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

Interim Report:

Partial Data Compilation

by

Nick Warren

TO: George Koistad, DOE
Jeff Tester, LASL G-5
Phil Halleck, LASL G-7

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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 (120 Ω) 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.

References

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- Trice, R., and Warren, N., "Preliminary Study of a Correlation of Acoustic Velocity and Permeability in Two Granodiorites from Dry Well GT-2 at Fenton Hill in the Valles Caldera, New Mexico," LASL Report No. LA-6851-MS (1977).
- Warren, N., and Tiernan, M., "Systematics of Crack-Controlled Mechanical Properties for a Suite of Conway Granites from the White Mountains, New Hampshire," Tectonophysics, in press (1980).
- Warren, N., "Rock Physics Characterization of Conway Granite from a DOE Borehole, Conway, New Hampshire," 51 pp., LASL report LA-8102-MS, 1979.
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DATA COMPILATIONS

Modal Analysis
Suite of Seven Samples from LASL

Sample	Density (gm/cm ³)	No. of counts	mineral	mode
Granite	2.63	count #1 = 1000 count #2 = 1000	Quartz Plagioclase K-feldspar Biotite Opakes	33.3 ± 4 36.4 ± 7 29.5 ± 11 1.2 ± 0.3 0.1 <hr/> 100.6
Diorite	2.87	count #1 = 1000	Plagioclase Alteration (sericite) Quartz Chlorite Hornblende Clinopyroxene Opaque Sphene	40.7 42.8 2.6 2.9 4.8 3.9 2.1 0.2 <hr/> 100.0
Gneiss	2.64	count #1 = 1000	Quartz Plagioclase K-feldspar Biotite Chlorite Opaque	28.0 60.3 5.3 5.1 0.9 0.4 <hr/> 100.0
Quartzite	2.64	count #1 = 1000	Quartz Opaque Altered (feldspar) Biotite	94.3 1.4 3.8 0.5 <hr/> 100.0
Quartzite Z.P.	2.65	count #1 = 1000	Quartz Ziron Brown Gunge (highly altered feldspar?) Opaque	98.1 1.1 0.4 0.4 <hr/> 100.0
rble	2.83	count #1 = 1000	Calcite Opaque Chlorite Epidote	98.8 0.5 0.4 0.3 <hr/> 100.0

GRANITE

SAMPLE ID: GRANITE VS B/2/77-RT
 SAMPLE LENGTH= 33.339
 TIME BASE FACTOR= 2.0 (MICROSEC)

P(BARS)	T1(MS)	T2(MS)	VEL(KM/S)
0.0	6.360	1.463	3.404
10.0	6.352	1.463	3.410
20.0	6.302	1.463	3.445
30.0	6.289	1.463	3.454
40.0	6.239	1.464	3.491
50.0	6.202	1.464	3.518
75.0	6.170	1.464	3.542
100.0	6.147	1.464	3.560
150.0	6.088	1.462	3.603
200.0	6.043	1.462	3.639
300.0	6.001	1.462	3.673
400.0	5.953	1.462	3.712
500.0	5.938	1.465	3.727
755.0	5.910	1.465	3.750
1010.0	5.887	1.465	3.770
1510.0	5.853	1.465	3.799
2010.0	5.831	1.468	3.821
3000.0	5.777	1.468	3.869
4010.0	5.741	1.468	3.901
4510.0	5.736	1.468	3.905
5010.0	5.721	1.471	3.922
5510.0	5.707	1.471	3.935
6010.0	5.689	1.471	3.952
4400.0	5.727	1.471	3.917
4010.0	5.718	1.471	3.925
3000.0	5.741	1.471	3.904
2010.0	5.802	1.471	3.849
1005.0	5.881	1.471	3.780
525.0	5.973	1.472	3.704
255.0	6.033	1.472	3.655
100.0	6.164	1.472	3.553
50.0	6.243	1.472	3.494
10.0	6.345	1.472	3.421
0.0	6.451	1.472	3.348

SAMPLE ID: GRANITE VP B/10/77-RT
 SAMPLE LENGTH= 33.339
 TIME BASE FACTOR= 2.0 (MICROSEC)

P(BARS)	T1(MS)	T2(MS)	VEL(KM/S)
0.0	4.451	1.473	5.598
10.0	4.398	1.473	5.639
20.0	4.352	1.473	5.790
30.0	4.347	1.473	5.800
40.0	4.319	1.471	5.853
50.0	4.312	1.471	5.867
75.0	4.282	1.471	5.930
100.0	4.247	1.471	6.005
150.0	4.408	1.471	5.676
200.0	4.184	1.471	6.144
300.0	4.151	1.471	6.220
400.0	4.132	1.471	6.264
500.0	4.113	1.471	6.309
750.0	4.099	1.471	6.343
1005.0	4.082	1.471	6.384
1505.0	4.074	1.471	6.404
2000.0	4.068	1.469	6.414
3000.0	4.049	1.469	6.461
4000.0	4.024	1.469	6.524
4500.0	4.017	1.469	6.542
3950.0	4.023	1.468	6.524
2990.0	4.039	1.468	6.484
2010.0	4.054	1.468	6.446
1010.0	4.082	1.468	6.377
515.0	4.110	1.469	6.312
240.0	4.159	1.469	6.197
100.0	4.228	1.469	6.042
45.0	4.283	1.469	5.924
10.0	4.355	1.469	5.776

