CORRELATION OF PERMEABILITY, VELOCITY, STRAIN AND CRACK SPECTRA
FOR A SUITE OF SEVEN LASL ROCK SAMPLES

Interim Report:
Partial Data Compilation

by
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INTRODUCTION

In 1977, Trice and Warren showed a correlation between the pressure dependence of the permeability and a function of velocity for two granodiorites from the LASL HDR borehole. ("Preliminary Study on the Correlation of Acoustic Velocity and Permeability in Two Granodiorites from the LASL Fenton Hill Deep Borehole, GT-2, Near the Valles Caldera, New Mexico," report LA-6851-MS). We are now expanding on this original study.

A study was started in which compressional and shear velocities, static strain, and permeabilities were measured for a suite of 7 rocks from LASL. The sample included two gneisses (cored parallel and perpendicular to the plane of foliation), a diorite, a granite, two quartzites and a marble.

Most of the data were collected by Mr. Trice in 1977 for a Ph.D. thesis. It was not reduced before he took a leave of absence. Since then he has had a career change. This last year we began our own study to reduce the data, to test its goodness, and to apply the best portions to the originally proposed correlation study. During these last two years, we have greatly strengthened the techniques for studying such problems. Since the data here were taken at the beginning of this period, I expect them to be highly useful but not definitive. They will clearly serve to test ideas and to help suggest new experiments to be done. Measurements on the same cores can be repeated and improved in future work.

Because of the breadth of this initial experimental study, we expect to write several reports which will make use of these data.
**Data Compilation**

This interim report is a partial compilation of data, presented simply as a useable inventory and as a reference source of data for other studies in the future.

The import of this data set is that for each sample it consists of measurements of four physical properties all of which are controlled by the sample's microstructure. Therefore, the sets of data for any one rock are expected to show strong cross-correlations, and to provide insight into the inverse problem of predicting physical properties from petrostructural models.

**Interim Report**

The compilation here is not finalized. As of this date (September, 1980) the following need to be done:

- Petrographic descriptions need to be completed.
- Mineralogical analysis need to be verified.
- The goodness of the data and the errors in the data reduction need to be checked.

Bearing in mind these limits, the data presented here are directly useable.

**Physical Properties**

The quantities measured are:

1) compressional velocity
2) shear velocity
3) static strain
4) permeability
All quantities were measured at room temperature as functions of hydrostatic pressure. In general, the first three quantities were measured on single samples. Separate, larger cores were needed for the permeability experiments. Some sets of measurements were made simultaneously. Measurements were always made in the axial direction of the cylindrically-shaped samples, although samples had different orientations to petrofabric. Descriptions of experimental procedures are given in the Appendices.

**Velocities**

Velocities were measured using pulse transmission. Compressional and shear velocities were measured independently. Three Mhz PZT transducers were used. The technique was an early version of that described in LASL informal report LA-8102-MS, and in the Appendix here.

**Strains**

Strains were determined using BLH FAE 37 12 59 gauges (120Ω) and a wheatstone bridge.

Both velocities and strain were measured in the axial direction of samples. Samples were uniformly cored to a diameter of 16.64 mm, lengths were nominally 30 mm.

**Permeability**

Permeabilities were measured using a modification of the permeameter built under the Hot Dry Rock project at LASL. Samples were 53.9 mm in diameter, and nominally 50 mm in length. In the configuration used by Trice, permeabilities were measured in the axial direction using water as the pore
fluid. The permeabilities were calculated indirectly from the time-dependence of the decay of a pressure pulse of water flowing into the sample. Pressure-decay data were obtained for a matrix of values of confining pressures and mean pore pressures.

The raw pressure decay curves are compiled here. The quality of the data is variable. Reduced permeabilities as functions of effective pressure (confining pressure minus mean pore pressure) are given for three samples.

