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VESIAC State-of-the-Art Report

SOUND VELOCITIES IN ROCKS AND MINERALS

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Figures in this report were adapted from the following sources: figure 1 from D. Bancroft, Physical Review, Vol. 59, 1941, pp. 588-593, Fig. 1; figure 3 from F. Birch, American Mineralogist, Vol. 35, 1950, pp. 644-650, Fig. 1; figures 4, 6, 17, and 19 from F. Birch, Journal of Geophysical Research, Vol. 65, 1960, pp. 1083-1102, Figs. 1, 2, 3, and 5; figures 5, 7, and 18 from G. Simmons, Journal of Geophysical Research, Vol. 69, 1964, pp. 1123-1130, Figs. 2, 3, and 5; figure 8 from G. Simmons, Proceedings of the Institute of Electrical and Electronics Engineers, Vol. 53, No. 10, pp. 1337-1346, Fig. 5; figure 16 from D. Tocher, Transactions of the American Geophysical Union, Vol. 38, 1957, pp. 89-94, Fig. 6; figure 20 from T. J. Ahrens and S. Katz, Journal of Geophysical Research, Vol. 68, 1963, pp. 529-537, Fig. 6; figure 21 from D. S. Hughes and C. Maurette, Revue de'Institut Francais du Petrole et Annales Combustibles Liquides, Vol. 12, 1957, pp. 730-752, Fig. 9; figure 22 from J. Ide, Journal of Geology, Vol. 45, 1937, pp. 689-716, Fig. 4; figure 23 from F. Birch, Bulletin of the Geological Society of America, Vol. 54, 1943, pp. 263-286, Fig. 4; figures 25 and 26 from H. J. McSkimin, Journal of the Acoustical Society of America, Vol. 31, 1959, pp. 287-295, Figs. 2 and 9.

PREFACE

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ABSTRACT

This state-of-the-art report summarizes experiments and data on sound velocities in rocks and minerals and projects useful lines of research. The report discusses in detail the three common measuring techniques now employed: (1) resonance methods, (2) pulse-transmission methods (time-of-flight), and (3) ultrasonic-interferometric methods.

Promising techniques, both direct and indirect, are described; the most important of these is the resonance of small spheres. Methods of estimating elastic constants at high pressure and high temperature are indicated.

The data extant on the sound velocities in rocks and minerals are considerable and are tabulated in several appendixes. The lack of systematic coverage and quality of these data are discussed.

A method of estimating unmeasured properties in a class of rocks, using data already reported for that class, is reviewed. Techniques of estimating isotropic sound velocities from single-crystal elastic-constant data are reviewed.

CONTENTS

FIGURES

TABLES

SYMBOLS

a, b, c	Crystallographic axes
C_{ij}	Elastic constants
C_o	Bulk sound velocity
C_p	Specific heat at constant pressure
d	Diameter
E	Young's modulus
f	Natural frequency
h	Planck's constant
H	Enthalpy
k	Boltzmann's constant
$K = B_s$	Bulk modulus
ℓ	Length of specimen
m	Mass
M	Molecular weight
$\bar{n}$	Mean index of refraction
N	Avogadro's number
p	Number of atoms in the formula
P	Pressure
Q	Quality factor whose inverse is a measure of the damping
S_{ij}	Elastic compliances
t	Time
V_m	Mean sound velocity
$V_p = V_D$	Velocity of compressional waves
$V_s = V_R$	Velocity of shear waves
Z	Critical parameter
α, β, γ	Angles between crystallographic axes
γ	Gruneisen's constant
θ	Debye temperature; thermal (θ_t) or acoustic (θ_a)
λ	Wavelength
μ	Shear modulus
ρ	Density
σ	Poisson's ratio

SOUND VELOCITIES IN ROCKS AND MINERALS

1
INTRODUCTION

Geophysics and certain other fields of geology have the task of correlating field measurements of seismic velocity (i.e., in situ measurements of sound velocity) with laboratory measurements of sound velocity taken on isolated rocks and minerals. The goal of this task is a better understanding of the structure and history of the earth's interior and crust and the development of techniques to solve geologic problems. This task is important because sound velocity is one of the few experimental properties measurable at depth in the earth.

Section 2 of this report is a survey of the experimental techniques now employed which are used with confidence by experimentalists. Section 3 discusses several methods which are presently being explored and have promise of becoming standard methods; some ideas of extrapolation to higher pressures and temperatures are indicated. Section 4 discusses the status of the field and includes a review of a new method of correlating existing data on rocks to predict unmeasured properties with an example of its use on basalts. The data are presented in the appendixes, which allow the reader to retrieve data in various ways: velocity vs. temperature, velocity vs. pressure, mineralogical and petrological content, references, and single-crystal data on important minerals. These appendixes are included as a reference for researchers in the field.

While this state-of-the-art report was being completed, Dr. Gene Simmons kindly sent us an advance copy of a review paper entitled "Ultrasonics in Geology." Since readers of this report will have access to that review, certain topics covered by Simmons have been de-emphasized here. Therefore, several topics receive less attention in this report than their importance would otherwise warrant. In particular, we do not emphasize greatly the pulse-transmission technique, since much of Simmon's review is concerned with that technique alone. The reader will also find that there is a certain amount of overlap between the two reviews: this was unavoidable in presenting a balanced picture of the present state of the art. In this report, all of section 3, most of section 4, and the appendixes represent topics not covered by Simmons' review.

2
TECHNIQUES

2.1. GENERAL

Three basic types of methods are now used to measure sound velocity directly or indirectly through the measurement of elastic constants: (1) resonance methods, in which the specimen is somehow induced to vibrate at its natural resonance frequencies; (2) pulse-transmission (time-of-flight) methods, in which the transit time of a high-frequency pulse through a dimension of the specimen is measured; and (3) ultrasonic-interferometry methods, in which internal reflections of the same wave train are made to interfere so that a null, or pseudo-resonance, can be achieved by suitably controlling the wavelength of the imposed pulse.

The choice of method depends upon the circumstances of the experiment, such as the size and quality of the specimen, the electronic resources of the apparatus, and the personal preferences of the experimenter. The best compromise found by F. Birch and his colleagues for most rocks is the pulse-transmission method. With this technique, sound velocities have been measured versus pressure and temperature even on field specimens. On the other hand, resonance and interferometric techniques have proved to be the most reliable for single crystals, synthetically prepared polycrystalline aggregates, and fine-grained, low-porosity rocks. The cogent details of each method are summarized in table I.

The common choice of specimens until recently has been between rocks and gem-quality minerals. Multiple reflections at high frequency cannot be obtained from rocks because of the low quality of the specimen; therefore, the method used must be either resonance or pulse transmission. For gem-quality crystals, ultrasonic interferometry is commonly used (resonance is used in a few cases) because a higher accuracy can be achieved than with pulse transmission. High accuracy is required because of the strong dependence of sound velocity on direction, even in isometric single crystals.

Difficulties arise in correlating single-crystal constants with the isotropic values of sound velocity, V_p and V_s, which are the desired quantities in geophysics. There is a practical difficulty stemming from the immense amount of basic data required to determine the variation of the elastic constants of a low-symmetry crystal with pressure and temperature. A theoretical difficulty stems from the need for considerable mathematical dexterity in crystal tensor analysis for the proper interpretation of these data.

There is now, however, a third choice. Because of recent advances in ceramic technology, it is possible to prepare a polycrystalline specimen of a mineral which approaches gem quality. On such a specimen, the variation of V_p and V_s with pressure and temperature can be deter-

mined by using ultrasonic interferometry to a precision that cannot be achieved by pulse transmission. Such a synthetically prepared aggregate avoids the theoretical difficulty of integration of single-crystal determinations and the experimental difficulties attending the measurements of velocity on rocks versus pressure and temperature. Using this method, the values of V_p and V_s have been determined up to 4 kb and up to 1500°C on periclase and corundum. These difficulties are avoided, however, at the price of another: obtaining a suitable synthetic specimen.

TABLE I. SUMMARY OUTLINE OF TECHNIQUES FOR MEASURING SOUND VELOCITIES

Method	Frequency	High Pressure	High Temperature	Accuracy
Resonance				
Resonance of Cylinders and Prisms $V = 2\ell f/n$	1-30 kc/s	V_p, No V_s, Yes	Yes	5%
Composite Oscillator $V = 2\ell f/n$	90-250 kc/s	No	Yes	1-2%
Wedge $V = 2\ell f$	1-12 Mc/s	No	No	5%
Pulse Transmission				
Variable Delay Line $V = \ell/t$	50 kc/s to 10 Mc/s	Yes	Yes	1-3%
Pulse Echo $V = 2\ell/t$	10 Mc/s	Yes	No	0.5%
Total Internal Reflection $V = V_{liq}/(\sin i_c)$	1-5 Mc/s	P < 2kb	No	0.5-1.0%
Ultrasonic Interferometry				
Phase Comparison $V = 2\ell f_n/(n + \gamma/2\pi)$	10-60 Mc/s	Yes	Yes	0.01%
Pulse Superposition $V = 2\ell/\sigma$	10-60 Mc/s	Yes	Yes	0.04%

2.2. RESONANCE METHODS

2.2.1. RESONANCE VIBRATIONS OF CYLINDERS AND PRISMS. For many years the elastic properties of materials were determined by various static experiments: bending, twisting, compressing, or otherwise deforming a specimen. These methods proved satisfactory for metals and glasses, but were unreliable for rocks because of an appreciable inhomogeneity

of composition, texture, etc. Ide [1] introduced the dynamic method of resonance vibrations of cylindrical specimens in various modes: extensional, flexural, and torsional. The resonance method is a standing-wave phenomenon based upon the principle of an open organ pipe in which the length contains an integral number of half-wavelengths, $\ell = n(\lambda/2)$. The phase velocity of the wave is then $V = \lambda f = 2\ell f/n$ or $V = 2\ell f$ for the fundamental frequency. Birch [2] included a correction factor: $V = 2\ell f/(1 + \alpha)^{1/2}$.

The principal modes of vibration are the extensional, the flexural, and the torsional. Cylindrical specimens are commonly used to avoid shape corrections due to nonuniform cross-sections. Pochhammer [3] and Love [4] have derived theoretical expressions to describe the motion for the extensional and torsional modes of vibration of thin cylindrical rods. For the torsional mode, the velocity is always that of a shear wave traveling in an unbounded medium $(\mu/\rho)^{1/2}$, and these theoretical solutions apply rigorously regardless of the length of the rod, even when it is so short as to become a disk [5]. Although the fit to the theoretical solution is not as precise for the extensional mode, it has been shown experimentally [6] that if the length-to-diameter ratio (ℓ/d) is greater than 5 or 6 the wave travels with the "bar velocity," $(E/\rho)^{1/2}$, of the Pochhammer-Love solution within a negligible error.

Bancroft [5] and Silaeva and Shamina [7] have discussed the effect of the diameter-to-wavelength ratio (d/λ) upon the motion. There is no dispersion for the torsional mode, but experimental results for the extensional mode agree with the Pochhammer-Love theory only for $d/\lambda < 1.4$ (see fig. 1). As $d/\lambda \to \infty$, the velocity approaches the Rayleigh-wave phase velocity. For these reasons and others of a practical nature, the frequency range used is on the order of 1 to 30 kc/s.

The energy necessary to induce the vibrations is coupled into the specimen via a transducer (electromagnetic, magnetostrictive, electrostatic, piezoelectric). The receiver may be located at either end of the specimen or may be slid along the rod to locate the position of the nodes and antinodes of the wave.

Measurements may be made on jacketed specimens in a pressure medium and at high temperatures. The motion of the extensional modes is damped at high pressures, but the torsional modes are unaffected.

The equipment is simple to construct and fairly accurate. It is possible to work with very porous aggregates, although the specimens must be uniform in the direction of the axis of the cylinder [8]. Errors, including uncertainties due to grain size and porosity, limit the accuracy to $\pm 5\%$, but the method has been most useful for obtaining V_s of rocks at high temperatures and pressures.

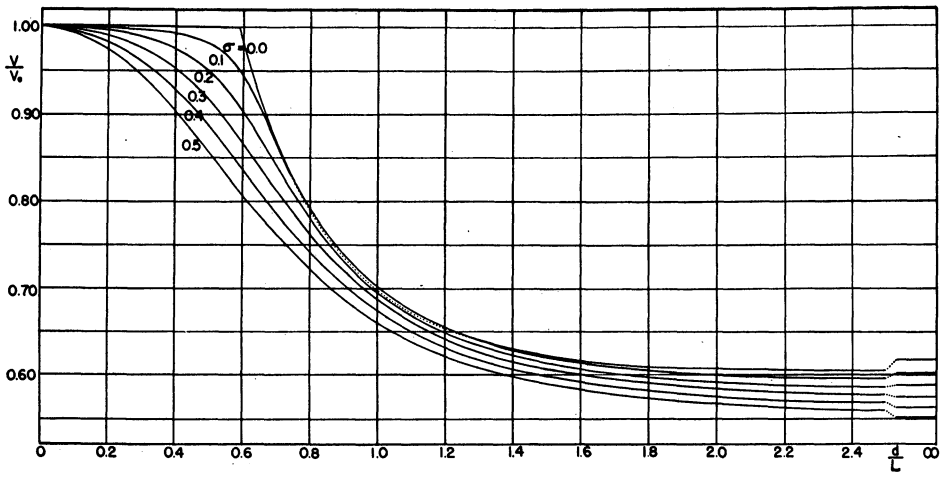

FIGURE 1. V/V_0 AS A FUNCTION OF d/λ FOR VARIOUS σ IN THE RESONANT EXTENSIONAL VIBRATIONS OF THIN CYLINDERS. V_0 = bar velocity = $(E/\rho)^{1/2}$, d = diameter of rod, L = λ = wavelength, σ = Poisson's ratio [5].

The corrections which must be made for measurements made on cylindrical specimens are simple. However, resonant measurements in ceramic and metallurgical research have in general been made on rectangular prisms, using the commonly referred to Förster's method which requires rather detailed shape corrections [9].

All equipment and techniques for measuring the mechanical resonance frequencies of prismatic specimens are described in detail by Spinner and Tefft [10], Wachtman and Tefft [11], and others.

One disadvantage of this method arises from the limitation on the size of the specimen. When the length is less than 3 in., the torsional fundamental resonance frequency of a material having high elastic moduli, such as Al_2O_3, MgO, or SiC, exceeds 40 kc/s, so special equipment and experimental techniques are required to obtain accurate results. Moreover, all three dimensions (length, width, and thickness) are critically involved in the calculation of the elastic moduli from the resonance frequency. From a practical point of view, it is quite difficult to fabricate small specimens with a uniform cross-sectional dimension.

Another problem to be considered is the shape-correction factor in the equation relating the elastic moduli to the resonance frequency. Although the value computed from Pickett's theoretical equation [9] agrees fairly well with the empirically determined value when the ratio of cross-sectional width to depth is near 1, the former gives a higher value than the latter by about 1.8% when the ratio approaches 10 [12]. A similar difference in the correction factor between the empirical and theoretical relations has been obtained when the depth-to-length

ratio is increased [13]. Therefore, it has been recommended that for rectangular specimens the ratio of length to either cross-sectional dimension should not be less than 3 to 1 [10]. When an accuracy within 0.1% is required, the ratio is preferably not less than 6 to 1. Therefore, it is difficult to determine the elastic moduli of specimens in massive structure.