SAMPLE ID: GRANITE SS 8/10/77-RT

GAUGE FACTOR= 2.050

INITIAL RESISTENCE= 124.700 (OHMS)

CORRECTION FACTOR= 3.712(OHMS) I.E., DELTA R @ PRES.=0.0 BARS

P(BARS)	DELTA R(OHMS)	CUMM. STRAIN	VOL. STRAIN
0.0	3.712	0.00000	0.00000
10.0	3.719	0.00003	0.00008
20.0	3.722	0.00004	0.00012
30.0	3.724	0.00005	0.00015
40.0	3.726	0.00006	0.00017
50.0	3.728	0.00006	0.00019
75.0	3.734	0.00009	0.00027
100.0	3.739	0.00011	0.00033
150.0	3.751	0.00016	0.00047
200.0	3.761	0.00020	0.00059
300.0	3.779	0.00027	0.00081
400.0	3.794	0.00033	0.00099
500.0	3.812	0.00040	0.00121
750.0	3.852	0.00056	0.00169
1005.0	3.892	0.00073	0.00218
1505.0	3.973	0.00105	0.00316
2000.0	4.048	0.00135	0.00406
3000.0	4.195	0.00195	0.00584
4000.0	4.341	0.00254	0.00761
4500.0	4.413	0.00283	0.00848
3950.0	4.333	0.00250	0.00751
2990.0	4.188	0.00192	0.00576
2010.0	4.042	0.00133	0.00399
1010.0	3.985	0.00070	0.00209
515.0	3.808	0.00039	0.00116
240.0	3.760	0.00019	0.00058
100.0	3.733	0.00008	0.00025
45.0	3.720	0.00003	0.00010
10.0	3.711	-0.00000	-0.00001
0.0	3.708	-0.00002	-0.00005

	mv	psi
P _C	18.100	6368
P _h	18.119	6141
P _L	17.879	6060

DIORITE

SAMPLE ID: DIORITE VS 8/6/77-RT
 SAMPLE LENGTH= 34.573
 TIME BASE FACTOR= 2.0 (MICROSEC)

P(BARS)	T1(MS)	T2(MS)	VEL(KM/S)
0.0	6.444	1.443	3.457
10.0	6.437	1.443	3.461
20.0	6.441	1.443	3.459
30.0	6.438	1.443	3.461
40.0	6.433	1.443	3.464
50.0	6.432	1.443	3.465
75.0	6.432	1.443	3.465
100.0	6.428	1.443	3.468
150.0	6.423	1.443	3.471
200.0	6.418	1.443	3.475
300.0	6.406	1.443	3.483
400.0	6.394	1.443	3.492
500.0	6.386	1.443	3.497
750.0	6.348	1.443	3.524
1000.0	6.323	1.443	3.542
1500.0	6.279	1.443	3.575
1995.0	6.275	1.443	3.578
3010.0	6.211	1.443	3.626
4010.0	6.169	1.443	3.659
4500.0	6.157	1.443	3.657
3975.0	6.166	1.442	3.559
3020.0	6.187	1.442	3.643
2000.0	6.227	1.442	3.613
990.0	6.319	1.442	3.544
525.0	6.379	1.441	3.501
265.0	6.387	1.441	3.495
100.0	6.422	1.441	3.470
50.0	6.433	1.441	3.463
10.0	6.452	1.441	3.450
0.0	6.457	1.441	3.446

SAMPLE ID: DIORITE VP 8/1/77-RT
 SAMPLE LENGTH= 34.573
 TIME BASE FACTOR= 2.0 (MICROSEC)

P(BARS)	T1(MS)	T2(MS)	VEL(KM/S)
0.0	4.293	1.469	6.121
10.0	4.289	1.469	6.130
20.0	4.289	1.469	6.130
30.0	4.284	1.469	6.141
40.0	4.276	1.470	6.161
50.0	4.273	1.470	6.167
75.0	4.270	1.470	6.174
100.0	4.270	1.470	6.174
150.0	4.268	1.469	6.175
200.0	4.265	1.469	6.183
300.0	4.260	1.469	6.194
400.0	4.259	1.469	6.195
500.0	4.253	1.469	6.209
750.0	4.240	1.469	6.233
1000.0	4.217	1.469	6.291
1490.0	4.195	1.469	6.341
2005.0	4.173	1.468	6.391
3015.0	4.147	1.468	6.453
4010.0	4.125	1.468	6.506
4515.0	4.117	1.468	6.526
5000.0	4.103	1.470	6.565
5515.0	4.100	1.470	6.573
6010.0	4.099	1.470	6.575
4995.0	4.100	1.470	6.573
4010.0	4.115	1.468	6.531
3000.0	4.130	1.468	6.494
2005.0	4.155	1.468	6.433
1005.0	4.199	1.469	6.330
515.0	4.237	1.469	6.245
255.0	4.253	1.469	6.209
110.0	4.271	1.469	6.169
50.0	4.273	1.469	6.165
10.0	4.279	1.469	6.152
0.0	4.288	1.469	6.132

