yields realistic estimates of rock microstructure.

Figures 3, 4, and 5 show comparisons of the pressure dependences of permeability data for Westerly granite, and ERDA samples 8580 and 9522 to the functional behavior of acoustic data for equivalent samples. The cubic function of the elastic modulus was postulated by considering the form of the Kozeny relation for permeability and an expression for elastic

moduli in terms of pore strains and crack porosities (the same expression as used to derive the elastic models given in Tables 1 and 2). The C_0 's are the mineralogical or high pressure values of the modulus C .

The relative agreement between the shapes of the permeability curves and the elastic modulus curves strongly suggests that the same crack network controls both the pressure dependence of the fluid flow and of acoustic wave propagation. This preliminary finding encourages us to further attempt to determine the goodness of using acoustic methods to measure and monitor microstructure and microstructure dependent bulk physical properties such as permeability.

REFERENCES

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2. Hadley (1976), J.G.R., 81, (20) pp. 3484-3494.
- Simmons, G., and W. F. Brace (1965), J.G.R. 70, (22) pp. 5649-5656.
- Trice R., and N. Warren, 1976: in preparation.
- Warren, N. (1976), "Characterization of Moduli-Pressure Systematics of Rock: Dependence on Microstructure", presented at "Nature and Physical Properties of the Earth's Crust", to be published as a monograph.

Table 1
Granodiorite 8581
Data versus model 8581-71576-IV
(Pressure in Kb, Moduli in Kb)

<u>Pressure</u>	<u>C¹</u>	<u>N.S.C.</u>	<u>Δ%</u>	<u>Pressure</u>	<u>G¹</u>	<u>N.S.C.</u>	<u>Δ%</u>
0.0	697	677	-2.9	0.0	262	269	+2.7
0.055	708	700	-1.1	0.060	273	277	+1.6
0.11	747	724	-3.1	0.11	283	282	-0.3
0.24	841	838	-0.3	0.27	311	313	+0.6
0.49	953	943	-1.0	0.54	330	338	+2.4
0.98	1025	996	-2.8	0.775	337	343	+1.6
1.5	1048	1033	-1.4	1.02	343	349	+1.7
2.0	1058	1072	+1.3	2.0	361	364	+0.9
3.5	1072	1082	+1.0	3.0	364	365	+0.1
5.0	1089	1092	+0.3	4.97	364	368	+0.9
7.0	1099	1105	+0.5	5.8	370	369	-0.3

1 from table A

Model parameters

$$G_0 = 380$$

$$v_0 = 0.25$$

<u>a/b</u>	<u>ω₀</u>
1	0.010
90	0.001
500	0.0007
1900	0.0004

Table 2

Westerly Granite
Data versus Model WG 71476-I
(Pressure in Kb, Moduli in Kilobars)

Pressure	C^1	N.S.C.	$\Delta\%$	G^1	N.S.C.	$\Delta\%$
0	443	562	+26.7	200	228	+14.0
.1	596	590	-1.0	240	273	+13.7
.4	749	692	-7.6	280	266	-5.0
.7	809	789	-2.5	290	291	+0.3
1	859	852	-0.8	300	306	+2.0
2	894	898	+0.4	310	316	+1.9
3	940	950	+1.0	320	327	+2.2
5	963	997	+1.4	333	336	+0.9
10	1038	1007	-3.0	340	337	-0.9

¹ (from Simmons and Brace, 1965.)

$\rho = 2.65$

Pressure	K_s^2	S.C.	$\Delta\%$
0	120	124	+3.3
.1	185	195	+5.4
.2	263	249	-5.3
.5	346	356	+2.9
1	407	434	+6.6
2	463	477	+3.0
3	485	519	+0.7
5	503	550	+9.3
7	518	557	+7.5
9	535	557	+4.1

Model Parameters

$G_0 = 341.65$

$\nu_0 = 0.248$

a/b	ω_0
1	.006
120	.0009
200	.0016
850	.001
2000	.0001

² (from Brace, 1965.)

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5