One advantage of the resonance method is its applicability to measurements of the elastic constants at high temperature. There are many reports available on the temperature dependence of the elastic constants of ceramic compounds such as Al_2O_3, MgO, ThO_2, etc. [14-17]. Such data not only provide knowledge of elastic properties at elevated temperature, but also are necessary to determine other physical constants, such as the Gruneisen constant at high temperature, which is an important parameter in the theory of thermodynamics. To determine the Gruneisen constant, very accurate data on the temperature dependence of bulk modulus are required. Since the bulk modulus is determinable only indirectly from the data of Young's modulus and the shear modulus, a little discrepancy in these elastic moduli between two data obtained by different investigators could represent a large difference in the values of bulk modulus.

The use of resonance techniques such as Förster's method to determine elastic constants is well known to metallurgists and ceramic engineers. It has not been used extensively in the geological sciences. Its feasibility has been demonstrated recently by results on synthetically prepared polycrystalline aggregates of MgO and Al_2O_3. To prove the point, we now review some work recently completed by Anderson and Soga [18].

Hot-pressed specimens of polycrystalline MgO and Al_2O_3 were supplied by Avco Corporation. Two rectangular bars of different sizes, approximately $9.7 \times 1.6 \times 0.9$ cm and $9.0 \times 0.9 \times 0.6$ cm, were cut from a disk specimen. The bulk densities of the specimens were obtained from the mass and volume calculated from the dimensions. The elastic moduli were determined by the dynamic resonance method using Magnatest Elastomat Type FM-500. Young's modulus was computed independently from the flexural flatwise and edgewise vibrations, and the shear modulus was computed from the torsional vibration. The correction to elastic moduli for size, shape, and Poisson's ratio was made by using the equations and tables presented by Spinner and Tefft [10]. The results are shown in table II. In figure 2, Young's modulus and shear modulus of polycrystalline Al_2O_3 are given as a function of porosity of the specimen. The scatter of the data probably results from the inhomogeneity of the specimen. To ensure the extrapolation of these values to the zero porosity, the elastic moduli of another polycrystalline Al_2O_3 having higher density were measured. This is a specimen known as "Lucalox," commercially sold by General Electric; it has cylindrical shape, so the corrections for shape and Poisson's ratio are simplified. The figure includes these data.

TABLE II. ELASTIC CONSTANTS OF POLYCRYSTALLINE MgO AND Al_2O_3 DETERMINED BY RESONANCE METHOD [18]

Specimen No.		Density (g/cm^3)	Porosity (%)	Young's Modulus (kb) Flatwise	Young's Modulus (kb) Edgewise	Shear Modulus (kb)
MgO	1	3.581	0.06	3097	3090	1306
MgO	2	3.572	0.31	3092	3060	1304
MgO	3	3.567	0.45	3087	3076	1301
Al_2O_3	5	3.941	1.13	3850	3864	1579
Al_2O_3	6	3.923	1.58	3700	3729	1507
Al_2O_3	7	3.913	1.83	3732	3768	1520
Al_2O_3	8	3.865	3.04	3545	3556	1445
Al_2O_3	9	3.843	3.59	3342	3382	1373
Al_2O_3	10	3.801	4.62	3447	3463	1408
Al_2O_3	11	3.787	5.00	3249	3299	1335
Al_2O_3 Lucalox	12	3.972	0.35	3986*	3981*	1616

*The values are from the fundamental mode, first overtone, and second overtone of flexural vibration.

The extrapolation of Young's modulus to the zero porosity gives the value of 3100 kb for MgO and 4020 kb for Al_2O_3; that of the shear modulus gives 1305 kb for MgO and 1640 kb for Al_2O_3. Table III compares these values with data reported by various investigators. The agreement is quite good.

Table IV compares the elastic constants of polycrystalline Al_2O_3 and MgO obtained by the resonance method with the results obtained on the same specimens by the ultrasonic-interferometry method (sec. 2.4). The agreement of the data seems excellent, especially for the specimen Al_2O_3 (I); this was ideal for the comparison because it was fabricated uniformly with less than 0.5% porosity and because it was cylindrical so that no shape correction for shear modulus and little correction for Young's modulus are required in the resonance technique. This proves that the bar resonance method is quite adequate to obtain elastic constants with high precision. Once both Young's modulus and the shear modulus are known, the velocities of sound can be computed from the standard equations given in table V.

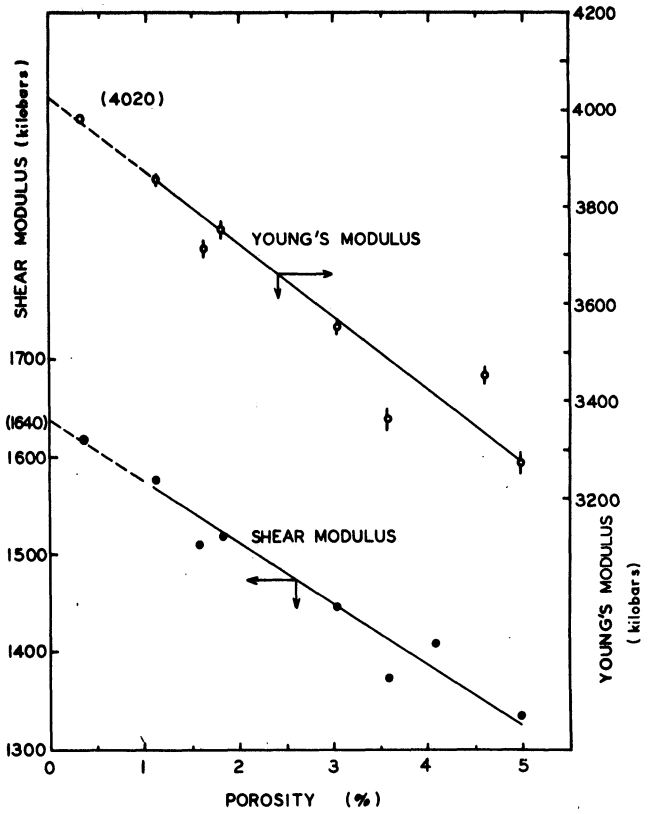

FIGURE 2. ELASTIC MODULI OF POLYCRYSTALLINE Al_2O_3 AS A FUNCTION OF POROSITY [18, 19]

TABLE III. ELASTIC MODULI OF PORE-FREE POLYCRYSTALLINE MgO AND Al_2O_3 [18]

	MgO		Al_2O_3	
Reference	Young's Modulus	Shear Modulus	Young's Modulus	Shear Modulus
Spriggs et al. [20, 21]	3178	1395	4060	--
Chung et al. [22, 23]	3050	1290	4050	1650
Knudsen [24]	--	--	4102	--
Anderson and Soga [18]	3100	1305	4020	1640

TABLE IV. ELASTIC CONSTANTS OF POLYCRYSTALLINE Al_2O_3 AND MgO DETERMINED BY VARIOUS TECHNIQUES

Modulus (kb)	MgO (II) Avco D64B Sample 1 ρ = 3.572		Al_2O_3 (I) GE Lucalox Sample 12 ρ = 3.972		Al_2O_3 (II) Avco 1495A Sample 5 ρ = 3.941	
	Ultrasonic Interferometry	Resonance	Ultrasonic Interferometry	Resonance	Ultrasonic Interferometry	Resonance
Young's	3053	3080	3988	3985	3903	3853
Shear	1286	1304	1613	1616	1583	1575
Bulk	1624	1611	2516	2487	2436	2318

TABLE V. RELATIONSHIP BETWEEN SOUND VELOCITIES AND ELASTIC MODULI OF ISOTROPIC BODIES

	K & μ	K & E	K & σ	E & σ	E & μ
ρV_p^2	$K + \frac{4}{3}\mu$	$3K\frac{3K + E}{9K - E}$	$3K\frac{1 - \sigma}{1 + \sigma}$	$\frac{E(1 - \sigma)}{(1 + \sigma)(1 - 2\sigma)}$	$\mu\frac{4\mu - E}{3\mu - E}$
ρV_s^2	μ	$3K\frac{E}{9K - E}$	$3K\frac{1 - 2\sigma}{2 + 2\sigma}$	$\frac{E}{2 + 2\sigma}$	μ

2.2.2. COMPOSITE OSCILLATOR. The composite-oscillator method applies the basic principles of the method of resonant vibrations of cylinders to single-crystal or polycrystalline specimens. Balamuth [25] and Rose [26] have developed the theoretical basis for this method, and Birch [27] has outlined their work: if a crystal specimen (mass = m_1, resonant frequency = f_1) is cemented to a piezoelectric crystal of the same cross section (mass = m_2, resonant frequency = f_2), the resultant "composite oscillator" will have a resonant frequency f given [26] by:

$$m_1 f_1 \tan \pi(f/f_1) + m_2 f_2 \tan \pi(f/f_2) = 0 \qquad (1)$$

If f, f_1, and f_2 are nearly equal ($\pm 10\%$), then equation 1 simplifies ($\pm 2\%$) to [27]:

$$f_1 = f + (f - f_2)\frac{m_2}{m_1} \qquad (2)$$

If f and f_2 can be measured, then f_1 may be obtained from equation 2. Compressional- and shear-cut piezoelectric crystals are used to excite the extensional and shear vibrational modes.

For the extensional mode, $V = 2f_1 \ell = (E/\rho)^{1/2}$; as in the resonance method, the propagation velocity is distorted if $\ell/d < 5$ [5], but Birch [27] estimates the error to be less than 1% for $\ell/d > 2$. There are no such conditions for the shear mode in which the velocity corresponding to the fundamental frequency is $V_s = (\mu/\rho)^{1/2}$. The shape of the cross section is not important for the extensional mode, but the shear mode becomes complicated for shapes other than circular cylinders [28]. X-cut quartz bars of square cross section with two electrodes are thus convenient for the extensional vibrations, while Y-cut quartz rods of circular cross section with four electrodes are most useful for the shear mode.

An alternating potential applied to the electrodes in the piezoelectric crystals induces the required vibrations in the composite oscillator. The range of frequencies employed in this method is 90 to 250 kc/s, depending upon the natural frequency of the specimen. Occasionally, the specimen is driven at an overtone for convenience, but too large a ratio of m_2 to m_1 exaggerates the frequency difference $(f - f_2)$ in equation 2 [27]. The resonant frequency of the freely vibrating composite oscillator is determined by monitoring the electrical impedance between the electrodes (see fig. 3). This impedance exhibits a sharp decrease at the resonant frequencies.

This method can be used on single-crystal specimens as small as a few millimeters in length with an accuracy of 1% to 2% and is readily adaptable to measurements at high temperatures. However, it requires the use of a set of quartz crystals of various lengths so that the frequency of the composite oscillator falls near f_1 and f_2. This method has not been used for measurements at elevated pressures.

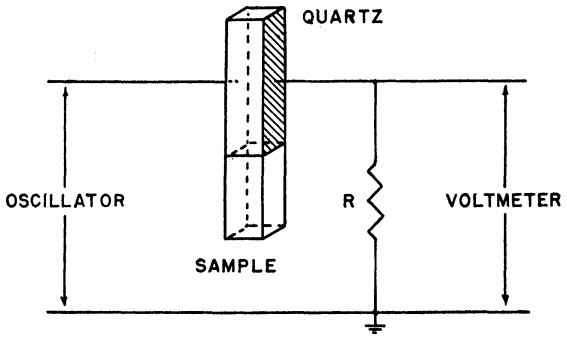

FIGURE 3. SCHEMATIC DIAGRAM FOR THE CIRCUIT OF THE COMPOSITE OSCILLATOR [27]

2.2.3. WEDGE. The composite-oscillator method requires a set of quartz crystals of various lengths to provide a range of frequencies. Since the resonant frequency of a piezoelectric crystal is inversely proportional to its length, a crystal wedge provides a source of continuously varying frequency in one crystal. Bhagavantam and Bhimasenachar [29] have adopted the use of X-cut quartz and Y-cut tourmaline wedges (f = 1 to 12 Mc/s) for this purpose. Bhagavantam [30] provides an outline of this method. The piezoelectric crystal and the specimen are juxtaposed between two electrodes, forming a parallel plate condenser. This condenser is then placed in a glass cell with the lower plate just touching the surface of a liquid medium such as carbon tetrachloride. As the electrical oscillator excites the wedge, an ultrasonic beam passes through the specimen and into the liquid. The transmitted beam is observed by means of the Debye-Sears diffraction effects. The points of maximum intensity in the pattern correspond to the resonant frequencies of the crystal specimen. As in the other methods, the velocities of the elastic waves are then calculated from $V = 2f_e\ell$ and $V_s = 2f_s\ell$, corresponding to the bar $(E/\rho)^{1/2}$ and the shear $(\mu/\rho)^{1/2}$ velocities, respectively.

This method is capable of determining velocities within 5% [30] and is suitable for work on single crystals and fine-grained, low-porosity rocks or polycrystalline aggregates of single crystals. It requires only small specimens but is not suitable to work at high pressures or temperatures. Sundara Rao [31] has raised some doubts about the use of wedges because of spurious peaks in their emitted spectra. Since the resonant points are determined by monitoring the intensity of the transmitted beam, errors will be introduced if all frequencies in the piezoelectric crystal are not excited equally.

2.3. PULSE-TRANSMISSION METHODS

2.3.1. THE VARIABLE DELAY LINE. The ultrasonic-pulse-transmission technique is based upon the creation of a short train of high-frequency vibrations and the measurement of its propagation time through the specimen. Attempts prior to World War II [32] to use travel times of pulses failed because of the lack of adequate electronic equipment [33]. The development of pulse circuitry and fast-writing oscilloscopes during the war-time research and the studies at the Bell Telephone Laboratories of the piezoelectric properties of crystals made this method feasible [34].

The pulses (50 kc/s to 10 Mc/s) are generated by crystal transducers attached to the specimen (see fig. 4). The pulse transmission time (or "time of flight") is measured by direct observation of the time between the "shot" and the arrival of the pulse or by matching the onset of the pulse transmitted through the specimen with that of a pulse transmitted through a

variable-length mercury delay line (see fig. 5). Simmons [36] has an excellent discussion of the advantages and disadvantages of the various transducers (ceramic and single crystal) used to generate the compressional- and shear-wave pulses.