SAMPLE ID: DIORITE SS_8/1/77-R1

GAUGE FACTOR= 2.050

INITIAL RESISTENCE= 124.700 (CHMS)

CORRECTION FACTOR= 3.778(CHMS) I.E., DELTA R @ PRES.=0.0 DARS

P(BARS)	DELTA R(CHMS)	CUMM. STRAIN	VOL. STRAIN
0.0	3.778	0.00000	0.00000
10.0	3.781	0.00001	0.00004
20.0	3.783	0.00002	0.00006
30.0	3.785	0.00003	0.00008
40.0	3.787	0.00004	0.00011
50.0	3.788	0.00004	0.00012
75.0	3.792	0.00006	0.00017
100.0	3.796	0.00007	0.00022
150.0	3.803	0.00010	0.00030
200.0	3.812	0.00014	0.00041
300.0	3.827	0.00020	0.00059
400.0	3.841	0.00025	0.00076
500.0	3.853	0.00030	0.00091
750.0	3.896	0.00048	0.00143
1000.0	3.936	0.00064	0.00191
1490.0	4.007	0.00092	0.00277
2005.0	4.082	0.00123	0.00368
3015.0	4.223	0.00180	0.00539
4010.0	4.357	0.00234	0.00701
4515.0	4.423	0.00260	0.00781
5000.0	4.484	0.00285	0.00854
5515.0	4.548	0.00311	0.00932
6010.0	4.608	0.00335	0.01004
4995.0	4.486	0.00286	0.00857
4010.0	4.365	0.00237	0.00710
3000.0	4.239	0.00186	0.00558
2005.0	4.102	0.00131	0.00392
1005.0	3.959	0.00073	0.00219
515.0	3.883	0.00042	0.00127
255.0	3.843	0.00026	0.00079
110.0	3.819	0.00017	0.00050
50.0	3.811	0.00013	0.00040
10.0	3.804	0.00010	0.00031
0.0	3.801	0.00009	0.00028

HI PRESSURE (MV) - DIORITE PERMRN #3 8

16.74 16.76 16.78 16.80 16.82 16.84

	mv	psi
P _C	17.205	6053
P _h	16.786	5690
P _L	16.481	5586

TIME (SEC) $\times 10^1$

	mv	psi
P _C	16.858	5931
P _H	12.625	4279
P _L	11.559	3918

GNEISS PARALLEL TO FOLIATION

SAMPLE ID: GNEISS PAR VS 9/8/77-3T
 SAMPLE LENGTH= 32.658
 TIME BASE FACTOR= 2.0 (MICROSEC)

P(BARS)	T1(MS)	T2(MS)	VEL(KM/S)
0.0	7.173	1.463	2.860
10.0	7.146	1.463	2.873
20.0	7.063	1.463	2.916
0.3	7.002	1.463	2.948
40.0	6.867	1.463	3.022
50.0	6.826	1.463	3.045
75.0	6.788	1.463	3.066
100.0	6.688	1.463	3.125
150.0	6.539	1.462	3.215
200.0	6.441	1.462	3.280
300.0	6.357	1.462	3.336
400.0	6.291	1.462	3.381
500.0	6.251	1.459	3.408
750.0	6.176	1.459	3.462
1005.0	6.126	1.459	3.499
1480.0	6.168	1.459	3.468
2000.0	6.146	1.460	3.485
3000.0	6.085	1.460	3.531
4010.0	6.068	1.460	3.544
4500.0	5.986	1.460	3.608
4005.0	6.062	1.459	3.547
3000.0	6.079	1.459	3.534
2020.0	6.120	1.459	3.503
1350.0	6.158	1.459	3.475
1000.0	6.199	1.462	3.447
505.0	6.200	1.462	3.446
255.0	6.297	1.462	3.377
100.0	6.457	1.462	3.269
55.0	6.565	1.462	3.200
10.0	6.848	1.462	3.032
0.0	7.171	1.462	2.860

SAMPLE ID: GNEISS PAR VP 9/11/77-RT
 SAMPLE LENGTH= 32.658
 TIME BASE FACTOR= 2.0 (MICROSEC)

P(BARS)	T1(MS)	T2(MS)	VEL(KM/S)
0.0	4.938	1.466	4.703
10.0	4.684	1.466	5.074
20.0	4.634	1.466	5.154
30.0	4.621	1.466	5.175
40.0	4.603	1.469	5.210
50.0	4.564	1.469	5.276
75.0	4.541	1.469	5.315
100.0	4.491	1.469	5.403
150.0	4.432	1.471	5.515
200.0	4.402	1.471	5.571
300.0	4.337	1.471	5.697
400.0	4.297	1.471	5.778
500.0	4.277	1.467	5.811
750.0	4.252	1.467	5.863
1000.0	4.209	1.467	5.955
1500.0	4.176	1.467	6.028
1995.0	4.151	1.473	6.097
3000.0	4.127	1.473	6.153
4005.0	4.094	1.473	6.230
4500.0	4.079	1.473	6.256
3950.0	4.101	1.473	6.213
3005.0	4.130	1.473	6.146
2010.0	4.142	1.473	6.118
1025.0	4.198	1.473	5.992
525.0	4.259	1.477	5.870
250.0	4.333	1.477	5.717
100.0	4.432	1.477	5.526
45.0	4.514	1.477	5.377
10.0	4.679	1.477	5.100

