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**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**

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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

by

R. Trice
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ABSTRACT

Acoustic velocity and strain data were obtained on two GT-2 samples as part of a study using acoustic data to infer or characterize volume-averaged 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 1 kbar, 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 controls both permeability and elastic properties.

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I. 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-averaged bulk physical properties, both in laboratory-size samples and in the vicinity of a borehole. 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 near the Valles Caldera, New Mexico, which are being experimentally developed by the Los Alamos Scientific Laboratory (LASL) with ERDA funding.

In the second part of this paper, general pressure-dependent formulations of ultrasonic moduli and permeability are summarized. In the third section, ultrasonic measurements on two core samples from the LASL GT-2 well are presented and discussed. In the fourth section, these experimental results are related to permeability along with a correlation of acoustics and permeability for Westerly granite.

II. ACOUSTIC MODULI AND PERMEABILITY FUNCTIONS

A. Elastic Moduli Pressure Dependence

Ultrasonic velocities of rock, as functions of pressure, are sensitive to the volume-averaged microstructure and its pressure dependence. The effect of microstructure is expressible through formulations for acoustic moduli or compliances on pore strains and porosity. A fairly unrestricted equation for an elastic compliance is of the form:

$$i\phi/i\phi_0 = 1 + \sum_{\alpha} \frac{\alpha_{\eta}}{1 - t_{\eta}} \frac{i\alpha^{\epsilon_h}}{i\epsilon_0} \quad (1)$$

In Eq. (1) $i\phi$ is a general compliance of a porous material and $i\phi_0$ is the corresponding compliance of the solid material. The quantity α_{η} is the porosity (ratio of pore volume to matrix volume) of the α th type of pore, and t_{η} is the total porosity. The subscript i denotes coordinates and $i\alpha^{\epsilon_h}/i\epsilon_0$ the ratio of the pore strain ($i\alpha^{\epsilon_h}$) to the solid (reference) material strain ($i\epsilon_0$).

Development of this expression is given in Warren and Nashner (1976). The equation follows from a general formulation of volume strain in terms of referred porosity (Warren, 1973; 1971). The general formulation is restricted only by the definition of moduli (linear, first-order differentials) and compatibility with infinitesimal strain theory over the whole porosity domain. Equation (1) is further restricted by conditions arising from the use of the reciprocal theorem, namely, that the matrix material is homogeneous, isotropic, and continuously welded (no loose grains). Pore pressure effects on the matrix of the material are not included here but would appear as a positive term on the left-hand side of the equation.

From Eq. (1) the pressure dependence of an acoustic compliance is given by the pressure dependence of the strain ratios $\alpha^{\epsilon_h}/\epsilon_0$ and the porosities α_{η} . Porosity depends on pressure as the volumetric pore strain $\alpha \Delta V_h / \alpha V_h$:

$$\alpha_{\eta}(P^*) = \alpha_{\eta}(P^* = 0) \left(1 - \frac{\alpha \Delta V_h}{\alpha V_h} \right), \quad 0 \leq P^* \leq 1$$

where P^* is the pressure, normalized to the closing pressure of the pore. The pressure dependence of a pore strain ratio depends on the power law dependence of pore strain on pressure. For a linear pore strain, the ratio $\alpha^{\epsilon_h}/\epsilon_0$ is a constant and the porosity decreases linearly with pressure. A compliance for a cracked material, therefore, in which the cracks are modeled by oblate ellipsoids has a dependence on pressure given only by the superposition of pore strains with pressure.

If pore strains go as some power (r) of pressure, then the porosity of any one pore type varies as

$$\alpha_{\eta}(P^*) = \alpha_{\eta}(P^* = 0) \cdot [1 - P^{*r}] .$$

The pore strain ratio goes as P^{*r-1} . For compacted materials in which grain contacts deform as the $2/3$ power of the traction across the contacts, the predicted dependence of compliance on pressure at low pressures goes as $P^{-1/3}$, in agreement with soil theory.