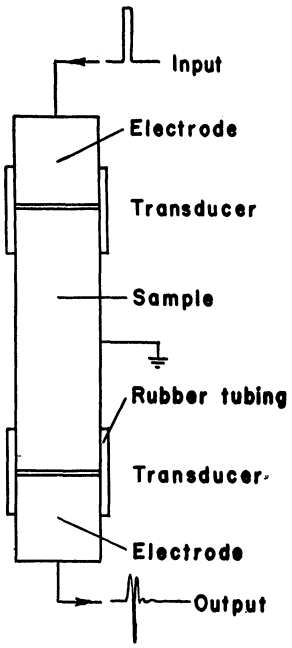

FIGURE 4. ARRANGEMENT OF THE SPECIMEN AND TRANSDUCERS FOR THE PULSE-TRANSMISSION TECHNIQUE [33]

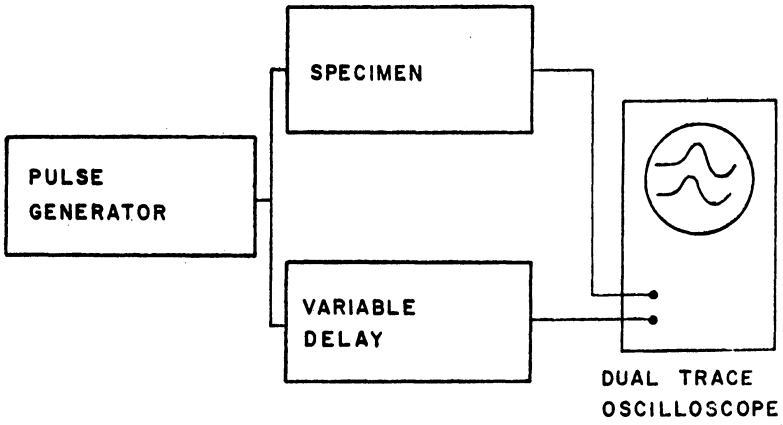

FIGURE 5. SCHEMATIC DIAGRAM FOR THE VARIABLE-DELAY-LINE METHOD OF PULSE TRANSMISSION [35]

There are certain theoretical and practical considerations when designing an experiment using the pulse-transmission technique [7, 33]. Love [4] showed that the first motion resulting from an arbitrary disturbance in an isotropic medium is propagated with the velocity of compressional plane waves in an unbounded medium, $\left(\frac{K + 4\mu/3}{\rho}\right)^{1/2}$. A number of investigators have experimentally verified this by comparing the observed V_p with that calculated from independently measured elastic constants [7, 33, 37-39].

The most convenient shape for the specimen is a right circular cylinder. For clear observation of the compressional arrival the length-to-diameter ratio ℓ/d should be less than about 5 [40]; as ℓ/d increases, more of the initial compressional energy is delayed by boundary reflections and eventually V_p recedes into the noise level, and the observed first arrival travels

with the bar velocity $(E/\rho)^{1/2}$ [33]. It has been determined experimentally [41] that the diameter-to-wavelength ratio (d/λ) must be greater than about 5 to minimize dispersion for the compressional pulse. When the wavelength becomes less than about three times the diameter of the grains in the specimen, the energy is scattered and the pulse becomes distorted [37]. Within the range of these dimensional restrictions, the compressional-wave velocity is found to be independent of the frequency of the transmitted pulse [42-44]. There is no dispersion predicted or observed for pulses generated by the shear-wave transducers.

Much of the work using the pulse-transmission technique has dealt only with the first arrival (either compressional or shear, depending upon the transducer). Iida and Kumazawa [45, 46] used the direct second arrival to determine V_s without much success. Hughes et al., [39] determined V_s by using a secondary arrival, the so-called PSP phase, which accompanies a P wave traveling longitudinally in a cylinder. Part of the P-wave energy is converted to S-wave energy at the cylinder wall, traverses the cylinder obliquely as an SV wave, and is reconverted to P at the opposite wall. The delay time (PSP - P) of this phase depends only upon V_p, V_s, and d, so its determination leads directly to a value for V_s. This method has proved somewhat satisfactory for metals, limestones, marbles, and quartzites, but for coarse-grained rocks there are serious errors in the transformed pulse caused by interference and reflection at grain boundaries [47]. The precision of these measurements is low (good to two significant figures at best) because of a low signal-to-noise ratio and the remaining P motion [36]. The amount of pulse distortion is increased at high pressures [48]. Finally, unless the medium is isotropic and uniform, there is no unique delay time for the secondary arrival [33], but it does give a rough idea of V_s while measuring V_p [36]. This P-S conversion used for the PSP arrival is found to be negligibly small for $d/\lambda > 20$ [37]. For the measurement of V_s itself, see reference 35.

The pulse-transmission technique has been used extensively in the last 15 years because it does not require homogeneous or isotropic specimens, can be used for porous specimens, and is readily adaptable for measurements at high pressures and temperatures. Chick of Brown University is presently working on modifications of this method to improve the accuracy attainable. The crux of the method is to compare two waveforms, one of which is often badly distorted; the measurement therefore depends upon the operator's judgment of the position of a crest or the onset of a wave (see figs. 6 and 7). At present, the accuracy of this method is 1% to 3%, which is quite adequate when dealing with imperfect rock specimens but is not as good as is desired for very fine grained specimens or single crystals [36]. An improvement sufficient to determine with confidence the pressure derivative of the sound velocity would be most welcome.

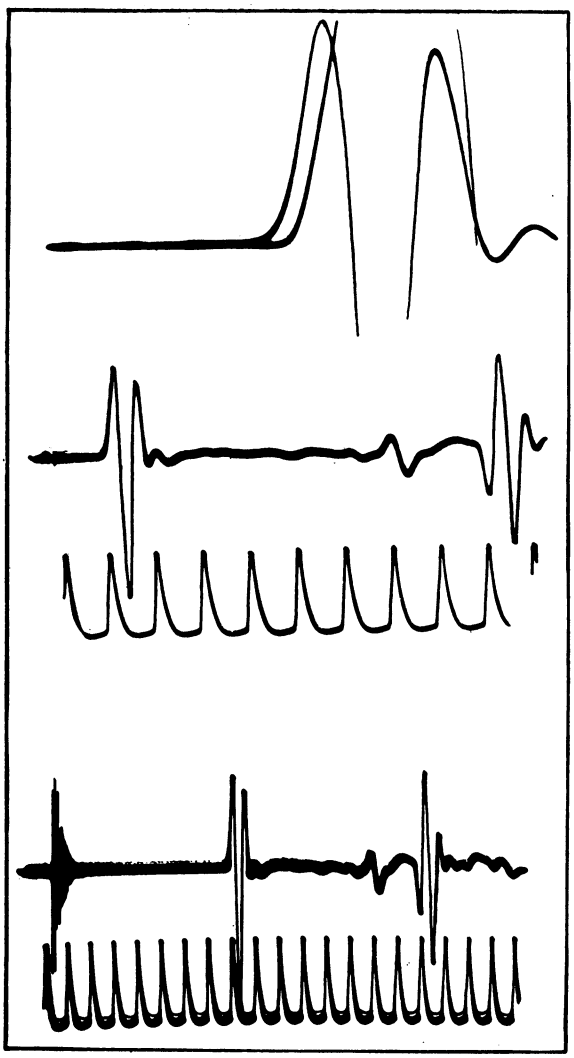

FIGURE 6. OSCILLOSCOPE TRACES FOR V_p MEASUREMENTS ON NIPISSING DIABASE AT 8 kb. The lowest photograph shows microsecond timing marks on the trace; on the other, reading from the left, can be seen the electrical pickup from the pulse, the first arrival, PSP, and a reflection of P from the outer end of the backing piece. The middle photograph shows the same pulse as the lower one with a faster sweep, the pulse now displaced from the screen. The top photograph shows the same pulse again, with still faster sweep; only the first arrival with the Hg signal slightly displaced from coincidence is shown [33].

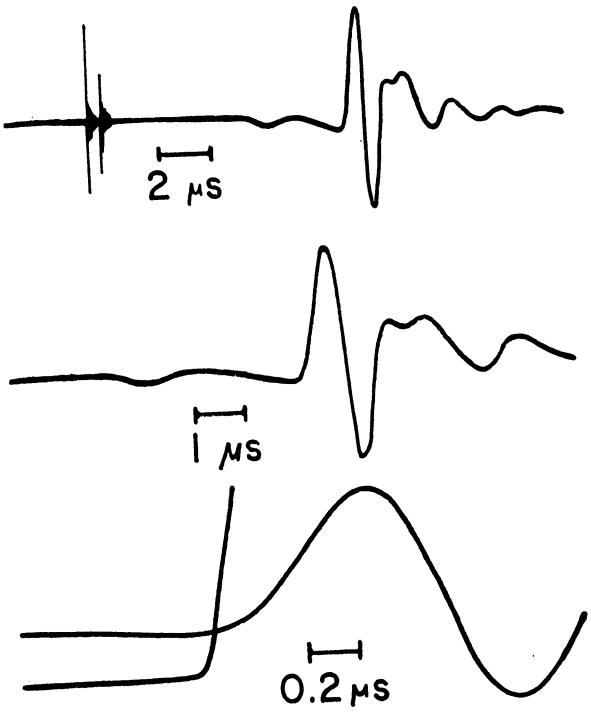

FIGURE 7. OSCILLOSCOPE TRACES FOR V_s MEASUREMENTS ON WESTERLY GRANITE USING AC-CUT QUARTZ TRANSDUCERS. The lower trace on the expanded time scale shows the Hg signal set for the beginning of S [35].

2.3.2. PULSE ECHO. For very fine grained materials (< 0.5 mm) which can transmit high-frequency pulses without distortion, Birch [33] prefers "pulse-echo" technique of Lazarus [49]. This is essentially a pulse-transmission technique in which the time delay for a pulse to propagate through the specimen, be reflected at the free end, and return to the transducer is determined by displaying the applied pulse and the successive echoes on the linear time scale of an oscilloscope. Lazarus corrects for the time delay in the seal between the transducer and the specimen and for the change of length with pressure. The circuitry required is considerably simpler than that of McSkimin's interferometric techniques, and it is possible to attain an accuracy of $\pm 0.5\%$ [50].

2.3.3. TOTAL INTERNAL REFLECTION. The total-internal-reflection method utilizes the basic principles of pulse transmission with some modification of the apparatus.

A plane compressional wave incident upon a liquid-solid interface produces both a refracted compressional wave and a refracted shear (SV) wave (see fig. 8). The sound velocity in solids is generally higher than in liquids, so, as in optics, when a beam of ultrasonic energy passes from a liquid to a solid, the phenomenon of "total internal reflection" will occur beyond a critical angle of incidence. For elastic waves, there are two such critical angles, one for compressional and one for shear waves if the velocity of the liquid is less than the shear velocity in the solid. The velocity in the solid is then $V = V_{liq}/\sin i_{crit}$. Bez-Bardili [51] was the first to use this principle to determine sound velocities. In this method, a plate of the sample is rotated in the path of an ultrasonic beam in a liquid. As the specimen is rotated, the transmitted signal first exhibits a sharp dip in intensity at the compressional critical angle and then vanishes entirely at the shear critical angle. Bez-Bardili detected the emergent beam using the Debye-Sears diffraction method of optics. Schneider and Burton [52] used a second piezoelectric crystal to detect the transmitted beam. Krishnamurthi and Balakrishna [53] have adapted the pulse technique of Pelham and Galt [54] to sound-velocity measurements. The use of the pulsed input allows the elimination of internal reflections in the system which may be a serious handicap with a continuous wave input [55].

Krishnamurthi and Balakrishna [53] and Gregory [55] estimate that the critical angle can be determined within 0.1°, which corresponds to a velocity uncertainty of about 0.5% to 1.0% for compressional waves. The shear critical angle can usually be determined slightly more accurately than the compressional angle. Krishnamurthi and Balakrishna also noted that because of refraction the emergent beam is shifted laterally with respect to the incident beam (see fig. 8), so the receiving transducer must either cover a large area or be capable of being moved laterally to pick up the transmitted beam.

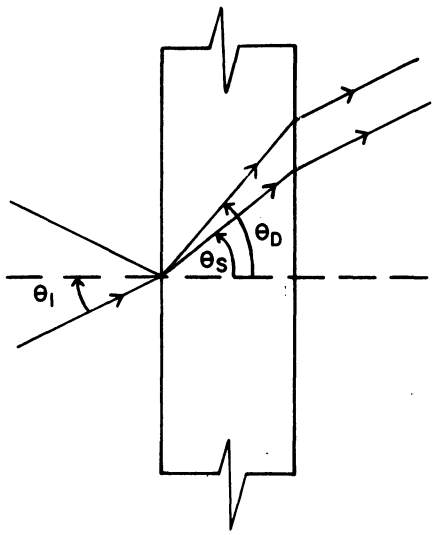

FIGURE 8. REFLECTED COMPRESSIONAL WAVE AND REFRACTED SHEAR (θ_S) AND COMPRESSIONAL (θ_D) WAVES PRODUCED BY COMPRESSIONAL WAVE INCIDENT AT ANGLE θ_1. At critical angles the refracted waves disappear. Note lateral shift of incident beam as it traverses the crystal [36].

Velocities are observed to decrease and attenuation of the transmitted signal is observed to increase with increasing grain size of the specimen [56], and the results become doubtful when the grain dimensions approach the wavelength of the applied signal. For the frequencies generally used (1 to 5 Mc/s), this limits the method to materials in which the average grain diameter is less than 1 mm. The total-internal-reflection method may be applied to inhomogeneous materials if these materials are elastically isotropic within the dimensions of the specimens.

Gregory [55] obtained reliable values of V_s at elevated pressures using jacketed specimens. This method has not yet been used at pressures above 1 kb, and the transducer system would probably have to be modified for use at higher pressures [36]. Bhagavantam [30] found this method unsuitable for high-temperature work, but Simmons [36] states that the apparatus of King and Fatt [57] could be easily adapted for measurements at high temperatures.

2.4. ULTRASONIC-INTERFEROMETRY METHOD

2.4.1. GENERAL COMMENTS. The review by Simmons [36] of this method is adequate for most purposes. Simmons' remarks should be expanded for those readers especially interested in measurements on minerals or well-sintered aggregates.

During the past 15 years, ultrasonic-interferometric techniques have been developed to the point where the sound-velocity measurement to within 1 part in 10^4 can be made. The principle of this method is shown schematically in figure 9. On one end of the specimen a quartz transducer is cemented with a very viscous grade of polystyrene fluid, such as Dow Chemical Company V-9, which transduces a high-frequency electromagnetic signal into a sound wave. Arrows in figure 9 represent the directions of the incident wave and the first reflected waves. The same transducer records a series of echoes of decreasing amplitude, separated by equal time intervals (t) as shown in the figure. The sound velocity of the specimen is determined by measuring the transit time of one wave or by counting the number of waves in a specimen of known thickness. X-cut quartz is used to obtain the longitudinal sound velocity (V_p), and Y-cut or AC-cut is used for the shear sound velocity (V_s). In an isotropic substance, such as a well-sintered ceramic, the two velocities V_p and V_s are sufficient to describe all elastic properties of the specimen when the density is known.