SAMPLE 10: GNEISS PAR SS 8/8/77-R1

GAUGE FACTOR= 2.050

INITIAL RESISTANCE= 124.700 (OHMS)

CORRECTION FACTOR= 3.592(OHMS) I.E., DELTA R @ PRES.=0.0 BARS

P (BARS)	DELTA R (OHMS)	CUMV. STRAIN	VOL. STRAIN
0.0	3.598	0.00000	0.00000
20.0	3.603	0.00002	0.00006
20.0	3.607	0.00004	0.00011
30.0	3.612	0.00006	0.00017
40.0	3.618	0.00008	0.00024
50.0	3.622	0.00010	0.00029
75.0	3.632	0.00014	0.00041
100.0	3.643	0.00018	0.00054
150.0	3.660	0.00025	0.00075
200.0	3.675	0.00031	0.00093
300.0	3.703	0.00042	0.00127
400.0	3.729	0.00053	0.00158
500.0	3.752	0.00062	0.00186
750.0	3.804	0.00083	0.00249
1005.0	3.852	0.00102	0.00307
1480.0	3.937	0.00137	0.00410
2000.0	4.026	0.00172	0.00517
3000.0	4.177	0.00233	0.00700
4010.0	4.334	0.00296	0.00889
4500.0	4.406	0.00325	0.00976
4005.0	4.332	0.00296	0.00887
3000.0	4.178	0.00234	0.00701
2020.0	4.025	0.00172	0.00516
1350.0	3.912	0.00126	0.00379
1000.0	3.851	0.00102	0.00306
505.0	3.757	0.00064	0.00192
255.0	3.701	0.00041	0.00124
100.0	3.657	0.00024	0.00071
55.0	3.640	0.00017	0.00051
10.0	3.615	0.00007	0.00021
0.0	3.602	0.00002	0.00005

GNEISS, PERPENDICULAR TO FOLATION

SAMPLE ID: GNEISS PERP VS 8/2/77-RT
 SAMPLE LENGTH= 27.971
 TIME BASE FACTOR= 2.0 (MICROSEC)

P(BARS)	T1(MS)	T2(MS)	VEL(KM/S)
0.0	6.594	1.465	2.727
10.0	6.511	1.465	2.772
20.0	6.452	1.465	2.804
30.0	6.389	1.465	2.840
40.0	6.298	1.463	2.893
50.0	6.211	1.463	2.946
75.0	6.109	1.463	3.010
100.0	6.028	1.463	3.064
150.0	5.924	1.465	3.135
200.0	5.872	1.465	3.173
300.0	5.797	1.465	3.228
400.0	5.741	1.465	3.271
500.0	5.709	1.465	3.295
760.0	5.615	1.465	3.339
1005.0	5.613	1.465	3.372
1505.0	5.565	1.465	3.411
2000.0	5.531	1.466	3.440
3010.0	5.493	1.466	3.473
4010.0	5.473	1.466	3.490
4505.0	5.463	1.466	3.499
4005.0	5.468	1.462	3.491
2995.0	5.485	1.462	3.476
2005.0	5.511	1.462	3.454
1015.0	5.554	1.462	3.418
510.0	5.627	1.464	3.359
255.0	5.740	1.464	3.271
105.0	5.853	1.464	3.186
55.0	5.973	1.464	3.102
10.0	6.278	1.464	2.905
0.0	6.493	1.464	2.781

SAMPLE ID: GNEISS PERP VP 8/7/77-RT
 SAMPLE LENGTH= 27.971
 TIME BASE FACTOR= 2.0 (MICROSEC)

P(BARS)	T1(MS)	T2(MS)	VEL(KM/S)
0.0	4.367	1.491	4.953
10.0	4.311	1.491	4.959
20.0	4.289	1.491	4.999
30.0	4.248	1.491	5.073
40.0	4.226	1.489	5.110
50.0	4.212	1.489	5.136
75.0	4.152	1.489	5.252
100.0	4.101	1.489	5.354
150.0	4.075	1.491	5.412
200.0	4.013	1.491	5.545
300.0	3.959	1.491	5.667
400.0	3.924	1.491	5.748
500.0	3.907	1.489	5.784
760.0	3.881	1.489	5.947
1005.0	3.843	1.489	5.941
1500.0	3.805	1.489	6.039
2000.0	3.787	1.489	6.086
3010.0	3.756	1.489	6.169
4010.0	3.731	1.489	6.239
4500.0	3.721	1.489	6.266
5005.0	3.719	1.488	6.269
5500.0	3.717	1.488	6.274
6000.0	3.712	1.488	6.289
4990.0	3.728	1.488	6.244
4015.0	3.738	1.486	6.210
3005.0	3.758	1.486	6.156
2010.0	3.772	1.486	6.118
1000.0	3.825	1.486	5.979
500.0	3.888	1.484	5.818
260.0	3.969	1.484	5.628
105.0	4.064	1.484	5.421
55.0	4.179	1.484	5.189
10.0	4.322	1.484	4.929
0.0	4.431	1.484	4.746