These relations can be applied to the problem of inverting ultrasonic velocity data into microstructure. An important result will be that rocks with igneous textures (typical microfractured rock) show velocity-pressure characteristics compatible with essentially linear pore closure laws, an observation which will be used in comparing acoustic data to permeability data in Sec. IV.

B. Permeability

Permeability depends on the open conduit paths through a rock and the pressure dependence of the conduit cross sections.

For simple conduits parallel to the direction of flow, the form of Kozeny's relation is easily derived (Scheidegger, 1960, Chap. 6):

$$k = c \frac{\gamma^3}{S^2} , \quad (2)$$

where c is a constant, γ is the porosity given by the active conduit system, and S is given by,

$$S = \frac{\text{conduit circumference}}{\text{sample cross-sectional area}} , \text{ or} \quad (3)$$

$$S = \frac{\text{conduit surface area}}{\text{sample volume}} . \quad (4)$$

The form of Eq. (2) was originally derived for simple conduits and packed grains. An equivalent theoretical derivation for fractured rock has not been successfully carried out. Problems arise from a number of sources, including (1) tortuous paths (the pressure gradient length $\underline{L}'$ is much longer than

sample length $\underline{L}$), (2) pinch-off (the closing of cracks due to pressure or chemical effects pinches off portions of the flow network, thus removing them from the conduit system, and (3) the assumption of one-dimensional laminar fluid flow (i.e., there is a wet surface layer on the crack surfaces). This assumption cannot hold as cracks become extremely narrow.

Nevertheless, if laminar flow is assumed to hold, then the form of the pressure dependence of permeability is still suggested from Eq. (2). Tortuosity affects the estimate of the absolute value of $\underline{k}$, and pinch-off (and the pressure dependence of tortuosity) enters into the pressure dependence of the quantities γ and S , which characterize the conduit system.

Equation (2) can be recast:

$$k = c\gamma/S_0^2, \quad (5)$$

where S_0 is a characteristic of the pores, and

$$S_0 = A_h/V_h \sim 1/b$$

where $\underline{b}$ is a characteristic pore dimension (crack width).

We suggest that the extent to which the microstructure affecting the ultrasonic velocities and the conduit structure affecting permeability are the same may be determined by comparing the relative pressure dependence of these two properties.

Under the simplest assumption of a single crack population which closes linearly with hydrostatic pressure:

$$k(P) \sim (1 - P^*)^3$$

for

$$P^* \leq 1$$

since

$$\gamma \sim (1 - P^*)$$

and

$$b \sim (1 - P^*) .$$

Also, from Eq. (1)

$$\phi/\phi_0 - 1 \sim (1 - P^*) .$$

The pressure dependence of the permeability may vary as the third power of the acoustic moduli data.

For igneous textured rocks in which pore deformation is essentially close to linear, both permeability and the elastic compliances may then be controlled by successively closing populations of cracks. Comparison of the third power of the moduli with permeability may then indicate whether a dominant crack network affecting velocity is the same as that affecting permeability.

For nonlinear pore strains (such as observed in some sandstones and compacted sands), the simplest assumptions give

$$k \sim (1 - P^{*r})^3$$

and

$$\phi/\phi_0 - 1 \sim (1 - P^{*r}) P^{*r-1} ,$$

so a cubic relation is not predicted to hold between the pressure dependence of permeability and acoustic data.

III. ACOUSTIC AND STRAIN DATA FOR TWO GRANODIORITES FROM LASL WELL GT-2, FENTON HILL

A. Samples

Two suites of rock samples from well cores have been obtained. The first suite consisted of samples 8581 and 9519 from drill core GT-2. The second suite includes three samples from drill core TC-1, two samples designated 92-1256 and a second piece of 9519 from drill core GT-2. Characterization of

the first suite of samples is complete, with the results being presented in this report. Measurements on the second suite of samples are just commencing.