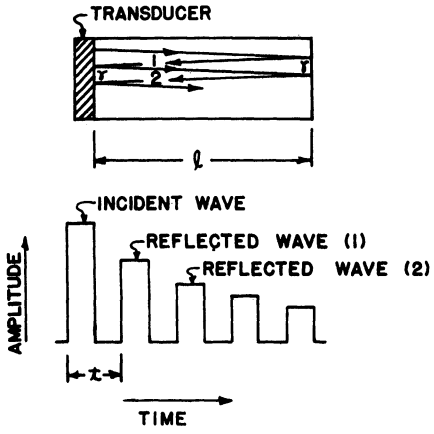

FIGURE 9. PRINCIPLE OF ULTRASONIC-INTERFEROMETRY TECHNIQUE [18]

As described by McSkimin [58], the main advantage of the ultrasonic method is its applicability to small specimens without loss of accuracy. Measurement to within 1 part in 10^4 can be obtained. If the error within 1 part in 10^3 is allowed, it is possible to measure the elastic constants of a specimen as small as 2 mm thick and 10 mm in diameter. Another advantage is its applicability under high pressure. However, measurement at temperatures higher than 300°C cannot be made because of the temperature limitations of the seal and the transducer.

The chief disadvantage of the interferometric method is that high frequencies must be used. The absorption of sound varies at some high power of frequency, so velocity measurements cannot be made on solids which have many defects, pores, or grains. Transmission of high frequencies cannot be observed when the porosity is greater than about 5% because of the scattering of the sound at the pores. Although the construction of such a system (see fig. 10) is not complicated except for a few electronic parts such as a harmonic generator and a mixer, the specimen must be prepared with great care. To obtain accurate results, which cannot be done on a small specimen by any other method, flatness to 1/4 wavelength of light and parallelism to within 10 sec of arc may be necessary. Since such a specimen can be prepared only by specially equipped shops, the cost becomes extremely high when many specimens are needed.

Various methods have been introduced to solve the problem of accurately measuring the time interval or number of waves in the specimen. The phase-comparison method and the pulse-superposition method have been successful for measuring sound velocities of small specimens.

2.4.2. PHASE COMPARISON. The phase-comparison method consists of superimposing the echoes of two pulses which have made different numbers of round trips [59]. If the echoes are made exactly in phase by a critical adjustment of the carrier frequency, the expression for phase angles may be written as

$$\gamma - \frac{2\ell\omega_n}{V} = -2\pi n \tag{3}$$

where V is the velocity of propagation, $\omega_n = 2\pi$ times the pseudoresonant frequency (f_n), ℓ is thickness, n is the number of waves, and γ is the phase shift caused by the seal between the transducer and the specimen. Consequently, the velocity is expressed by

$$V = \frac{2\ell f_n}{n + (\gamma/2\pi)} \tag{4}$$

McSkimin [59] has proven experimentally that size and shape effects are reduced to effectively zero whenever there are at least 100 wavelengths of sound in the specimen thickness. High frequencies (10-20 Mc/s) are generally used to minimize these effects.

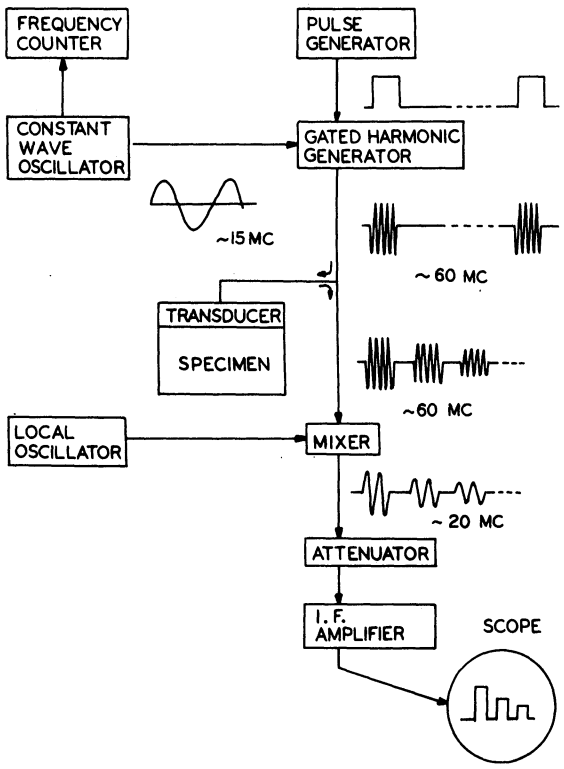

FIGURE 10. ULTRASONIC INTERFEROMETER [18]

The main advantage of this phase-comparison method is that the absolute velocity can be determined very accurately without the error introduced from coupling, since the transducer coupling effect can be evaluated. This method also makes it possible to measure the velocity on a specimen with linear dimensions as small as 2 mm.

The experimental details of the phase-comparison technique are discussed by Anderson and Schreiber [60].

2.4.3. PULSE SUPERPOSITION. The pulse-superposition method uses an RF pulse applied to the transducer at intervals approximately equal to the round-trip delay time of waves traveling in the specimen [61]. So that the superposed echoes can be observed just after the

last applied pulse, a few applied pulses are omitted periodically. When the echoes are brought into phase by adjusting the time spacing T between applied signals, a maximum in the resulting pulse amplitude occurs. This satisfies the equation

$$\delta = \frac{T}{p} - \frac{1}{f}\left(\frac{n}{p} - \frac{\gamma}{2\pi}\right) \tag{5}$$

where δ is the round-trip delay time, f is the radio frequency in the pulse, n is an integer which may be either positive or negative, and γ is a phase angle associated with waves reflected at the transducer end. Since T is approximately some multiple p of δ, the applied pulse occurs once for every round-trip delay when p = 1. Usually, a number of measurements of T at various frequencies between f_γ, the resonance frequency of the transducer, and $0.9f_\gamma$ are made to obtain the difference in T between f_γ and another frequency f. An important experimental procedure is to find the resonance corresponding to n = 0 [61]. If n = 0, the delay time is given by

$$\delta = T + (\gamma/2\pi f) \tag{6}$$

The velocity in the sample is $V = 2\ell/\delta$, where ℓ is the sample length.

The advantage of the pulse-superposition method is that the coupling to the transducer is taken into account, so that this method is well suited to measurements aimed at pressure and temperature variations. The effect of coupling between transducer and specimen can be made negligibly small. The accuracy of this method is within a few parts in 10^4, while that of the phase-comparison method is within 1 part in 10^4 [62]. With pulse superposition, however, it is possible to send a strong signal into the specimen so that the velocity can be measured even if the attenuation is high. The pulse-superposition method has been successfully used to measure the sound velocities on specimens with more than 1% porosity, while the phase-comparison method failed at that porosity. The limitations of both techniques are expected to depend upon various factors besides porosity, such as grain size and grain-boundary condition.

Anderson and Schreiber have made precision measurements on synthetic polycrystalline specimens of periclase (MgO) [60] using the phase-comparison method and upon corundum (Al_2O_3) [63] using the pulse-superposition method. Their measurements of V_p and V_s at room temperature and pressures up to 4 kb provide an accurate determination of the pressure derivatives of the sound velocities:

MgO:

$$V_p = 9.7662 + 7.711 \times 10^{-3}\ P\ \text{km/s}$$

$$V_s = 5.9635 + 4.351 \times 10^{-3}\ P\ \text{km/s}$$

Al_2O_3:

$$V_p = 10.845 + 5.175 \times 10^{-3} P \text{ km/s}$$

$$V_s = 6.3730 + 2.207 \times 10^{-3} P \text{ km/s}$$

These results are given here because of the significance of these oxides in the composition of the earth and because the data in the appendixes (MS01-03, AA02-03) cannot adequately represent the precision of this work.

The experimental details of the pulse-superposition technique are given by Schreiber and Anderson [63].

3
NEW METHODS OF DETERMINING VELOCITY: DIRECT AND INDIRECT

3.1. RESONANCE OF SMALL SPHERES; DIRECT MEASUREMENT OF V_s

The shear velocity and internal friction of a small sphere can be determined by measuring the fundamental free-oscillation frequencies of the sphere and the decay of its vibration. A brief description of the method developed by Fraser and LeCraw [64] follows.

The sphere is placed on a shear-mode piezoelectric transducer which vibrates with an imposed electric field so that the frequency can be controlled. When the frequency of the vibrating transducer is equal to the appropriate free oscillations of the sphere, energy will be absorbed from the electromechanical system, resulting in an abrupt change of the waveform pattern on the oscilloscope. The appropriate mode number can be determined by analyzing the series of resonance frequencies, since the series of frequencies of free oscillation is given by the equation

$$f_n = a_n \frac{V}{d} \tag{7}$$

where V is the shear-wave velocity, d is the diameter, and a_n is a number dependent upon the order number n and the type of oscillation and can be obtained by solving the appropriate spherical wave equations as outlined by Love [4].

This technique is well known in seismology as a means of estimating phase velocities within the earth and determining its elastic constants by measuring the period of free oscillations of the earth after a large earthquake. Until quite recently, however, it has not been applied to small specimens because of the complicated electronic setup. Fraser and LeCraw [64] recently proved, using single crystals of yttrium gallium garnet and yttrium aluminum garnet as

examples, that this method can be used to measure the elastic and anelastic properties of solids as functions of both frequency and temperature.

The internal friction is determined as follows. The transducer, which vibrates at one of the sphere's resonant frequencies, is switched to a receiver so that the free decay of the sphere's vibration is recorded on an oscilloscope. The internal friction can be calculated from this decay curve. The disadvantage is that only the shear velocity can be determined directly. To describe the elastic properties of an isotropic polycrystalline solid, two independent elastic constants are necessary. Another technique must be used to obtain one more elastic constant. By measuring the spheroidal mode in addition to the torsional mode, it may be possible to define both sound velocities.

A preliminary experiment was performed by D. Fraser of Bell Telephone Laboratories, Inc., on the polycrystalline MgO obtained from the University of California. The diameter of the MgO specimen used was about 0.45 cm. The shear sound velocity was measured as 6.0 km/s, which agrees well with the value obtained on the same sample by means of the ultrasonic technique (5.966 km/s).

The technique of resonance of small spheres will be an important one in determining a small specimen's elastic constants. In general, it is difficult to determine the shear modulus rather than the Young's of a solid because the torsional fundamental resonant frequency in the standard-resonance technique is much higher than the flexural fundamental resonant frequency and therefore exceeds the upper limit of the standard-resonance technique when the rod is short. This new technique will solve this problem.

There are three major advantages to this technique. First, shear velocity can be determined on a sphere as small as 2 mm in diameter. Such a small sphere can be fabricated fairly easily by successively grinding away the corners of a polyhedron and then applying a tumbling process of a two-pipe technique. Second, no bond is required between the transducer and specimen in this technique; thus the errors introduced by absorption of energy in the bond are eliminated. This is ideal for determining the internal-friction measurement. Third, spheres are easy to fabricate. Even with specimens as small as 2 mm, sphericity can be maintained to within 0.1%,* limiting the error in V_s to $\pm 0.5\%$.

For geology this technique is especially promising. Since the diameters of the specimens may be as small as a few millimeters, it may be possible to measure the shear velocity of individual grains of a rock and compare the results with velocity in the rock itself. Resonance

*D. Prentiss, private communication.

of dense rocks, where the Q is not too low, is possible by making spheres up to 10 cm in diameter.

A problem which must be solved before this technique can fulfill its promise in mineralogy is the mode splitting due to anisotropy of a crystalline lattice. This field of theoretical mechanics would be suitable for PhD theses.

3.2. SPECIFIC HEAT OF A POWDER: INDIRECT MEASUREMENT OF V_s

The isotropic shear velocity V_s of inorganic materials such as minerals and rocks can be estimated from low-temperature specific-heat measurements [65]. This property promises to be very useful because it enables one to determine the seismic shear velocity of a material independently of the state of aggregation of the samples. This correspondence between acoustics and calorimetry is based upon a principle of lattice dynamics which states that at sufficiently low temperatures the optical vibrations of a solid are quiescent and the vibrational energy arises solely from acoustic vibrations. This correspondence is conveniently stated in terms of Debye temperatures. The low-temperature specific heat is represented by a scalar parameter called the thermal Debye temperature, θ_t, and the acoustic contribution of specific heat is represented by the acoustic Debye temperature, θ_a. Thus, at temperatures near absolute zero,

$$\theta_t = \theta_a \tag{8}$$

In terms of the sound velocities for an isotropic body [66, 67],

$$\theta_a = \frac{h}{k}\left(\frac{9\rho N}{4\pi M/p}\right)^{1/3}\left(\frac{2}{V_s^3} + \frac{1}{V_p^3}\right)^{-1/3} \tag{9}$$

where h, k, and N are physical constants, M/p is the mean atomic weight (molecular weight divided by the number of atoms determining the molecular weight), ρ is the density, and V_s and V_p are the shear and compressional velocities, respectively.

It is more convenient to write the above expression in terms of the mean sound velocity, V_m:

$$\frac{3}{V_m^3} = \frac{2}{V_s^3} + \frac{1}{V_p^3} \tag{10}$$

Combining equations 8, 9, and 10, we have

$$\theta_t = 231.3\left(\frac{\rho}{M/p}\right)^{1/3} V_m \tag{11}$$

V_m is in kilometers per second, and the numerical factor arises from the physical and numerical constants in the preceding equations. Both V_p and V_s are needed to define θ_t. A closer examination, however, reveals that to a good approximation V_s alone defines θ_t. This can be demonstrated by solving for the ratio of V_s/V_m and substituting for V_p/V_s the equivalent function of Poisson's ratio σ.

Anderson [68] showed that if the Poisson's ratio has a value between 0.15 and 0.35, which includes most materials,

$$V_s \approx \left(\frac{\theta_t}{280}\right)\left(\frac{M/p}{\rho}\right)^{1/3} \text{ km/s} \qquad (12)$$

Equation 12 is the desired equation which has practical uses in geophysics. Knowledge of the mean atomic weight, density, and the low-temperature specific heat (from which θ_t can be defined) is sufficient to compute V_s. A few examples showing the use of equation 12 are given in table VI; the agreement is shown to be quite good for MgO, Al_2O_3, and W.

TABLE VI. CALCULATION OF SHEAR VELOCITY FROM THE THERMAL DEBYE TEMPERATURE AND COMPARISON WITH MEASURED VALUES

Solid	Debye Temp. (Thermal (Sp. Heat) θ_t (^oK)	Mean Atomic Weight M/p	Density ρ (gm/cm3)	Calc. Shear Velocity from Eq. 12 V_s (km/s)	Meas. Shear Velocity (Polycryst.) V_s (km/s)	Ref. for Measured Shear Velocity
MgO	946 [69]	20.3	3.583	6.02	5.993	75
					6.02	65
Al_2O_3	1045 [70]	20.4	3.986	6.45	6.44	22
BeO	1200 [71]	12.5	3.01	6.87	7.11	76
Al	428 [72]	26.98	2.698	3.29	3.13	47
Fe	445 [73]	55.84	7.872	3.06	3.20	47
W	380 [74]	183.90	19.20	2.89	2.86	77

Discrepancies between measured and calculated values of V_s can arise in three ways. First, equation 8 may not be completely valid. This question has been discussed by Alers [78], who found that equation 8 holds for crystalline nonmetals. Equation 8 may not be valid for metals because of the electronic contribution of specific heat. This is demonstrated in table VI by errors resulting from using equation 12 on Al and Fe. Second, the approximation that

$V_s = 0.9V_m$ is not valid for materials with a very low Poisson's ratio. The value of σ for BeO is 0.11, and there is a corresponding lack of agreement for V_s, as shown in table VI. Third, the value of θ_t derived from specific-heat data may be incorrectly determined. The method of finding θ_t from specific heat recommended by Barron et al. [79] should be followed. Specific-heat measurements are often reported at liquid-nitrogen or higher temperatures. Values of C_p in this temperature range will probably lead to poor estimates of V_s by equation 12, since C_p is then influenced by optical vibrations in addition to the acoustic vibrations.