SAMPLE ID: GNEISS PERP 99 6/1/77-RT

GAUGE FACTOR= 2.050

INITIAL RESISTANCE= 127.700 (CHMS)

CORRECTION FACTOR= 3.756(OHMS) I.E., DELTA R @ PRES.=0.0 BARS

P(BARS)	DELTA R(CHMS)	CUMM. STRAIN	VOL. STRAIN
0.0	3.756	0.00000	0.00000
10.0	3.759	0.00001	0.00004
20.0	3.764	0.00003	0.00009
30.0	3.767	0.00004	0.00013
40.0	3.773	0.00007	0.00020
50.0	3.776	0.00008	0.00024
75.0	3.784	0.00011	0.00033
100.0	3.795	0.00015	0.00046
150.0	3.814	0.00023	0.00068
200.0	3.829	0.00029	0.00086
300.0	3.855	0.00039	0.00117
400.0	3.879	0.00048	0.00145
500.0	3.905	0.00055	0.00176
760.0	3.959	0.00080	0.00240
1005.0	4.007	0.00095	0.00296
1500.0	4.099	0.00135	0.00405
2000.0	4.189	0.00170	0.00511
3010.0	4.362	0.00239	0.00716
4010.0	4.525	0.00303	0.00900
4500.0	4.603	0.00333	0.01000
5005.0	4.683	0.00365	0.01095
5500.0	4.759	0.00395	0.01184
6000.0	4.833	0.00424	0.01272
4990.0	4.681	0.00364	0.01092
4015.0	4.531	0.00305	0.00915
3005.0	4.355	0.00237	0.00712
2010.0	4.192	0.00172	0.00515
1000.0	4.010	0.00100	0.00300
500.0	3.914	0.00062	0.00187
260.0	3.857	0.00040	0.00119
105.0	3.816	0.00024	0.00071
55.0	3.797	0.00016	0.00048
10.0	3.771	0.00006	0.00018
0.0	3.758	0.00001	0.00002

	mv	psi
P _C	17.493	6154
P _h	15.481	5247
P _L	15.063	5106

	mv	psi
P _C	17.483	6151
P _H	12.580	4264
P _L	11.705	3967

QUARTZITE

SAMPLE ID: OTZITE VS 8/11/77-RT
 SAMPLE LENGTH= 33.271
 TIME BASE FACTOR= 2.0 (MICROSEC)

P(BARS)	T1(MS)	T2(MS)	VEL(KM/S)
0.0	6.507	1.472	3.304
10.0	6.473	1.472	3.326
20.0	6.457	1.472	3.337
30.0	6.427	1.472	3.357
40.0	6.398	1.468	3.374
50.0	6.372	1.468	3.392
75.0	6.313	1.468	3.434
100.0	6.248	1.468	3.480
150.0	6.149	1.469	3.555
200.0	6.092	1.469	3.598
300.0	6.004	1.469	3.658
400.0	5.934	1.469	3.726
500.0	5.886	1.471	3.768
750.0	5.828	1.471	3.818
1000.0	5.803	1.471	3.840
1500.0	5.761	1.471	3.878
2005.0	5.740	1.471	3.897
3015.0	5.75	1.471	3.929
4020.0	5.689	1.471	3.944
4515.0	5.679	1.471	3.953
4000.0	5.681	1.470	3.950
3000.0	5.699	1.470	3.934
2005.0	5.724	1.470	3.911
995.0	5.765	1.470	3.873
520.0	5.863	1.465	3.783
250.0	5.980	1.465	3.684
100.0	6.166	1.465	3.539
50.0	6.278	1.465	3.456
10.0	6.433	1.465	3.349
0.0	6.543	1.465	3.276

SAMPLE ID: OTZITE VP 8/3/77-RT
 SAMPLE LENGTH= 33.271
 TIME BASE FACTOR= 2.0 (MICROSEC)