Specifically for the first two samples, the numbers 8581 and 9519 refer to the depth, in feet, of the section of core from which the samples were taken. Both samples are from the same biotite quartz monzonite body, with sample 8581 coming from near the upper contact with overlying gneiss and 9519 coming from near an extrapolated lower contact with rock of the same composition but markedly different foliation. A brief petrographic analysis shows that both samples have typical granitic texture. Grain sizes are on the order of 1 to 2 mm. Sample 8581 is moderately fractured and has heavily altered feldspars. Sample 9519 is less fractured and altered than 8581, but both features are present. The bulk samples are cylindrical with dimensions as follows: 8581 - length = 5.077 cm, diam = 1.657 cm; 9519 - length = 2.541 cm, diam = 1.657 cm. Both of the sample cylinders were cored parallel to the axis of the drill core.

B. Experimental

Acoustic velocity measurements were made on the two core samples, using 1-MHz and 3-MHz X-cut and Y-cut PZT transducers. Opposing cylinder ends were polished to a parallelism of ± 0.001 inch before the transducers were mounted, using a tiny amount of Duco cement for bonding. Static strain measurements were made, using BLH linear strain gauges of 120 Ω and 350 Ω resistance, mounted on the cylinder faces of the cores, using Dexter Epoxy-Patch two-part epoxy. The entire sample assemblies were then jacketed with Dow-Corning Sylgard silicone epoxy for the hydrostatic pressure runs. Both of the samples were cycled through at least one pressure run, to insure proper seating of the strain gauges before any strain measurements were taken.

Measurement of acoustic wave velocities was made, using direct pulse transmission time-of-flight techniques with corrections to sample length, as dictated by strain measurements. Tabulated velocity data are presented in Appendix A. A Wheatstone bridge circuit was used to measure the static strains, which are accurate to within $\pm 0.02\%$ strain.

C. Data

1. 8581. Compressional wave velocities on sample 8581 over the pressure range 0 to 7000 bars yield an extremely well-behaved curve, with the variation in velocity not more than ± 0.02 km/s (less than 0.4%) between up and down

cycles at the same pressure. Shear velocity measurements over the pressure range 0 to 5800 bars are qualitatively similar to the compressional velocity data. Below 2000 bars on the up cycle, the shear velocity curve appears to be less well behaved because of difficulty in picking the S arrival, due to mode conversion. Both the compressional and shear velocities for sample 8581 are presented in Fig. 1, as a function of hydrostatic pressure. Zero-pressure velocities of 5.09 km/s and 3.12 km/s for compressional and shear modes, respectively, yield a zero-pressure Poisson's ratio of 0.199. The velocity profiles are typical of those for good crystalline rocks, with most of the pressure-sensitive behavior disappearing by 2-kbars pressure, and the curves becoming essentially linear. Moreover, there is no significant hysteresis between up and down cycles for this sample.

Linear static strain measurements on sample 8581, between the pressures 0 and 6500 bars, were made using two strain gauges. One gauge was oriented parallel to the axis of the cylinder and one gauge was oriented circumferentially. The sample was initially run through a pressure cycle of 0 to 5000 bars with no measurements taken. Strains measured on each gauge between 0 and 1000 bars are identical with respect to up and down cycles. Absolute values of the strains diverge to about 0.03% at 1000 bars between the length gauge and the circumferential gauge. Above 1000 bars, the curves for the up-pressure cycle from each gauge are essentially linear and parallel. This is also true of the down-cycle curves. At a point near 2 kbars, on the down run, both gauges indicate strains diverging from those of the up run. This divergence on the calculated volumetric strain curve (Fig. 2) reaches a maximum of 0.09% total strain at 2 kbars. The up and down cycles converge again at 1 kbar. It is not known whether the divergence at 2 kbars is real or is due to a possible electrical problem affecting readings on both gauges.

A crack porosity of 0.21% was determined by extrapolation of the linear portion of the volumetric strain curve above 2 kbars. Total porosity, calculated from measured and theoretical densities is 1.93%. The certainty of this value is limited by having used a general mineralogical modal analysis supplied by LASL for another portion of sample 8581.