From the results of Alers [78], it would appear that equation 8 is valid for all crystalline materials of interest to petrology. It may, however, not apply to inorganic glasses. It has been proven that equation 8 does not hold for vitreous silica [80], but that it does hold for quartz. Therefore, equation 12 may not be useful for obtaining the shear velocity of glasses of geological interest, such as obsidian and tektites.

It should be possible to measure V_s by suitable low-temperature specific-heat techniques on all types of geological specimens: rocks, crystals, sediments, dust, pumice, or aggregates. The resulting value of V_s will be independent of microstructure effects arising from grain boundaries and pores, and will correspond to the dense isotropic solid at zero porosity. If the material retrieved from the lunar surface is dust or small pebbles, equation 12 may prove to be a practical method of measuring the shear velocity of the rocks from which the material was derived.

The calculation of V_s by equation 12 is as accurate as other standard techniques for measurements on rocks and crystals. Pores and grains make the determination of V_s on field-specimen aggregates using resonance or acoustics somewhat uncertain. The determination of V_s on single crystals is uncertain because of the tensor properties of the crystal; V_s must be determined by an imposed averaging scheme. For example, if one averages the single-crystal elastic constants of alumina [81], one can say only that the true value of V_s lies somewhere between the Voigt limit, $V_s = 7.453$ km/s, and the Reuss limit, $V_s = 6.349$ km/s [68].

3.3. COMPRESSION OF A SOLID: DIRECT MEASUREMENT OF BULK MODULUS K IN A PRESS OR IN A SHOCK WAVE

This method is an old one reported in the literature, but it is included here because, although it is used for minerals, it is not a standard method of determining the velocity of sound of rocks. The compression measurement consists of measuring the variation of volume (or length) of a substance with pressure and finding the limiting slope of the data at zero pressure to determine the compressibility, or its reciprocal, the bulk modulus. There are three methods: an isothermal measurement of volume (or length) change, typified by the experiments of

Bridgman [82] and Weir [83]; measurement of the lattice constants with pressure by X-rays, typified by the experiments of Drickamer and Perez-Albuerne [84], McWhan [85], and Takahashi and Bassett [86]; and compression deduced from shock waves, typified by McQueen and Marsh [87]. While shock-wave measurements yield $\sqrt{K/\rho}$, the other measurements yield K. Isothermal-compression measurements, such as those made by Weir and McWhan, can be made upon powders; this can be important to geological problems.

The chief disadvantage of this method is that when compression is applied to rocks, spurious effects of grains, pores, and cracks cause erroneous results. Brace [88] comments that "For most purposes, further measurement of rock compressibility is pointless. Efforts might be profitably expended on refinement of mineral compressibilities or their extension to higher pressure and temperature."

3.4. INFRARED REFLECTION OF A DIATOMIC SOLID: INDIRECT MEASUREMENT OF K

This method is of special usefulness since it applies only to diatomic solids. It has been used successfully to find the bulk modulus of MgO, SiC, and ZnO [75]. It would presumably be useful for CoO, NiO, MnO, BN, and ZnS, but not for Fe_2O_3, SiO_2, quartz, etc. The method and its application to MgO have been described by Anderson and Glynn [75].

The advantages of the infrared-reflectivity method stem from the fact that the measurement is obtained from an optical signal reflected from a surface. The method is nondestructive. It requires little thickness of specimen and requires no holder, clamp, or transducer. The signal can be transmitted through appropriate windows. Consequently, it can be used on thin films or on specimens which are heated to very high temperatures. The most critical requirement is to obtain a highly polished flat surface. A coarse surface causes scattering of infrared and results in the reduction of reflectivity. However, the same absorption band can be achieved even though such a reduction of reflectivity occurs for porous materials. Therefore, the bulk modulus of a material with zero porosity can be obtained from the data of the same material having fairly high porosity.

The chief disadvantage is that only one elastic constant is found, so that the shear constant or Poisson's ratio cannot be determined. Another disadvantage is that the value of compressibility is determinable only within a few percent. However, it may be the only method available for examining the elasticity of a thin film. It is unfortunate that structures more complicated than diatomic solids show structured reflection bands which cannot be analyzed by this method.

A description of the results found by Anderson and Glynn for MgO is given below.

The reflection band was measured on the polycrystalline MgO specimen of gem quality obtained from the University of California. The reflectivities were determined by a point-by-point measurement. The intensity of the reflection from the sample onto a thermocouple was compared with that of the reflection from the front surface of a high-quality rhodium mirror. The mirror was assumed to have a reflectivity of 97% for wavelengths greater than 1 μ.

By analysis of the reflection band between 4 and 30 μ, the absorption wavelength λ_o was found to be 25.0 ± 0.1 μ. The index of refraction was 1.783, and the dielectric constant was 9.8. These measurements used in the appropriate equation [75] gave the value of the bulk modulus as K = 1640 kb. The ultrasonic measurement on the same specimen was K = 1711 kb. The main source of error is the determination of λ_o and the dielectric constant.

3.5. A COMPOSITE METHOD USING THE DEBYE TEMPERATURE AND THE BULK MODULUS: INDIRECT MEASUREMENT OF V_p AND V_s

Surveys of the literature often reveal that even when data on the sound velocities are missing, there nevertheless are data on the specific heat and the isothermal compressibility. The latter data are prevalent because these measurements can be taken on granular or crystalline materials. Scalar quantities can be obtained even for monocrystals.

By combining the methods described in sections 3.2 and 3.3, Soga and Anderson [18] showed that exact equations would be deduced for given values of Poisson's ratio σ. If K and σ are known, the other isotropic moduli and velocities are easily found. The two critical equations are defined in terms of a critical parameter Z,

$$Z = \frac{k}{h}\left(\frac{3Np\rho}{4\pi M}\right)^{-1/3} \cdot \theta \cdot \left(\frac{K}{\rho}\right)^{1/2} \tag{13}$$

which is a function of σ, according to

$$Z = \left\{ \frac{3}{\left[\frac{1+\sigma}{3(1-\sigma)}\right]^{3/2} + 2\left[\frac{2(1+\sigma)}{3(1-2\sigma)}\right]^{3/2}} \right\}^{1/3} \tag{14}$$

where h is Planck's constant, k is Boltzmann's constant, N is Avogadro's number, ρ is the density, M is the molecular weight of the solid, p is the number of atoms in the molecule, and θ is the Debye temperature.

Thus, M/p is known from the composition, and given ρ, K, and θ, Z can be calculated. Then the value of σ is found which gives the same value of Z. In this way σ and Z are both

found. The two sound velocities are then given by

$$\rho V_p^2 = 3K\frac{(1 - \sigma)}{(1 + \sigma)}$$

and

$$\rho V_s^2 = \frac{3}{2}K\frac{(1 - 2\sigma)}{(1 + \sigma)}$$

To aid in the conversion, a listing of Z versus σ is given in table VII. An example showing the precision of this method for four oxide compounds is given in table VIII. It is evident that the computed values of the elastic moduli are quite accurately determined by this method.

3.6. ESTIMATING SOUND VELOCITIES FROM THE REFRACTIVE INDEX: INDIRECT MEASUREMENT OF V_s AND V_p

Only a few physical properties can be measured on microscopically sized solids such as grains of powders; perhaps the easiest measurement is of the refractive index. The measurement of sound velocity, on the other hand, is not an easy task under the best circumstances and becomes quite difficult for small samples. The difficulty is compounded if the sample is a crystalline solid of low symmetry. The relative difficulty of the two measurements is demonstrated by the fact that there is a great amount of refractive-index data in the literature on oxides, while the data on sound velocity are scanty by comparison.

Any method of using refractive-index data to estimate the sound-velocity data is valuable to researchers concerned with the mechanical properties of minerals and inorganic compounds. Anderson [91] showed that for oxide compounds the compressional and shear sound velocities can be estimated from two properties determinable on very small samples: (1) the mean refractive index $\bar{n}$, and (2) a compositional parameter called the mean atomic weight, M/p (the molecular weight divided by the number of atoms in the formula). This new method is apparently restricted to oxide compounds (simple oxides like MgO, silicates like Mg_2SiO_4, and complicated minerals like tourmaline).

A large number of oxides have the same value of M/p, so that within broad limits the index of refraction alone determines the sound velocity irrespective of phase, composition, or crystalline symmetry. This is analogous to the determination of density from the refractive index (the Gladstone-Dale law) commonly used by mineralogists.

In this discussion, sound velocity is the isotropic sound velocity that a dense polycrystalline solid would have at zero porosity, and refractive index is the arithmetic mean of the crystalline refractive indexes.

TABLE VII. CONVERSION TABLE BETWEEN Z AND POISSON'S RATIO

Poisson's Ratio	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
0.000	1.3279	1.3260	1.3241	1.3222	1.3203	1.3184	1.3166	1.3147	1.3128	1.3109
0.010	1.3090	1.3071	1.3052	1.3034	1.3015	1.2996	1.2977	1.2958	1.2940	1.2921
0.020	1.2902	1.2883	1.2865	1.2846	1.2827	1.2808	1.2790	1.2771	1.2752	1.2734
0.030	1.2715	1.2696	1.2677	1.2659	1.2640	1.2621	1.2603	1.2584	1.2565	1.2547
0.040	1.2528	1.2510	1.2491	1.2472	1.2454	1.2435	1.2417	1.2398	1.2379	1.2361
0.050	1.2342	1.2324	1.2305	1.2286	1.2268	1.2249	1.2231	1.2212	1.2194	1.2175
0.060	1.2157	1.2138	1.2120	1.2101	1.2082	1.2064	1.2045	1.2027	1.2008	1.1990
0.070	1.1971	1.1953	1.1934	1.1916	1.1897	1.1879	1.1860	1.1842	1.1824	1.1805
0.080	1.1787	1.1768	1.1750	1.1731	1.1713	1.1694	1.1676	1.1657	1.1639	1.1620
0.090	1.1602	1.1584	1.1565	1.1547	1.1528	1.1510	1.1491	1.1473	1.1454	1.1436
0.100	1.1418	1.1399	1.1381	1.1362	1.1344	1.1325	1.1307	1.1288	1.1270	1.1252
0.110	1.1233	1.1215	1.1196	1.1178	1.1159	1.1141	1.1123	1.1104	1.1086	1.1067
0.120	1.1049	1.1030	1.1012	1.0993	1.0975	1.0957	1.0938	1.0920	1.0901	1.0883
0.130	1.0864	1.0846	1.0827	1.0809	1.0790	1.0772	1.0753	1.0735	1.0716	1.0698
0.140	1.0680	1.0661	1.0643	1.0624	1.0606	1.0587	1.0569	1.0550	1.0531	1.0513
0.150	1.0494	1.0476	1.0457	1.0439	1.0420	1.0402	1.0383	1.0365	1.0346	1.0328
0.160	1.0309	1.0290	1.0272	1.0253	1.0235	1.0216	1.0197	1.0179	1.0160	1.0142
0.170	1.0123	1.0104	1.0086	1.0067	1.0048	1.0030	1.0011	0.9992	0.9974	0.9955
0.180	0.9936	0.9917	0.9899	0.9880	0.9861	0.9843	0.9824	0.9805	0.9786	0.9767
0.190	0.9749	0.9730	0.9711	0.9692	0.9673	0.9655	0.9636	0.9617	0.9598	0.9579
0.200	0.9560	0.9541	0.9522	0.9504	0.9485	0.9466	0.9447	0.9428	0.9409	0.9390
0.210	0.9371	0.9352	0.9333	0.9314	0.9295	0.9276	0.9257	0.9237	0.9218	0.9199
0.220	0.9180	0.9161	0.9142	0.9123	0.9103	0.9084	0.9065	0.9046	0.9027	0.9007
0.230	0.8988	0.8969	0.8949	0.8930	0.8911	0.8891	0.8872	0.8853	0.8833	0.8814
0.240	0.8794	0.8775	0.8755	0.8736	0.8716	0.8697	0.8677	0.8658	0.8638	0.8619
0.250	0.8599	0.8579	0.8560	0.8540	0.8520	0.8501	0.8481	0.8461	0.8441	0.8421
0.260	0.8402	0.8382	0.8362	0.8342	0.8322	0.8302	0.8282	0.8262	0.8242	0.8222
0.270	0.8202	0.8182	0.8162	0.8142	0.8122	0.8101	0.8081	0.8061	0.8041	0.8021
0.280	0.8000	0.7980	0.7959	0.7939	0.7919	0.7898	0.7878	0.7857	0.7837	0.7816
0.290	0.7796	0.7775	0.7754	0.7734	0.7713	0.7692	0.7671	0.7651	0.7630	0.7609
0.300	0.7588	0.7567	0.7546	0.7525	0.7504	0.7483	0.7462	0.7441	0.7419	0.7398
0.310	0.7377	0.7356	0.7334	0.7313	0.7291	0.7270	0.7248	0.7227	0.7205	0.7184
0.320	0.7162	0.7140	0.7119	0.7097	0.7075	0.7053	0.7031	0.7009	0.6987	0.6965
0.330	0.6943	0.6921	0.6899	0.6877	0.6854	0.6832	0.6810	0.6787	0.6765	0.6742
0.340	0.6720	0.6697	0.6674	0.6651	0.6629	0.6606	0.6583	0.6560	0.6537	0.6514
0.350	0.6491	0.6468	0.6444	0.6421	0.6398	0.6374	0.6351	0.6327	0.6303	0.6280
0.360	0.6256	0.6232	0.6208	0.6184	0.6160	0.6136	0.6112	0.6088	0.6063	0.6039
0.370	0.6015	0.5990	0.5965	0.5941	0.5916	0.5891	0.5866	0.5841	0.5816	0.5791
0.380	0.5765	0.5740	0.5715	0.5689	0.5663	0.5638	0.5612	0.5586	0.5560	0.5534
0.390	0.5508	0.5481	0.5455	0.5428	0.5402	0.5375	0.5348	0.5321	0.5294	0.5267
0.400	0.5240	0.5212	0.5185	0.5157	0.5129	0.5101	0.5073	0.5045	0.5017	0.4989
0.410	0.4960	0.4931	0.4902	0.4873	0.4844	0.4815	0.4785	0.4756	0.4726	0.4696
0.420	0.4666	0.4636	0.4605	0.4575	0.4544	0.4513	0.4482	0.4450	0.4419	0.4387
0.430	0.4355	0.4323	0.4291	0.4258	0.4225	0.4192	0.4159	0.4125	0.4092	0.4058
0.440	0.4023	0.3989	0.3954	0.3919	0.3883	0.3848	0.3812	0.3775	0.3739	0.3702
0.450	0.3665	0.3627	0.3589	0.3551	0.3512	0.3473	0.3433	0.3393	0.3353	0.3312
0.460	0.3270	0.3228	0.3186	0.3143	0.3100	0.3056	0.3011	0.2966	0.2920	0.2873
0.470	0.2826	0.2777	0.2728	0.2679	0.2628	0.2576	0.2524	0.2470	0.2415	0.2359
0.480	0.2301	0.2243	0.2182	0.2120	0.2056	0.1991	0.1923	0.1852	0.1779	0.1703
0.490	0.1623	0.1539	0.1451	0.1357	0.1256	0.1146	0.1025	0.0887	0.0724	0.0512

TABLE VIII. COMPARISON OF THE VALUES COMPUTED FROM θ AND K AND THE EXPERIMENTAL VALUES OF ISOTROPIC ELASTIC MODULI [18]

Material	Young's Modulus (kb)		Shear Modulus (kb)	
	Computed*	Experimental	Computed*	Experimental
MgO	3180	3100 ± 50 [19]	1340	1310 ± 20 [19]
Al_2O_3	4150	4040 ± 60 [19]	1660	1640 ± 30 [19]
BeO	3810	3880 [89]	1430	1470 [89]
TiO_2	2790	2835**	1085	1117**

*Since the compressibility used in the computation is based on static measurements, the computed values should be compared with the isothermal elastic constants. For the shear modulus the isothermal value is equal to the adiabatic, while for Young's modulus the isothermal is about 1% lower than the adiabatic at room temperature.