P(BARS)	T1(MS)	T2(MS)	VEL(KM/S)
0.0	4.912	1.472	4.835
10.0	4.783	1.472	5.024
20.0	4.774	1.472	5.038
30.0	4.771	1.472	5.043
40.0	4.743	1.473	5.087
50.0	4.724	1.473	5.117
75.0	4.671	1.473	5.202
100.0	4.641	1.473	5.251
150.0	4.572	1.473	5.368
200.0	4.560	1.473	5.389
300.0	4.490	1.473	5.514
400.0	4.461	1.473	5.567
500.0	4.440	1.474	5.609
755.0	4.397	1.474	5.691
1000.0	4.377	1.474	5.730
1500.0	4.349	1.474	5.786
2000.0	4.312	1.472	5.858
3005.0	4.301	1.472	5.890
4005.0	4.281	1.472	5.922
4505.0	4.271	1.472	5.943
3975.0	4.287	1.473	5.912
2995.0	4.331	1.473	5.821
2005.0	4.351	1.473	5.780
1000.0	4.384	1.473	5.715
515.0	4.395	1.471	5.589
250.0	4.476	1.471	5.536
110.0	4.552	1.471	5.399
45.0	4.623	1.471	5.279
10.0	4.767	1.471	5.047
0.0	4.995	1.471	4.721

SAMPLE ID: GTZITE SS 8/11/77-R1

GAUGE FACTOR= 2.050

INITIAL RESISTANCE= 124.700 (OHMS)

CORRECTION FACTOR= 3.998(OHMS) I.E., DELTA R @ PRES.=0.0 BARS

P(BARS)	DELTA R(OHMS)	CUM. STRAIN	VOL. STRAIN
0.0	3.998	0.00000	0.00000
10.0	4.007	0.00004	0.00011
20.0	4.013	0.00006	0.00010
30.0	4.018	0.00008	0.00024
40.0	4.024	0.00011	0.00032
50.0	4.029	0.00013	0.00030
75.0	4.043	0.00018	0.00055
100.0	4.057	0.00024	0.00072
150.0	4.070	0.00032	0.00097
200.0	4.098	0.00040	0.00121
300.0	4.132	0.00054	0.00162
400.0	4.162	0.00066	0.00199
500.0	4.188	0.00077	0.00230
750.0	4.253	0.00103	0.00309
1000.0	4.313	0.00127	0.00382
1500.0	4.426	0.00173	0.00519
2005.0	4.537	0.00218	0.00653
3015.0	4.748	0.00303	0.00909
4020.0	4.954	0.00386	0.01159
4545.0	5.054	0.00427	0.01280
4000.0	4.948	0.00394	0.01152
3000.0	4.743	0.00301	0.00903
2005.0	4.533	0.00216	0.00649
995.0	4.308	0.00125	0.00376
520.0	4.196	0.00080	0.00240
250.0	4.123	0.00051	0.00152
100.0	4.070	0.00025	0.00087
50.0	4.047	0.00020	0.00059
10.0	4.019	0.00006	0.00025
0.0	4.004	0.00002	0.00007

	mv	psi
P _c	18.086	6357
P _h	18.109	6138
P _L	17.923	6075

	mv	psi
P _c	17.771	6252
P _h	17.303	5865
P _L	17.129	5806

	mv	psi
P _C	17.705	6229
P _h	17.104	5797
P _L	16.780	5688

	mv	psi
P _C	17.585	6187
P _H	16.248	5507
P _L	15.725	5330

	mv	psi
P _c	17.564	6179
P _h	15.772	5346
P _L	15.214	5157

	mv	psi
P _C	17.503	6158
P _h	9.869	3345
P _L	9.380	3179

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SAMPLE ID: OTZITE ZP VS 3/11/77-RT
 SAMPLE LENGTH= 34.288
 TIME BASE FACTOR= 2.0 (MICROSEC)

P(BARS)	T1(MS)	T2(MS)	VEL(KM/S)
0.0	8.012	1.448	2.612
10.0	7.866	1.448	2.671
20.0	7.706	1.448	2.740
30.0	7.499	1.448	2.833
40.0	7.309	1.448	2.925
50.0	7.169	1.448	2.997
75.0	6.948	1.448	3.117
100.0	6.777	1.448	3.217
150.0	6.573	1.448	3.345
200.0	6.449	1.448	3.428
300.0	6.279	1.448	3.549
405.0	6.179	1.448	3.524
500.0	6.122	1.449	3.669
750.0	6.041	1.449	3.733
1000.0	5.993	1.449	3.773
1500.0	5.931	1.449	3.825
2005.0	5.888	1.448	3.861
3015.0	5.820	1.448	3.921
4025.0	5.779	1.448	3.958
4500.0	5.753	1.448	3.982
4010.0	5.764	1.448	3.972
3000.0	5.791	1.448	3.948
1995.0	5.863	1.448	3.883
995.0	5.962	1.448	3.798
505.0	6.065	1.447	3.712
250.0	6.242	1.447	3.575
100.0	6.624	1.447	3.312
50.0	6.962	1.447	3.109
10.0	7.592	1.447	2.790

SAMPLE ID: OTZITE ZP VP 3/3/77-RT
 SAMPLE LENGTH= 34.288
 TIME BASE FACTOR= 2.0 (MICROSEC)