**Crack Spectra**

We have derived crack spectra for the seven samples using the acoustic shear and compressional velocity data. These spectra assume a model composed of a linear superposition of linearly closing cracks. The spectra presented here have not been tested for and cleaned of bad data points. However, as discussed elsewhere (Warren and Tiernan, 1980, and in Tiernan, 1980), the basic morphology of the spectra is reflective of underlying texture and microstructure and consequently is useful as is.
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Granite
Crack Spectra

Squares - up run
Crosses - down run

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Diorite Crack Spectra

Squares - up run
Crosses - down run
HI PRESSURE (MV) - DIOIRITE PERMRN #8

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**Sample ID: Gneiss Por VS 9/8/77-RT**

Sample Length = 32.658

Time Base Factor = 2.0 (Microsec)

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**Sample ID: Gneiss Por VP 8/11/77-RT**

Sample Length = 32.658

Time Base Factor = 2.0 (Microsec)

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## SAMPLE 101 GNEISS PAR SS 8/8/77-ST

**Gauge Factor:** 2.050

**Initial Resistance:** 124,700 (Ohms)

**Correction Factor:** 3.598 (Ohms) i.e. Delta R @ Pres. = 0.0 Bars

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Crack Spectra

Gneiss, parallel to foliation

Squares - up run
Crosses - down run
HI PRESSURE (MV) - GNEISS PAR PERMAN #7

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TIME (SEC)
The graph shows the pressure (psi) over time for different phases.

- **Pc**: 16.363 psi
- **Ph**: 9.420 psi
- **PL**: 8.887 psi

The pressure decreases over time.
GNEISS, PERPENDICULAR TO FOLATION
### SAMPLE ID: GNEISS_PERP_VS. 8/27/77-RT

SAMPLE LENGTH = 27.971
TIME BASE FACTOR = 2.0 (MICROCSEC)

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Gneiss, parallel to foliation

Squares - up run
Crosses - down run

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Time Base Factor: 2.0 (MICROSEC)

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Quartzite Z.P.
Crack Spectra

squares - up run
crosses - down run
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\text{Pressure (MV)} & \text{ psi} \\
P_C & 16.777 \quad 5902 \\
P_h & 13.701 \quad 4644 \\
P_L & 13.286 \quad 4503
\end{align*}
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| SAMPLE LENGTH: 29.165 |
| TIME BASE FACTOR: 2.0 (MICROSEC) |

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Marble Crack Spectra

squares - up run
crosses - down run
\begin{align*}
\text{mv} & \quad \text{psi} \\
PC & 17.152 & 6034 \\
PH & 16.523 & 5600 \\
PL & 16.227 & 5500 \\
\end{align*}
VELOCITY AND STATIC STRAINS MEASUREMENTS: SAMPLES AND DATA

I. SAMPLES

All of the rock samples were nominally 25 to 30 mm in length and 16.65 mm in diameter. The flat ends were ground parallel to a tolerance of better than ± 0.01 mm.

For the velocity measurements, 3 MHz compressional or shear mode PZT transducers were bonded directly to the rocks. The transducer diameters were 16 mm.

For the strain measurements 120Ω strain gauges were epoxied directly to the samples, parallel to the axial direction. Strains were measured by balancing a bridge which gave directly the resistance of the gauge. Strains were determined to ± 1 x 10^-4.

Samples were jacketed with a soft two-part silicone elastomer. By this technique, reliable velocity and strain data were obtained at low pressure. A 7 Kb hydrostatic pressure vessel was used. The pressure medium was kerosene-petether. Pressures were measured with a Heise gauge.

A new technique was developed for the velocity measurements. Figure 1 shows a schematic of the configuration used in the travel time determination. Three pulse generators (PG), an amplifier (AMP), and an oscilloscope with three independent vertical input channels were used. These pulse generators supply a fiducial mark for the pulse travel time, generate an input pulse to the sample, and provide a moveable marker to measure the time delay between the fiducial mark and the first arrival of the acoustic signal.