**Based on the single-crystal data by Wachtman et al. [90].

The relation between sound velocity and refractive index is based upon the fact that for oxides the elastic constants are unique functions of the specific volume [92] and the refractive index is a unique function of the density [93]. As a result, by properly accounting for the molecular weight, the sound velocity is shown to be a unique function of the refractive index.

A major parameter classifying the oxides is the mean atomic weight M/p. Most existing data on sound velocity are for oxides with a mean atomic weight near 20. For such oxides, the sound velocities are given by the empirical equations:

$$V_s = 3(\bar{n}^2 - 1)\ \text{km/s} \tag{15}$$

$$V_p = 5(\bar{n}^2 - 1)\ \text{km/s} \tag{16}$$

These equations are plotted as solid lines in figures 11 and 12. The data for the oxides are listed in table IX and plotted as open circles in figures 11 and 12. It is seen that the correlation is valid for oxides representing various molecular weights, crystal symmetries, and compositions. The sound-velocity data are taken from references listed by Anderson and Nafe [92] and the refractive-index data from references in Anderson and Schreiber [93].

For oxides with the same refractive index, the mean atomic weight increases as the sound velocity decreases. This effect is shown for three garnets plotted in figures 11 and 12 as filled circles. The velocity data on two natural garnets were reported by Verma [94]. Garnet 1 con-

sists of a solid solution of spessarite and almandite, and garnet 2 is predominately almandite. The refractive-index values for these garnets are given by Verma as 1.814 and 1.817. The mean atomic weights calculated from Verma's data are 24.0 and 24.5. The third garnet is synthetic, a yttrium aluminum garnet grown at Bell Telephone Laboratories. The elastic constants were reported privately by E. G. Spencer. The isotropic elastic constants are computed by the Voigt-Reuss-Hill averaging scheme [95], yielding V_p = 8.60 km/s and V_s = 4.95 km/s. The refractive index is 1.833, and M/p is 23.10. The elastic constant data for ZnO, where the mean atomic weight is 40.6, is given by Bateman [96]. The resulting velocities are V_p = 5.96 km/s and V_s = 2.84 km/s. These low velocities for a material with such a high value of refractive index, 2.03, suggest that a high value of M/p materially lowers the sound velocity. These data are plotted as crossed circles in figures 11 and 12.

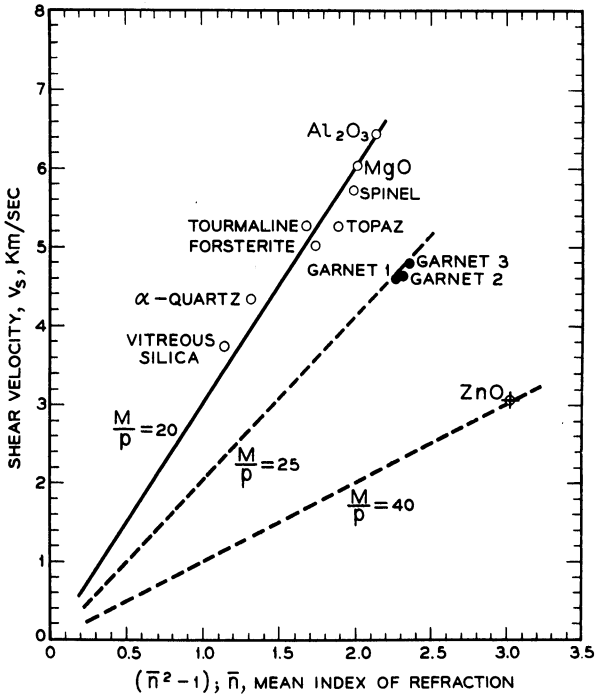

FIGURE 11. SHEAR VELOCITY AS A FUNCTION OF $(\bar{n}^2 - 1)$ FOR VARIOUS MINERALS. Solid line: $V_s = 3(\bar{n}^2 - 1)$ [91].

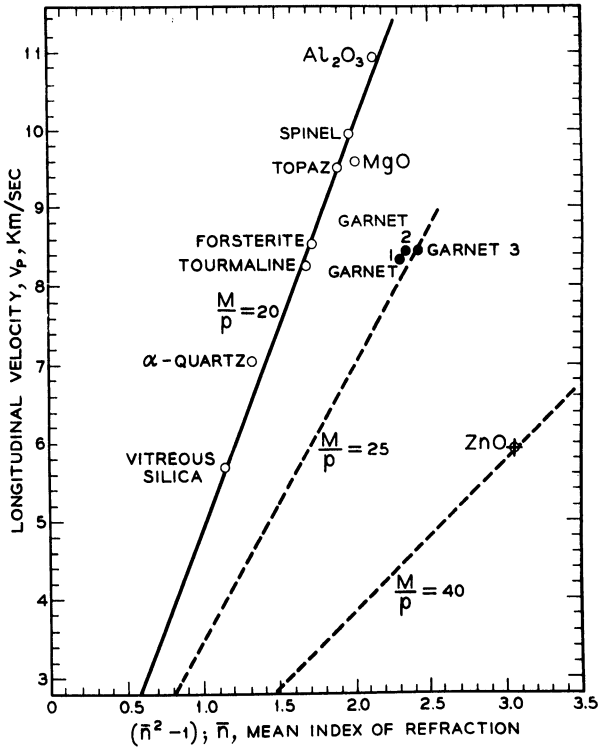

FIGURE 12. LONGITUDINAL (COMPRESSIONAL) VELOCITY AS A FUNCTION OF $(\bar{n}^2 - 1)$ FOR VARIOUS MINERALS. Solid line: $V_p = 5(\bar{n}^2 - 1)$[91].

TABLE IX. CALCULATED SOUND VELOCITIES FROM REFRACTIVE-INDEX DATA FOR MINERALS OBEYING BIRCH'S LAW ($M/p \cong 20$)*

Mineral Name	Ideal Chemical Formula	Molecular Weight M	Mean Atomic Weight M/p	Measured Refractive Index $\bar{n}$	Measured Density ρ	$\bar{n}^2 - 1$	Calc. Shear Velocity $\frac{3(\bar{n}^2 - 1)}{}$ (km/s)	Calc. Long. Velocity $\frac{5(\bar{n}^2 - 1)}{}$ (km/s)
Fused Silica	SiO_2	60.06	20.03	1.459	2.20	1.129	3.4	5.6
Tridymite	SiO_2	60.06	20.03	1.471	2.27	1.164	3.5	5.8
Cristobalite	SiO_2	60.06	20.03	1.486	2.34	1.208	3.6	6.0
Leucite	$KAlSi_2O_6$	218.26	21.82	1.501	2.47	1.253	3.8	6.3
Keatite	SiO_2	60.06	20.03	1.519	2.50	1.307	3.9	6.5
Carnegieite	$NaAlSiO_4$	142.07	20.29	1.521	2.51	1.313	3.9	6.6
Orthoclase	$KAlSi_3O_8$	278.35	21.41	1.522	2.55	1.316	3.9	6.6
Anorthoclase	$KNaAl_2Si_6O_{16}$	540.6	20.79	1.524	2.58	1.323	4.0	6.6
Microcline	$KAlSi_3O_8$	278.35	21.41	1.526	2.56	1.328	4.0	6.6
Albite	$NaAlSi_3O_8$	262.25	20.17	1.530	2.61	1.340	4.0	6.7
Chalcedony	SiO_2	60.06	20.03	1.535	2.63	1.356	4.1	6.8
Carnegieite	$NaAlSiO_4$	142.07	20.29	1.536	2.62	1.359	4.1	6.8
Quartz	SiO_2	60.06	20.03	1.547	2.65	1.393	4.2	7.0
Anorthite	$CaAl_2Si_2O_8$	278.22	21.40	1.583	2.77	1.506	4.5	7.5
Enstatite	$MgSiO_3$	100.41	20.08	1.590	2.87	1.528	4.6	7.6
Coesite	SiO_2	60.06	20.03	1.595	2.92	1.544	4.6	7.7
Sarcolite	$Ca_3Al_2Si_3O_{12}$	498.47	21.67	1.608	2.93	1.586	4.8	7.9
Akermanite	$(Mg, Ca)_3Si_2O_7$	272.66	~22.00	1.635	3.12	1.673	5.0	8.4
Andalusite	Al_2SiO_5	162.05	20.25	1.639	3.15	1.686	5.1	8.4
Mullite	$Al_6Si_2O_{13}$	425.94	20.28	1.644	3.23	1.702	5.1	8.5
Mullite	$Al_6Si_2O_{13}$	425.94	20.28	1.647	3.03	1.713	5.1	8.6
Forsterite	Mg_2SiO_4	140.73	20.10	1.652	3.22	1.729	5.2	8.6
Enstatite	$MgSiO_3$	100.41	20.08	1.654	3.18	1.736	5.2	8.7
Clinoenstatite	$MgSiO_3$	100.41	20.08	1.655	3.28	1.739	5.2	8.7
Jadeite	$NaAlSi_2O_6$	202.16	20.21	1.659	3.43	1.752	5.3	8.8
Sillimanite	Al_2SiO_5	162.05	20.25	1.667	3.23	1.779	5.3	8.9
Olivine	$(Mg, Fe)_2SiO_4$	?	(20.10 ?)	1.671	3.34	1.792	5.4	9.0
Diopside	$CaMgSi_2O_6$	216.58	21.65	1.676	3.28	1.809	5.4	9.0
Hypersthene	$MgSiO_3$	100.41	20.08	1.688	3.37	1.849	5.5	9.2
Schefferite	$MgCaSi_2O_4$	184.58	23.07	1.688	3.39	1.849	5.5	9.2
Jeffersonite	$MgCaSi_2O_6$	216.58	21.65	1.694	3.39	1.870	5.6	9.4
Pigeonite	$MgSiO_3$	100.41	20.08	1.697	3.42	1.880	5.6	9.4
Pyrope	$Mg_2Al_3Si_3O_{12}$	405.85	20.29	1.705	3.51	1.907	5.7	9.5
Kyanite	Al_2SiO_5	162.05	20.25	1.720	3.60	1.960	5.9	9.8
Spinel	$MgAl_2O_4$	142.28	20.32	1.723	3.60	1.990	6.0	10.0
Periclase	MgO	40.32	20.16	1.736	3.58	2.010	6.0	10.0
Corundum	Al_2O_3	101.96	20.39	1.762	4.00	2.100	6.3	10.5
Stishovite	SiO_2	60.06	20.03	1.806	4.28	2.262	6.8	11.3

*Ranked in order of increasing refractive index.

More velocity data must be analyzed before the effect of large M/p on velocity can be conclusively determined. Our best estimates are given by the dashed lines in figures 11 and 12, which represent guides for future work. These dashed lines must be regarded as tentative.

The solid lines in figures 11 and 12 representing equations 15 and 16 are not likely to be changed significantly by new data taken on solids with values of M/p near 20. Equations 15 and 16 are used to compute the sound velocities of oxide compounds and minerals with M/p = 20.5 ± 1.5. These minerals are listed in table IX, along with the reported data on M/p, refractive index, density, and the computed velocities. The refractive index and density data are taken from reference 97.

This method, which is valuable for oxide compounds, does not apply to other compounds [91] because their moduli are not unique functions of specific volume.

3.7. ESTIMATING SOUND VELOCITIES FROM SINGLE-CRYSTAL ELASTIC CONSTANTS: INDIRECT MEASUREMENT OF V_p AND V_s

To find the effect of calcite on sound velocity in rocks, it is desirable to know the value of V_p and V_s for pure calcite. Such values for a mineral are seldom available; instead, the elastic constants of the mineral are often found. These will, in general, not be isotropic, so the formula for determining V_p and V_s, which represent the velocity through perfectly dense polycrystalline aggregates, in terms of the elastic constants is required.

Unfortunately, the exact formulas have not yet been found, but simple formulas do exist which give the upper possible limits and the lower possible limits. For further details on an easy method, see reference 68. This method, called the Voigt-Reuss-Hill method, consists of finding the upper and lower limits of the bulk modulus and the shear modulus and then taking the arithmetic average. The following holds for any crystal class. The bulk modulus (maximum) by the Voigt approximation is:

$$K_V = \frac{1}{9}(C_{11} + C_{12} + C_{33}) + \frac{2}{9}(C_{11} + C_{23} + C_{13}) \tag{17}$$

The shear modulus (maximum) by the Voigt approximation is:

$$\mu_V = \frac{1}{15}(C_{11} + C_{22} + C_{33}) - \frac{1}{15}(C_{12} + C_{23} + C_{31}) + \frac{1}{5}(C_{44} + C_{55} + C_{66}) \tag{18}$$

The bulk modulus (minimum) by the Reuss approximation is:

$$\frac{1}{K_R} = (S_{11} + S_{22} + S_{33}) + 2(S_{12} + S_{23} + S_{13}) \tag{19}$$

The shear modulus (minimum) by the Reuss approximation is:

$$\frac{15}{\mu_R} = 4(S_{11} + S_{22} + S_{33}) - 4(S_{12} + S_{23} + S_{13}) + 3(S_{44} + S_{55} + S_{66}) \tag{20}$$

Given the elastic constants, C_{ij}, it is possible to find the four values K_V, K_R, μ_V, μ_R from equations 17-20. The Voigt-Reuss-Hill approximation is now found from the arithmetic mean of equations 17-20:

$$K_H = \frac{1}{2}(K_V + K_R)$$

$$\mu_H = \frac{1}{2}(\mu_V + \mu_R) \tag{21}$$

and the expected velocities are

$$V_p = \sqrt{\frac{K_H + 4/3\mu_H}{\rho}}$$

$$V_s = \sqrt{\frac{\mu_H}{\rho}} \tag{22}$$

For a discussion of how well these approximations taken from the crystal data predict the measured polycrystalline values, see reference 79. The extrapolated values of the moduli at zero porosity are the values of the measurement which must be used (see fig. 2, for example).