2. 9519. Five separate compressional wave velocity runs were made on sample 9519 over the pressure range 0 to 6.5 kbars. The sample was rejacketed and transducers changed three times. The unusual progression and degradation in the velocity profiles that occurred from run to run is shown in Fig. 3

(data are stacked--no absolute vertical scale). There are several features which the curves have in common. All the curves have very steep initial slopes and abrupt changes in slopes in the low-100-bars range. On the up-pressure runs none of the curves appear to be approaching linearity at high pressures; rather, the slope of the velocity data increases for each curve above 3 kbars. After repeated cycling, a hysteresis loop develops with a lower pressure closure between 2 and 2.5 kbars. In these later cycles real inflections occur in the pressure range of 100 bars and 2 kbars. Various other plateaus and cross-overs appear in this pressure range on the order of experimental accuracy.

Shear wave velocities were obtained on sample 9519 between 100 bars and 6 kbars (Fig. 4). The shear velocity run was made prior to the first compressional velocity run and shows essentially the same irregularities as the first compressional run; notably, the flattening of the curve between several hundred bars and about two kbars.

For sample 9519, only one strain gauge could be accommodated on the sample due to sample length. Strains were measured during the second and third runs. Volume strain was estimated to be three times the value of the linear strain from this axially oriented gauge and is shown in Fig. 5. The profile, unlike the velocity profiles, is quite smooth and linear above 1000 bars. Moreover, there is only a small amount of hysteresis below 1000 bars. Extrapolation of the linear portion of the volumetric strain curve back to zero pressure yields a crack porosity of less than 0.1%. Total porosity for 9519, estimated from theoretical and measured densities, is 2.19%.

D. Discussion

Figure 6 shows a plot of log compressional modulus ($\rho V_p^2 \equiv C$) versus pressure for samples 8581 and 9519 (third compressional run). Also shown is the curve for Westerly granite (calculated from the data of Simmons and Brace, 1965) to demonstrate the affinities and dissimilarities of the curves for 8581 and 9519 and Westerly granite. Such S-shaped curves are typical of good polycrystalline materials with some small amount of cracks (Warren and Trice, 1975).

The forms of these plots indicate that the elastic moduli for all three rocks are controlled predominantly by flat cracks. The distribution of closing pressures for 8581 and Westerly granite are similar, although the stronger

inflections in the data for 8581 indicate a comparatively larger crack population which closes in the pressure region of high hundreds of bars.

The curve for 9519 is less obviously S-shaped. Closing pressures in the low-hundred-bars region is suggested by the inflection in the plot in this pressure range. Under the repeated cycling, however, the low-pressure data for this sample begin to suggest nonlinear pore strains (and the micro-structure presumably alters). It is felt that failure occurred, perhaps along healed cracks, which introduced both rough asperities, giving rise to nonlinear pore strains at low pressure and increasing friction, thus generating the hysteresis loop at high pressure.

Effective in situ pressure for sample 9519 is between 600 and 1000 bars, and therefore, the velocity curve in this pressure range has the most practical significance. It is in this pressure range, also, that the velocity curves undergo the most change from one run to the next. It is interesting to consider for future study, therefore, whether in situ this granodiorite is susceptible to damage by cycling of fluid pressures, and whether "this phenomenon" can alter in situ permeability.

For 8581 and Westerly granite, model crack porosities have been generated from dynamic moduli data and are summarized in Warren (1976) and in Tables I and II here. For Westerly granite, the model crack distribution is in agreement with the dynamic and static moduli data and approximately with the porosity distribution from Hadley (1976). The functional form of the model moduli at pressures below about 1.5 kbars is controlled almost exclusively by the two porosity peaks near the aspect ratio (a/b) of 10^{-3} (Figs. 7 and 8).

The markedly lower static versus dynamic moduli of 8581 (Fig. 9) is not fit by the model given in Table I. The model static bulk modulus is about 100 kbars too high at low pressures. However, this problem is only a side issue and does not affect the results to follow.