P(BARS)	T1(MS)	T2(MS)	VEL(KM/S)
0.0	6.236	1.472	3.599
10.0	5.725	1.472	4.031
20.0	5.393	1.472	4.372
30.0	5.327	1.472	4.447
40.0	5.203	1.472	4.595
50.0	5.179	1.472	4.625
75.0	4.982	1.472	4.884
100.0	4.908	1.472	4.950
150.0	4.771	1.471	5.155
200.0	4.709	1.471	5.295
300.0	4.661	1.471	5.374
400.0	4.637	1.471	5.415
505.0	4.550	1.472	5.606
750.0	4.451	1.472	5.755
1005.0	4.425	1.472	5.806
1500.0	4.380	1.472	5.895
2010.0	4.353	1.471	5.949
2995.0	4.342	1.471	5.971
4005.0	4.331	1.471	5.994
4515.0	4.312	1.471	6.034
5000.0	4.309	1.470	6.039
4000.0	4.318	1.470	6.020
3010.0	4.346	1.470	5.961
2005.0	4.374	1.470	5.904
1010.0	4.412	1.469	5.825
510.0	4.519	1.469	5.621
260.0	4.586	1.469	5.500
110.0	4.743	1.469	5.236
50.0	4.937	1.469	4.943
10.0	5.243	1.469	4.543
0.0	6.427	1.469	3.458

SAMPLE ID: DTZITE ZP SS 8/23/77-RJ

GAUGE FACTOR= 2.050

INITIAL RESISTANCE= 124.700 (OHMS)

CORRECTION FACTOR= 3.358(OHMS) I.E., DELTA R @ PRES.=0.0 BARS

P(BARS)	DELTA R(OHMS)	CUMV. STRAIN	VOL. STRAIN
0.0	3.358	0.00000	0.00000
10.0	3.378	0.00008	0.00024
20.0	3.399	0.00016	0.00049
30.0	3.418	0.00024	0.00072
40.0	3.433	0.00030	0.00090
50.0	3.443	0.00034	0.00103
75.0	3.467	0.00044	0.00131
100.0	3.493	0.00054	0.00163
150.0	3.527	0.00068	0.00204
200.0	3.555	0.00079	0.00238
300.0	3.602	0.00098	0.00294
400.0	3.636	0.00112	0.00335
505.0	3.668	0.00125	0.00374
745.0	3.735	0.00152	0.00455
1010.0	3.802	0.00178	0.00535
1510.0	3.921	0.00226	0.00679
2020.0	4.035	0.00272	0.00816
3020.0	4.247	0.00357	0.01072
4010.0	4.450	0.00439	0.01317
4510.0	4.551	0.00480	0.01439
3990.0	4.443	0.00436	0.01309
2995.0	4.238	0.00354	0.01061
2000.0	4.025	0.00268	0.00804
1000.0	3.805	0.00180	0.00539
500.0	3.666	0.00124	0.00371
250.0	3.583	0.00090	0.00271
100.0	3.503	0.00056	0.00175
50.0	3.459	0.00041	0.00122
10.0	3.398	0.00016	0.00048
0.0	3.362	0.00002	0.00005

	mv	psi
P _C	17.420	6129
P _h	16.923	5736
P _L	16.664	5648

	mv	psi
P _C	17.292	6083
P _h	16.444	5574
P _L	16.111	5461

HI PRESSURE (MV) - QTZITE ZP PERMRN #8

	mv	psi
P _c	16.777	5902
P _h	13.701	4644
P _L	13.286	4503

MARBLE

SAMPLE ID: MARBLE VS 8/5/77 -9T
 SAMPLE LENGTH= 29.165
 TIME BASE FACTOR= 2.0 (MICROSEC)

P(BARS)	T1(MS)	T2(MS)	VEL(KM/S)
0.0	6.039	1.488	3.204
10.0	6.022	1.488	3.216
20.0	6.011	1.488	3.224
30.0	5.992	1.488	3.239
40.0	5.977	1.488	3.248
50.0	5.970	1.488	3.254
75.0	5.946	1.488	3.271
100.0	5.923	1.488	3.288
150.0	5.883	1.487	3.317
200.0	5.863	1.487	3.332
300.0	5.823	1.487	3.363
400.0	5.820	1.487	3.365
500.0	5.811	1.487	3.372
755.0	5.787	1.487	3.391
1005.0	5.763	1.487	3.410
1425.0	5.718	1.487	3.447
2000.0	5.716	1.488	3.449
3010.0	5.661	1.488	3.494
4010.0	5.618	1.488	3.531
4505.0	5.592	1.488	3.553
4000.0	5.594	1.488	3.552
3025.0	5.589	1.488	3.556
1995.0	5.658	1.488	3.497
1010.0	5.741	1.488	3.429
505.0	5.819	1.488	3.367
250.0	5.849	1.488	3.344
105.0	5.888	1.488	3.314
50.0	5.929	1.488	3.294
10.0	5.992	1.488	3.238
0.0	6.079	1.488	3.176

SAMPLE ID: MARBLE VP 8/10/77 -9T
 SAMPLE LENGTH= 29.165
 TIME BASE FACTOR= 2.0 (MICROSEC)