Appendix 9 shows the calculations in detail for a number of crystals of interest to geology. To follow through the analogy on calcite, we would find that V_p is probably 6.3 km/s, but between 5.9 and 6.7; and V_s is probably 3.3 km/s but between 2.9 and 3.6, according to the Voigt-Ruess-Hill approximation (see p. 18 of app. 9).

These values of the elastic constants representing limits, K_V and K_R, μ_V and μ_R, are probably too extreme (or low); but the values of the Hill mean are quite close to the expected values. This conclusion is substantiated by the recent theoretical work of Peselnick and Meister [98] who have applied the variational principles of anisotropic elasticity [99, 100] to polycrystalline aggregates of crystals possessing hexagonal and trigonal symmetries. They conclude that:

> The important feature here is that the variational method does effect a considerable improvement in both the shear and bulk moduli bounds, even though it may be meaningless from the experimental view to ask for such precision. Except for zinc, cadmium and calcite, the Hill values and the average value of the effective bounds are very nearly the same (< 0.5% of each other). This agreement strengthens the use of the Hill average for practical approximations.

Even for zinc, cadmium, and calcite, the worst cases indicated by Peselnick and Meister, the agreement of the Hill mean with the variational mean is satisfactorily close. The following listing is taken from table V of reference 98.

Material	Bulk Modulus		Shear Modulus	
	Hill Mean	Variational Mean	Hill Mean	Variational Mean
Cd	534.8	554.5	332.2	327.3
Zn	683.2	685.5	394.5	410.2
$CaCO_3$	747	751	307	301

We conclude that the use of the Hill mean is well established empirically by good agreement with another approximate method of calculation.

One example of the experimental confirmation of the Voigt-Ruess-Hill approximation is given by the work of Soga [101] on tantalum. Soga measured the elastic constants of single-crystal tantalum and computed the Young's modulus over a 500° temperature range by the Voigt-Ruess-Hill schemes. His values of E_V, E_R, and E_H are plotted in figure 13, and the value of E_H is compared with Köster's measurements of E for polycrystalline tungsten [102]. The agreement is excellent.

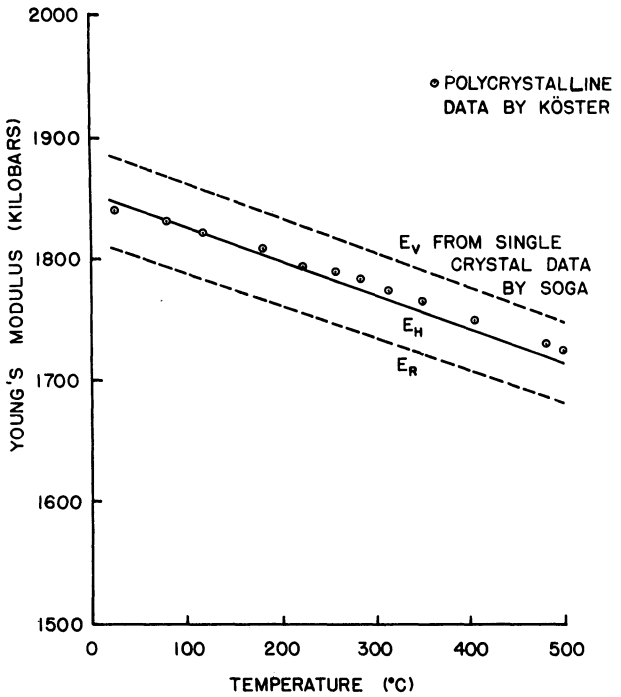

FIGURE 13. ISOTROPIC YOUNG'S MODULUS OF TANTALUM AS A FUNCTION OF TEMPERATURE [101]

3.8. ESTIMATING SOUND VELOCITIES FROM THE SPECIFIC VOLUME: CRUDE AND INDIRECT MEASUREMENT OF V_p AND V_s

Birch [103] showed that a majority of known oxide compounds with low iron content have a mean atomic weight virtually independent of composition, phase, or symmetry; this value of M/p is near 21. An extended list of these compounds is found in table I of Anderson and Schreiber [93]. Birch [104] showed that V_p is roughly proportional to density for oxide compounds at constant M/p. Lines were drawn by Birch and represented by

$$V_p = a + b\rho \tag{23}$$

where the value of a was displaced lower for higher M/p. Simmons [35] showed roughly the same relation for shear velocity, and a similar relationship for V_p in sediments was shown by Nafe and Drake [105]. These relationships are empirical.

Anderson and Nafe [92] found relationships between bulk modulus and specific volume and between shear modulus and specific volume. These relationships were not theoretically derived from first principles, but were shown to be related to interatomic potentials and can be regarded as quasitheoretical. The relationships are

$$\ell n\, K = -3.5\, \ell n\, V_o + \text{constant} \tag{24}$$

where V is the volume per ion pair given by $2M/p\rho$. A similar relationship holds for μ. The correlation included the minerals hematite, calcite, quartz, olivine, periclase, corundum, beryl, stishovite, spinel, topaz, garnet, and spodumene. A large value of M/p is found for hematite, while a small value is found for beryl and spodumene. Presumably, then, M/p does not affect the value of the constants in equation 24. Empirically, we have

$$K \cong 2.9 \times 10^6\, V_o^{-3.5}\ \text{kb} \tag{25}$$

and

$$\mu \cong 1.9 \times 10^6\, V_o^{-3.5}\ \text{kb} \tag{26}$$

These guides are rough but useful. For example, the specific volumes per ion pair [92] for corundum, olivine, and orthoclase are 10.24, 12.59, and 16.73 cc/mole. Using equation 25, we compute K = 2600, 1240, and 465 kb, which compare with the measured values 2512, 1313, and 473 kb. Using the above numerical values, we can estimate the sound velocities.

The result of this approach is that the relationships between sound velocity and density, at constant M/p, are

$$V_p = V_{p_o}\left(\frac{\rho}{\rho_o}\right)^x \tag{27}$$

and

$$V_s = V_{s_o}\left(\frac{\rho}{\rho_o}\right)^y \tag{28}$$

where x and y have values near 5/4 [92]. Equations 27 and 28 must be confirmed by further work, but they indicate how one might expect the velocities to change from dense rock to dense rock (or mineral to mineral) as the ambient density of the rocks changes.

3.9. DETERMINING THE ELASTIC CONSTANTS AND VELOCITY AT VERY HIGH PRESSURES: DIRECT AND INDIRECT MEASUREMENTS OF V_p, V_s, AND ϕ

The most obvious way to find the velocity of sound at high pressures is to measure it at the desired pressure. Sufficient measurements have been made at pressures up to about 10 kb that experiments in this pressure range can be considered routine. Great experimental obstacles have prevented many measurements above about 10 kb.

There are two ways to extend the measurements to higher pressure. One is to attempt measurements at the desired pressure and accept the resulting problems in pressure calibration and attenuation; the other is to attempt to extrapolate measurements of high accuracy made at lower pressure, the range of measurements being limited by the demands in precision.

An example of progress in the first method is the experiment of Ahrens and Katz [106, 107], who designed an ultrasonic-interferometric system to operate through opposing anvils (called Bridgman anvils) of a uniaxially loaded press. Using this technique, they were able to measure V_p and V_s through the phase transition calcite to aragonite. The main feature is that the transducers are outside the pressure system. There are attending problems in measurement of the path length, and in estimates of "effective pressure" in a nonuniform stress environment. Vigorous efforts to improve this experimental technique are underway, and we may expect further progress. An alternative to the Bridgman anvils is the "belt" apparatus, which is being improved by Montgomery at Minnesota Mining and Metallurgy Research Laboratories as a method of measuring V_p and V_s in the 60- to 100-kb range.

An example of the other method is the work of Anderson [108, 109] and Anderson and Schreiber [60, 63, 93]. Using the most precise techniques available, they have taken measurements of sound velocity versus pressure up to 4 kb on synthetic polycrystalline aggregates of very high quality. Their results for polycrystalline MgO and Al_2O_3 were given in section 2.4.3.

One wonders whether or not these equations can be extrapolated to higher pressures. Anderson [108] proposed that the bulk modulus could be extrapolated, namely

$$K = K_o + \left(\frac{dK}{dP}\right)_{P\to 0} P \tag{29}$$

Thus, the velocities are not linearly extrapolated, since the dimensions of velocity and elastic moduli are different. From the previous data, we have

$$K = 1692 + 3.95P \text{ kb, MgO} \tag{30}$$

$$K = 2504 + 4.00P \text{ kb, } Al_2O_3 \tag{31}$$

By comparing the values of compression predicted from equation 29 with measured compression, we can determine to what pressures equations 30 and 31 hold. The predicted equation [108] is:

$$\ell n\left(\frac{V_o}{V}\right) = \frac{1}{K'_o}\,\ell n\left[1 + K'_o\left(\frac{P}{K_o}\right)\right] \tag{32}$$

or

$$\ell n\left(\frac{V}{V_o}\right) = -0.253\,\ell n\left[1 + 3.95\left(\frac{P}{1692}\right)\right] \text{MgO} \tag{33}$$

$$\ell n\left(\frac{V}{V_o}\right) = -0.25\,\ell n\left[1 + 4.00\left(\frac{P}{2504}\right)\right] Al_2O_3 \tag{34}$$

Equations 33 and 34 successfully duplicated the isothermal compression experimental data of Perez-Albuerne and Drickamer [84] on MgO up to 350 kb, and the data of Hart and Drickamer [110] on Al_2O_3 up to 304 kb, the limits of these measurements. Further, equation 33 duplicated the shock-wave compression experiments of McQueen and Marsh [111] up to 1257 kb. The accuracies were within a few percent as indicated by tables X, XI, and XII. From this we conclude that equation 30 holds up to 1257 kb and equation 31 holds up to at least 300 kb, even though the data upon which these equations were based were measured only up to 4 kb. The agreement is remarkably accurate. This indicates that the hypothesis that K'_o is a constant is proven up to very high pressures. The velocity functions up to pressures where K'_o is still constant cannot be found until there is some information on the range of pressure where $d\mu/dP$ is a constant, or, alternatively, where $d\sigma/dP$ is a constant. On the other hand, one can be precise about the equation for the seismic parameter ϕ,

$$\phi = V_p^2 - \frac{4}{3}V_s^2 = \frac{K}{\rho}\,(\text{km/s})^2 \tag{35}$$

since ϕ is a function only of K and ρ. Anderson [109] showed that up to the pressure where equation 29 holds

$$\phi(P) = \phi_o\left[1 + K'_o\left(\frac{P}{K_o}\right)\right]^{K'_o - 1/K'_o} \tag{36}$$

TABLE X. COMPARISON OF DRICKAMER'S [84] MEASURED COMPRESSION ON MgO UP TO 350 kb WITH CALCULATED COMPRESSION USING 4-kb DATA

Drickamer's Measured Compression		Predicted from 4-kb Measurements $\ln\left(\frac{V}{V_o}\right) = -0.253 \ln\left[1 + 3.95\left(\frac{P}{1692}\right)\right]$	
P (kb)	Measured V/V_o	Calculated V/V_o	Error (%)
25	0.987	0.986	-0.10
50	0.974	0.972	-0.21
75	0.963	0.960	-0.31
100	0.951	0.948	-0.32
150	0.930	0.927	-0.32
200	0.910	0.908	-0.22
250	0.893	0.890	-0.34
300	0.877	0.874	-0.35
350	0.862	0.860	-0.23

TABLE XI. COMPARISON OF DRICKAMER'S [111] MEASURED COMPRESSION ON Al_2O_3 UP TO 300 kb WITH CALCULATED COMPRESSION USING 4-kb DATA

Drickamer's Measured Compression		Predicted from 4-kb Measurements $\ln\left(\frac{V}{V_o}\right) = -0.25 \ln\left[1 + 4.00\left(\frac{P}{2504}\right)\right]$	
P (kb)	Measured V/V_o	Calculated V/V_o	Error (%)
63	0.98	0.976	-0.4
128	0.96	0.954	-0.6
192	0.94	0.935	-0.5
256	0.92	0.918	-0.2
288	0.91	0.910	0.0
304	0.905	0.906	-0.1

TABLE XII. COMPARISON OF SHOCK-WAVE COMPRESSION FROM MCQUEEN AND MARSH [112] ON MgO UP TO 1257 kb WITH CALCULATED COMPRESSION USING 4-kb DATA

McQueen and Marsh Measured Shock Compression		Predicted from 4-kb Measurements	
		$\ell n\left(\frac{V}{V_o}\right) = -0.23\ \ell n\left[1 + 3.95\left(\frac{P}{169}\right)\right]$	
$\frac{P}{(kb)}$	Measured V/V_o	Calculated V/V_o	$\frac{Error}{(\%)}$
304.2	0.872	0.874	+0.23
483.6	0.831	0.827	-0.48
528.2	0.818	0.817	-0.12
615.7	0.799	0.799	0.00
683.1	0.787	0.787	0.00
855.8	0.758	0.759	+0.13
904.3	0.755	0.750	-0.67
949.8	0.746	0.745	-0.13
979.9	0.744	0.741	-0.41
1102.4	0.726	0.725	-0.14
1137	0.721	0.721	0.00
1257	0.708	0.708	0.00

Thus, the explicit functions of ϕ can be written, the one for MgO holding to 1257 kb and the one for Al_2O_3 holding to at least 300 kb:

$$\text{MgO:}\quad \phi = 48.1[1 + 3.91(P/1717)]^{0.742}\ (km/s)^2 \tag{37}$$

$$Al_2O_3\text{:}\quad \phi = 63.4[1 + 3.98(P/2520)]^{0.748}\ (km/s)^2 \tag{38}$$

In equations 37 and 38, the adiabatic values of K_o and K'_o were used, which are slightly different from the isothermal values used in equations 33 and 34.

This technique, of course, is limited to the pressures below phase transitions. Up to phase transition, it has excellent promise as a method of measuring velocity. To a fair approximation, equations 35 and 36 are linear with pressure to 100 kb.

3.10. DETERMINING THE ELASTIC CONSTANTS AT VERY HIGH TEMPERATURE: DIRECT AND INDIRECT MEASUREMENTS OF V_p, V_s, AND ϕ

Appendix 4 gives a survey of measurements of velocity in rocks taken on several types up to 200°C and on a few up to 500°C or 600°C. Such measurements can be considered a standard method. This topic is included in this section because of the promise that measurements on suitably prepared polycrystalline aggregates can be extended to the 1500°C level. For rocks, there is an important experimental condition to be considered, which was emphasized in Simmons' review: irreversible effects can be created by heating a rock. To remind the reader that an apparent temperature discontinuity of velocity in rocks may be spurious, we quote Birch [112]:

> It has been known since the time of Ide (1937) that the consequence of heating rocks at ordinary pressure is a progressive loosening of structure which leads to irreversible decreases of velocity . . . . In our experience . . . in high-temperature studies of V_S (Birch, 1943 and unpublished), the practice has been to raise the pressure to 4000 kg/cm^2 or more before heating. Even then, it is often necessary to carry out several cycles of heating and cooling in order to obtain a linear, reversible effect. In a number of cases, linear, reversible curves to as much as 500°C have been obtained; beyond this point, most rocks begin to exhibit an accelerated rate of decrease of velocity with temperature, which may sometimes be 'real', sometimes an effect of damage which presumably would not occur under the relatively steady conditions of the crust.