The important point of the modeling is that the acoustic properties of these rocks are well described by fairly simple model distributions of cracks, which have linear pressure dependencies. Therefore, it is of interest to compare the acoustic moduli data to the permeability data under the assumption of linear pore closure laws, using a cubic relation between the acoustic moduli and permeability.

IV. PERMEABILITY VERSUS ACOUSTIC DATA

Figures 10, 11, and 12 show plots of permeability, k , for Westerly granite (from Brace et al., 1968) 8580 and 9522 (from J. Potter, personal communication), compared to plots of C modulus data in the form:

$$(C_0/C(P) - 1)^3 .$$

The quantities $C(P)$ are from measurements, and in the case of Westerly granite, from the velocity data of Schock et al., (1974). The quantities C_0 are the estimated zero-porosity values of the C modulus. The values for C_0 were taken from mineralogy for Westerly granite and 8581; and for 9519, from the highest pressure data on the last compressional velocity-pressure run. Although the velocity-pressure relation for 9519 changed markedly with cycling, the absolute values of $C(P)$ are quite similar for all the curves. Data from the last pressure runs were used, since 9522 was effectively cycled several times in the course of the permeability experiment. The slope of the acoustic data function for 9519 at high pressures would be more shallow if C_0 had been chosen equal to the highest value obtained from the first pressure run.

These figures comparing acoustic and permeability data suggest that for microcracked rocks, such as granites within the measured pressure range, the network of crack structure controlling the pressure dependence of permeability is indeed the same as that controlling the acoustic wave propagation.

Greenberg and Brace (1969) suggest that at zero pressure, essentially the entire porosity of crystalline rocks is interconnected. This is based on the ability to measure porosity accurately by immersion techniques and the fact that the electrical resistivity of completely different kinds of crystalline rocks with the same total porosity is generally the same. In fact, if one calculates a zero-pressure permeability for rocks such as Westerly granite or ERDA 8581, using Kozeny's equation, and assumes a porosity of about 2%, a simplified bimodal pore geometry distribution, total interconnectivity, and reasonable pore-size parameters, the values obtained are quite reasonable (on the order of 10^{-6} darcys).

In a recent paper, Brace (1976) presents an equation for permeability in terms of porosity, electrical resistivity and mean hydraulic radius. Then using an empirical relationship between resistivity and porosity, he achieves

a relation dependent solely on porosity and mean hydraulic radius (see Eq. 3, Brace, 1976). By stipulating that the mean hydraulic radius remains constant, the pressure dependence of his equation is the same as the porosity term, cubic. This yields the same pressure dependence as the Kozeny relation we have presented in this paper. However, it differs from our equation in that it requires porosity to close with pressure without any change in mean hydraulic radius (i.e., S in Eq. (2) of this report is a constant).

The correlation of velocity data with permeability is very encouraging. Further results and progress will be mainly dependent on the availability of detailed permeability data, a reconsideration of the geometrical aspects and general applicability of the Kozeny relation to crystalline rock and determination of how the relatively small crack porosity controls the coupling of larger pore porosity.

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TABLE I
GRANODIORITE 8581

Data Versus Model 8581-71576-IV
(Pressure in kbars, Moduli in kbars)

Pressure	C ^a	N.S.C.	Δ%	Pressure	G ^a	N.S.C.	Δ %
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

^aLegend for Table I

C : Compressional modulus ($V_p^2 \rho$)
G : Shear modulus
 ω_0 : Porosity at zero pressure
a/b : Pore aspect ratio
(Major to minor axis)
N.S.C.: Non-self-consistent
Theoretical calculation
S.C. : Self-consistent
Theoretical calculation
Δ% : Percent deviation
 ν_0 : Mineralogical Poisson's ratio

Model parameters

$G_0 = 380$
 $\nu_0 = 0.25$

a/b	ω_0
1	0.010
90	0.001
500	0.0007
1900	0.0004

TABLE II

WESTERLY GRANITE

Data Versus Model WG 71476-I
(Pressure in kbars, Moduli in kbars)