PG1 supplies two outputs. First, it generates a trigger pulse which triggers both the oscilloscope horizontal sweep and PG2; second, PG1 gives an output pulse which is fed into one of the oscilloscope's vertical channels. The output signal from the sample is put through an amplifier and then goes to a second vertical channel on the oscilloscope. Note that with the sample taken out of the configur-
ation, the output pulse from PG1 can be set at the position of the output pulse from PG2 as seen on the oscilloscope. This pulse then serves as a t=0 marker because it has calibrated out all the delays in the configuration due to the electronic components and cables. PG3 generates a second marker pulse which is triggered by the variable delay trigger on the oscilloscope. Using this marker on the third vertical input channel of the oscilloscope, the time delay between the t=0 marker of PG1 and the acoustic arrival from the sample can be determined.

![Diagram of pulse transmission electronic systems](image)

Fig. 1
Pulse transmission electronic systems. See text for discussion.

This arrangement allows us to eliminate uncertainties on our travel-time measurements due to the electronics, and we achieve reproducibility of a few nanoseconds and an overall absolute uncertainty of about 1% for our travel-time determinations through any given sample.
II. **PERMEABILITY**

Permeabilities were measured using a modification of the permeameter built under the Hot Dry Rock project at LASL. Samples were 53.9 mm in diameter, and nominally 50 mm in length. In the configuration used by Trice, permeabilities were measured in the axial direction using water as the pore fluid. The sample holder, which was inserted into the hydrostatic vessel is shown in Figure A-1. The permeabilities were calculated indirectly from the time-dependence of the decay of a pressure pulse of water flowing into the sample. Pressure-decay data were obtained for a matrix of values of confining pressures and mean pore pressures.

**Basic Equations**

The permeability is related to the pressure drop by

\[ k = \frac{\mu_w \beta_w V_s \ell}{A \Delta P} \left( \frac{dP}{dT} \right) \]

where

- \( \mu_w \) = viscosity of water
- \( \beta_w \) = compressibility of water
- \( V_s \) = volume of system
- \( \ell \) = length of sample
- \( A \) = cross sectional area of sample
- \( \Delta P \) = pressure pulse applied
- \( dP/dT \) = slope at pressure decay curve.
Upper pressure line and transducer

Stainless steel anvil

Porous stainless steel plug

Sample

Teflon jacket

Clamp

Viton O-Ring

Lower pressure line

Experimental core holder

FIG. A-1
III. CRACK SPECTRA

Crack spectra are calculated from the compressional and shear velocities as function of pressure.

Spectra can be generated by twice differentiating precise strain-pressure data (Feves et al., 1977; Siegfried and Simmons, 1978). The assumption is made that the bulk non-linear strain of a rock is caused by a superposition of strains by various populations of cracks. Cracks within any one population close linearly with pressure. The populations are distinguished by their closing pressure $P_c$.

The crack spectra is thus the distribution function $v(P)$

$$v(P) = \frac{P^2 d\varepsilon}{dP^2}$$  \hspace{1cm} (1)

where $\varepsilon$ is the volumetric rock strain and $P$ is pressure. The absolute magnitude of $v$ is the zero pressure porosity of the crack population which closes between $P_c$ and $P + dP_c$.

Simmons et al. (1974) generates crack spectra by differential strain analysis (DSA) of carefully taken static strain data. In our study, the crack spectra are directly generated from the dynamic compressibility data $\beta(P)$.

$$\beta(P)^{-1} = \rho \left( \frac{V_p^2 - \frac{4}{3}V_s^2}{3} \right)$$ \hspace{1cm} (2)

where $V_p$ is the compressional wave velocity, $V_s$ is the shear wave velocity, and $\rho$ is the density.

The first coefficients of a spline curve through $\beta(P)$ are the slope of compressibility. Therefore, we generate crack spectra from the first derivative of the dynamic compressibility data rather than from twice differentiating strain data.
Two discussions of results using dynamic crack spectra are given in Warren and Tiernan (1980) and in Tiernan, (1980).

The gross features of the spectra are reasonable, and the basic morphology of the spectra, for any one rock, are reflected in both the up and down run data. Spectra features generated from the down run data are generally displaced to lower pressures from the same features observed in the up-run data.