P(BARS)	T1(MS)	T2(MS)	VEL(KM/S)
0.0	3.616	1.472	6.802
10.0	3.599	1.472	6.856
20.0	3.596	1.472	6.866
30.0	3.573	1.472	6.941
40.0	3.559	1.469	6.944
50.0	3.569	1.469	6.944
75.0	3.566	1.469	6.954
100.0	3.559	1.469	6.977
150.0	3.543	1.468	7.028
200.0	3.533	1.468	7.062
300.0	3.528	1.468	7.079
400.0	3.526	1.468	7.086
500.0	3.521	1.470	7.110
745.0	3.462	1.470	7.321
1005.0	3.459	1.470	7.332
1500.0	3.451	1.470	7.361
1990.0	3.442	1.467	7.384
3020.0	3.424	1.467	7.451
4010.0	3.407	1.467	7.517
4510.0	3.399	1.467	7.548
3990.0	3.417	1.465	7.471
3000.0	3.429	1.465	7.423
2000.0	3.439	1.465	7.387
995.0	3.453	1.465	7.335
515.0	3.464	1.463	7.288
255.0	3.523	1.463	7.079
100.0	3.543	1.463	7.011
50.0	3.560	1.463	6.954
10.0	3.571	1.463	6.918
0.0	3.603	1.463	6.814

SAMPLE ID: MARBLE SS 8/5/77-RT

GAUGE FACTOR= 2.050

INITIAL RESISTANCE= 124.700 (OHMS)

CORRECTION FACTOR= 4.024(OHMS) I.E..DELTA R @ PRES.=0.0 BARS

P (EARS)	DELTA R (OHMS)	CUM. STRAIN	VOL. STRAIN
0.0	4.024	0.00000	0.00000
10.0	4.027	0.00001	0.00004
20.0	4.028	0.00002	0.00005
30.0	4.029	0.00002	0.00006
40.0	4.031	0.00003	0.00008
50.0	4.032	0.00003	0.00010
75.0	4.034	0.00004	0.00012
100.0	4.037	0.00005	0.00016
150.0	4.043	0.00006	0.00023
200.0	4.048	0.00010	0.00029
300.0	4.061	0.00015	0.00045
400.0	4.071	0.00019	0.00057
500.0	4.082	0.00023	0.00070
755.0	4.112	0.00036	0.00107
1005.0	4.138	0.00046	0.00138
1495.0	4.190	0.00067	0.00201
2000.0	4.243	0.00089	0.00266
3010.0	4.343	0.00129	0.00387

SAMPLE ID: MARBLE SS 8/10/77-RT

GAUGE FACTOR= 2.050

INITIAL RESISTANCE= 124.700 (OHMS)

CORRECTION FACTOR= 3.603(OHMS) I.E..DELTA R @ PRES.=0.0 BARS

P(BARS)	DELTA R(OHMS)	CUMN. STRAIN	VOL. STRAIN
0.0	3.603	0.00000	0.00000
10.0	3.609	0.00002	0.00007
20.0	3.611	0.00003	0.00010
30.0	3.612	0.00004	0.00011
40.0	3.613	0.00004	0.00012
50.0	3.615	0.00005	0.00015
500.0	3.666	0.00025	0.00076
745.0	3.694	0.00037	0.00110
1005.0	3.725	0.00049	0.00147
1500.0	3.777	0.00070	0.00210
1990.0	3.827	0.00090	0.00271
3020.0	3.931	0.00132	0.00396
4010.0	4.026	0.00170	0.00511
4510.0	4.072	0.00189	0.00567
3990.0	4.022	0.00169	0.00506
3000.0	3.928	0.00131	0.00393
2000.0	3.827	0.00090	0.00271
995.0	3.721	0.00048	0.00143
515.0	3.666	0.00025	0.00076
255.0	3.636	0.00013	0.00040
100.0	3.618	0.00006	0.00018
50.0	3.613	0.00004	0.00012
10.0	3.607	0.00002	0.00005
0.0	3.605	0.00001	0.00002

	mv	psi
P _c	17.253	6070
P _h	17.214	5835
P _L	17.104	5797

	mv	psi
P _C	17.152	6034
P _H	16.523	5600
P _L	16.227	5500

	mv	psi
P _c	17.206	6053
P _h	15.614	5292
P _L	15.217	5158

	mv	psi
P _C	17.164	6038
P _H	11.340	3844
P _L	10.771	3651

APPENDIX

APPENDIX

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 $\pm .01$ 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 120 Ω 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 $\pm 1 \times 10^{-4}$.

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.

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

$$k = \frac{\mu_w \beta_w V_s l}{A \Delta P} \left(\frac{dP}{dT} \right)$$

where

- μ_w = viscosity of water
- β_w = compressibility of water
- V_s = volume of system
- l = length of sample
- A = cross sectional area of sample
- ΔP = pressure pulse applied
- dP/dT = slope at pressure decay curve.

Upper pressure line and transducer

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 $v(P)$

$$v(P) = P^2 d\epsilon / dP^2 \quad (1)$$

where ϵ 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 $\beta(P)$.

$$\beta(P)^{-1} = \rho(V_p^2 - \frac{4}{3}V_s^2) \quad (2)$$

where V_p is the compressional wave velocity, V_s is the shear wave velocity, and ρ 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.