Pressure	$C^{a,b}$	N.S.C.	$\Delta\%$	$G^{a,b}$	N.S.C.	$\Delta\%$
0.0	443	562	+26.7	200	228	+14.0
0.1	596	590	- 1.0	240	273	+13.7
0.4	749	692	- 7.6	280	266	- 5.0
0.7	809	789	- 2.5	290	291	+ 0.3
1.0	859	852	- 0.8	300	306	+ 2.0
2.0	894	898	+ 0.4	310	316	+ 1.9
3.0	940	950	+ 1.0	320	327	+ 2.2
5.0	983	997	+ 1.4	333	336	+ 0.9
10.0	1038	1007	- 3.0	340	337	- 0.9

Pressure	K_s^c	S.C.	$\Delta\%$		
0.0	120	124	+ 3.3		
0.1	185	195	+ 5.4	Model parameters	
0.2	263	249	- 5.3	$G_0 = 341.65$	
0.5	346	356	+ 2.9	$\nu_0 = 0.248$	
1.0	407	434	+ 6.6	a/b	w_0
2.0	463	477	+ 3.0	1	0.006
3.0	485	519	+ 0.7	120	0.0009
5.0	503	550	+ 9.3	200	0.0016
7.0	518	557	+ 7.5	850	0.001
9.0	535	557	+ 4.1	2000	0.0001

^aLegend for Table II

C	: Compressional modulus ($V_p^2 \rho$)	N.S.C.:	Non-self-consistent
G	: Shear modulus		Theoretical calculation
w_0	: Porosity at zero pressure	S.C.:	Self-consistent
a/b	: Pore aspect ratio (Major to minor axis)		Theoretical calculation
ν_0	: Mineralogical Poisson's ratio	$\Delta\%$	: Percent deviation

^bFrom Simmons and Brace, 1965. $\rho = 2.65$ ^cFrom Brace, 1965.

APPENDIX A

TABLE A-1

Shear Wave Velocity Data

GT2-8581		GT2-9519	
Pressure (bar)	Velocity (km/sec)	Pressure (bar)	Velocity (km/sec)
110	3.15	95	3.27
315	3.34	240	3.37
415	3.44	485	3.43
1010	3.61	980	3.47
1470	3.68	1980	3.53
2020	3.63	3015	3.57
4040	3.67	3600	3.62
5040	3.70	3970	3.66
5800	3.71	5000	3.69
4970	3.68	5950	3.73
3000	3.68	5000	3.69
2000	3.66	3990	3.70
1020	3.57	2045	3.55
775	3.54	1020	3.46
540	3.50	515	3.41
270	3.40	115	3.33
110	3.26		
60	3.20		
0	3.12		

APPENDIX A

TABLE A-2

Compressional Wave Velocity Data

GT2-8581		GT2-9519 (1st V _p run)	
Pressure (bar)	Velocity (km/sec)	Pressure (bar)	Velocity (km/sec)
0	5.09	0	5.94
55	5.13	30	5.98
100	5.27	190	6.20
240	5.59	480	6.25
490	5.95	1000	6.25
980	6.17	3035	6.43
1500	6.24	5075	6.44
2000	6.27	6500	6.50
3560	6.31	4980	6.46
5010	6.36	2995	6.37
7030	6.39	1950	6.24
5000	6.34	1010	6.22
3280	6.31	410	6.14
2020	6.25	210	6.12
1530	6.24	100	6.04
1020	6.15	40	5.90
520	5.97	0	5.85
250	5.67		
100	5.37		
40	5.30		

APPENDIX A

TABLE A-2 (Cont.)

Compressional Wave Velocity Data

GT2-9519 (2nd V_p run)		GT2-9519 (3rd V_p run)	
Pressure (bar)	Velocity (km/sec)	Pressure (bar)	Velocity (km/sec)
0	5.45	30	5.43
100	5.85	100	5.65
250	5.98	250	5.75
495	6.05	495	5.84
980	6.09	990	5.90
2050	6.13	2010	6.06
3020	6.14	3015	6.07
4005	6.18	4020	6.15
5005	6.25	5010	6.25
5500	6.31	3995	6.23
5020	6.29	2995	6.15
4000	6.24	2000	6.00
3030	6.21	1010	5.90
2020	6.06	485	5.78
1010	5.96	255	5.77
510	5.93	100	5.75
250	5.91	10	5.44
95	5.85		
40	5.81		

APPENDIX A

TABLE A-2 (Cont.)

Compressional Wave Velocity Data

GT2-9519 (4th V _p run)		GT2-9519 (5th V _p run)	
Pressure (bar)	Velocity (km/sec)	Pressure (bar)	Velocity (km/sec)
0	5.44	10	5.41
35	5.66	50	5.70
75	5.75	100	5.80
100	5.80	245	5.85
245	5.89	495	5.92
495	5.95	655	5.96
755	5.99	1010	6.02
1000	6.03	1250	6.09
1255	6.06	1505	6.07
1510	6.07	1745	6.11
1750	6.13	2015	6.13
2010	6.14	2520	6.16
2515	6.19	3000	6.20
3010	6.21	3510	6.21
3500	6.27	4005	6.27
3000	6.28	4490	6.30
2490	6.23	3500	6.32
1995	6.13	3000	6.29
1745	6.09	2500	6.26
1500	6.07	2000	6.13
1250	6.06	1750	6.07

APPENDIX A

TABLE A-2 (Cont.)

Compressional Wave Velocity Data

GT2-9519 (4th V _p run cont.)		GT2-9519 (5th V _p run cont.)	
<u>Pressure (bar)</u>	<u>Velocity (km/sec)</u>	<u>Pressure (bar)</u>	<u>Velocity (km/sec)</u>
1000	6.03	1500	6.09
755	6.02	1250	6.07
500	5.95	995	6.06
260	5.89	750	5.99
100	5.85	500	5.92
45	5.79	260	5.89
		100	5.85
		45	5.77

Fig. 1. Compressional (V_p) and shear (V_s) velocities versus pressure for granodiorite GT-2-8581.

Fig. 2. Volumetric strain versus pressure for granodiorite GT-2-8581.

Fig. 3. Change in compressional velocity - pressure profile for sample GT-2-9519, over a series of 5 cycles. Successive runs are stacked downward. The data are stacked for clarity and do not represent a large decrease in absolute values of V_p .

Fig. 4. Compression (V_p) and shear velocities (V_s) versus pressure for GT-2-9519.

Fig. 5. Volumetric strain versus pressure for GT-2-9519.

Fig. 6. Comparison of Functional terms of $\log C (C = V_p^2 \rho)$ versus $\log$ pressure for GT-2-9519, GT-s-8581, and Westerly granite. The data are stacked and do not represent large differences in absolute value.

Fig. 7. Model comparisons to Westerly granite data. $C = V_p^2 \rho$, $G = V_s^2 \rho$, K_d = dynamic bulk modulus, K_s = static bulk modulus. Data and references given in Table II.

Fig. 8. Comparison of model porosity versus aspect ratios to observed porosity and aspect ratios (after Hadley, 1976). Percent porosity is percent of total porosity. Spherical pore porosities ($\alpha = 1$) are not plotted. Stippled bars are Hadley's observed distribution. Solid bars are model parameter distributions.

Fig. 9. Static and dynamic bulk moduli for 8581 and Westerly granite (Westerly granite data from Schock et al., 1974).

Fig. 10. Permeability and the cubic function of acoustic data versus pressure for Westerly granite (permeability data from Brace et al., 1968), (Velocity data from Schock et al., 1974).

Fig. 11. Permeability and the cubic function of acoustic data versus pressure for GT-2-8580/8581 (permeability data on 8580) from J. Potter, personal communication.

Fig. 12. Permeability and the cubic function of acoustic data versus pressure for GT-2-9522/9519 (permeability data on 9522) from J. Potter, personal communication.