To reach temperatures above 600°C, the rock aggregate structure must be avoided. Dense polycrystalline ceramic specimens of MgO and Al_2O_3 have been prepared by Soga and Anderson [19], and they have achieved accurate measurements of the elastic constants to over 1100°C.

Anderson [113] derived an equation for the variation of the adiabatic bulk modulus with temperature. It is given by

$$K = K_{oo} - \frac{\gamma\delta\rho}{M/p} T\left[\frac{H(\Theta, T)}{T}\right] \tag{39}$$

In equation 39 every constant except K_{oo}, the bulk modulus at 0°K and 1 atmosphere, is determined or calculated from experiment. ρ is the density, M/p is the mean atomic weight, γ is the Gruneisen constant, and δ is a temperature-independent dimensional parameter given by

$$\delta = -\frac{d\ \ell n\ (K/dT)}{d\ \ell n\ (V/dT)} \tag{40}$$

The quantity in brackets in equation 39 is the thermal heat given by a table of Debye functions, using the Debye temperature θ and the actual temperature T. Thus the parameters in equation 39 can be determined by measurements in a small temperature range, and the bulk modulus

can be predicted at higher temperatures. Figure 14 shows the comparison between predicted bulk modulus and the actual data of Soga.

Another form of equation 39 is [19]

$$K = K_{oo} - \frac{\gamma\delta\rho}{M/p} H(T)$$

where H(T) is the measured enthalpy. At high temperature the enthalpy is linear with temperature, so that

$$K(T) = K(T_o) - \frac{\gamma\delta\rho}{M/p}[H(T) - H(T_o)] \tag{41}$$

Thus, the bulk modulus can be estimated as high as the enthalpy can be measured. Data on H often exist up to 2000°C. Some data on the velocities at very high temperature may be found by use of equation 41, but the exact relationships have yet to be determined.

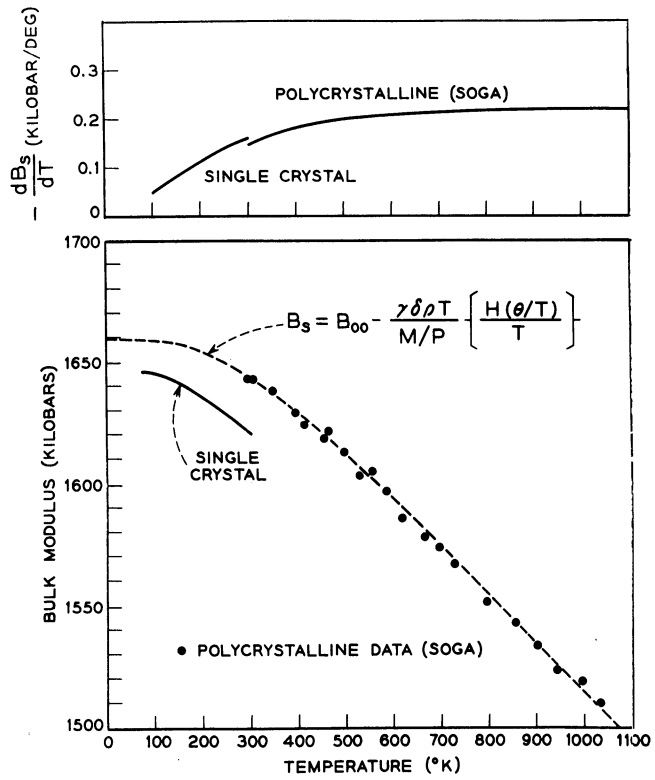

FIGURE 14. COMPARISON OF PREDICTED AND OBSERVED VALUES OF THE BULK MODULUS (B_S = K) AND ITS TEMPERATURE DERIVATIVE AS A FUNCTION OF TEMPERATURE [114]

4
CRITIQUE

4.1. PURPOSE

This report was planned to be of assistance to two kinds of readers: (1) the experimentalist who is designing apparatus to measure sound velocity, and (2) the geophysicist or geologist who has limited data on a material and wants also the value of the sound velocity in that material.

4.2. EXPERIMENTS TO PERFORM

In general, we feel that the pulse-transmission technique used by Birch will continue to be the most important method of obtaining data on real rocks. This technique represents a good compromise between accuracy of the experiment and quality of the specimen. There will be a perceptible shift from measurements on real rocks to measurements on synthetically prepared polycrystalline specimens. On synthetic specimens of high quality, interferometric methods can be used to measure accurate velocities with pressure and temperature. This method allows the precision required to find good pressure and temperature derivatives. Also on such specimens the temperature range can be substantially extended.

The resonance of small spheres will emerge as the most important new measurement technique. The ability to make good measurements on very small specimens will extend substantially our knowledge of mineralogy. Such a potential should hasten the solution of experimental and theoretical problems presently restricting its application. These problems will be less difficult than finding minerals of sufficient size to be measured by other techniques.

For geophysicists interested in understanding the inaccessible regions of the globe, methods of extrapolation will require the precision of ultrasonic interferometry. We expect that kind of experiment to grow among experimental geophysicists. The geophysicist who is also interested in internal friction measurements (not covered by this report) will tend to promote resonance or interferometric methods.

4.3. ESTIMATING SOUND VELOCITY FROM LIMITED DATA

The average researcher needing to know V_s or V_p will not be in a position to measure the property itself. Section 2 and the appendixes were written and presented especially for this reader. We have indicated how some limited data can be found.

There are a number of indirect methods for determining the velocity of sound in minerals. If the Debye temperature is known, V_s can be estimated. If the index of refraction and the

composition are known, V_s and V_p can be estimated. If the density is known and M/p can be determined, a rough estimate can be made.

A method of estimating velocities at very high pressure depends upon the condition that the bulk modulus is linear with pressure. The fact that the bulk modulus is linear with temperature will help estimates of the sound velocities at very high temperatures.

The reader will often encounter the case where some data on rocks are available at a particular pressure and temperature, but he requires data at another pressure or temperature. In this case, he can use the fact that the Poisson's ratio does not change substantially with pressure or temperature, and obtain Poisson's ratio at any condition of pressure and temperature. In this way a considerable amount of information on a rock can be estimated from limited data by using standard equations. This is the method proposed by Nafe and Drake [115] for basalts and will be discussed further in section 5, which deals with the data on rocks and how they are classified in this report.

5
DATA ON Vs AND Vp FOR ROCKS AND MINERALS

5.1. GENERAL COMMENTS

The data extant on rock and mineral velocities, as has been pointed out by Simmons [36], are not yet so numerous as to be unmanageable. Velocities have been measured versus pressure and temperature for several hundred rocks. An overabundance of data exists for certain common rocks such as granite, marble, and sandstone while very little is known about other rocks. The data also are not of uniform quality and precision because of differences in techniques and competence of investigators. Much of the best data were obtained by Birch and his former students and colleagues who learned their techniques in the Dunbar laboratory and who are now leaders in their own right. The contributions of Birch's school, both quantitative and qualitative, have placed us in a position to assess the future in this field.

In the appendixes we have attempted to present all of the data available as of June 1965 on the velocities of rocks and minerals. These data have been classified in a number of ways to expedite the retrieval of any desired information. In appendix 1, the properties (density, porosity, mean atomic weight, and compressional and shear sound velocities) of a multitude of rocks and minerals at room temperature and atmospheric pressure are given. The variation of V_p and V_s with pressure and temperature is presented in appendixes 2 through 5. The

petrographic modal analyses and the chemical analyses available for the rocks of appendixes 1 through 5 are given in appendixes 6 and 7. Appendix 8 is a reference table for all of the velocity data in appendixes 1 through 5 and is included so that the appendixes may be used as a reference source independently of the text of the report. In appendix 9, the properties of polycrystalline aggregates of certain minerals are calculated from the elastic constants of single crystals. The details involved in the preparation and presentation of the data in the appendixes are discussed more fully below.

The data in appendixes 1 through 3 have been organized and presented from a petrographic and mineralogical point of view. For a geophysicist, it would perhaps have been preferable to use a physical parameter such as density [33] to classify the data. Such a geophysical classification has great merit when the data are of uniform quality and precision. The data in the appendixes, as mentioned above, is not homogeneous. Since it was impossible to assign a quality factor to each bit of data, we group the data according to rock and mineral type and allow the reader to compare them.

Many schemes have been devised throughout the years to predict the elastic behavior of rocks on the basis of the known data. One of the schemes is discussed in detail in section 5.9. Recently, Nafe and Drake [115] presented a scheme based on the equations relating the elastic moduli of a homogeneous isotropic elastic material. The authors have applied their scheme to rocks of the granite and gabbro clans, the latter including gabbro, norite, diabase (dolerite), and basalt. These two clans are especially well suited to such a treatment since Poisson's ratio and the density are roughly constant for all the rocks in a class. Nafe and Drake assume:

$$\text{granite: } \rho = 2.65,\ \sigma = 0.26$$

$$\text{gabbro: } \rho = 3.00,\ \sigma = 0.28$$

Then, if one other elastic parameter is known, the elastic behavior is determined. Nafe and Drake plotted all the elastic parameters against the compressional sound velocity (see fig. 15).

This selection of V_p as the indicator variable is desirable inasmuch as V_p is the most accurately determinable parameter experimentally. Although it is necessary to use a different set of curves for every rock type, this scheme is useful in providing a graphical means of determining the degree to which a rock specimen behaves as a homogeneous isotropic elastic material.

The following subsections deal with explanations of the appendixes themselves.

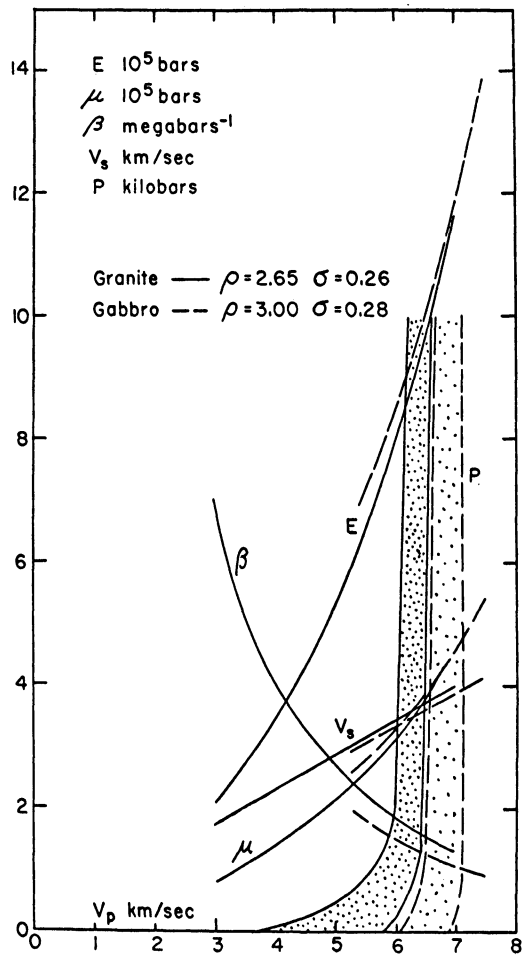

FIGURE 15. ELASTIC BEHAVIOR OF GRANITE AND GABBRO CLANS AS A FUNCTION OF COMPRESSIONAL VELOCITY BASED ON THE EQUATIONS RELATING THE ELASTIC MODULI OF A HOMOGENEOUS, ISOTROPIC, PERFECTLY ELASTIC MATERIAL [115]

5.2. PETROGRAPHY

The rocks in appendixes 1-3 are classified petrographically using the system of Williams, Turner, and Gilbert [116] (see Preface to Appendixes, p. 61).

The igneous rocks are arranged by degree of crystallinity and the volume percentages of mafic minerals and free silica. Those with mafic percentages less than 70% are divided into three groups according to the percentage of free silica: (1) oversaturated rocks which contain free silica of primary origin; (2) saturated rocks which contain neither free silica nor any un-

saturated minerals; and (3) undersaturated rocks which consist either wholly or in part of unsaturated minerals of mafic or feldspathic nature. Within these three groups the rocks may be separated into eucrystalline, generally extrusive or deep intrusive in origin, and dyscrystalline, generally extrusive or shallow intrusive in origin, according to the degree of crystallinity. The order of presentation within 1, 2, and 3 is approximately from acid to basic with the eucrystalline form followed by its dyscrystalline counterpart.

The igneous rocks in which mafic minerals constitute greater than 70% of the volume are classified under the ultramafic clan. Chemically, these rocks are generally ultrabasic with their SiO_2 content less than 45%; notable exceptions are the bronzitites (app. 7, p. 121).

Various fragmental igneous rocks and glasses conclude the subsection on igneous rocks.

A few identifying remarks on certain of the igneous rocks in this study are necessary. Albitite is a predominantly albite dike rock. Keratophyre (AD04) is an albite andesite. Norite is a gabbro with hypersthene predominating over the clinopyroxene. Strictly speaking, the olivine basalts from Hawaii and elsewhere presented in appendix 1 (BA07, BA08, BA09, BA11, BA18, BA21, BA23) should be in the nonfeldspathic group of the undersaturated rocks, but are presented with the remainder of the basalts for comparison. The trap rocks of the Deccan plateau of India are assumed to be close to basaltic composition [116, 117]. The term diabase has been adopted for rocks of gabbroic composition and texture intermediate between gabbro and basalt, in preference to the English term dolerite used in the Indian literature (see DB06, DB22). Harzburgite is a peridotite with orthopyroxenes accompanying the olivine. Chrysotile is the fibrous variety of serpentinite formed generally under static conditions, while antigorite is the flaky variety generally formed under stress conditions. The diabase glass (DB15) was produced by the General Electric Company from the Mt. Holyoke trap rock which is sometimes called the Westfield diabase. The chemical analysis in appendix 7 is that of the glass, but the modal analysis in appendix 6 is that of the parent rock.

The metamorphic rocks are not rigorously classified, but are ranked in approximate order of increasing metamorphic grade. The charnockites are included with the metamorphic rocks because many of them have the megascopic appearance of an acid plutonic gneiss [116]. An alternative classification would have been to include them with the igneous rocks as enstatite-hypersthene granites.

The sedimentary rocks are classified by the origin of their constituent material. The detrital rocks, containing primarily allogenic material, are the sandstones, shales, greywackes, and kaolin. The chemical and organic rocks, composed primarily of authigenic constituents, are the limestones, dolomites, and chalk.

5.3. MINERALOGY

The majority of the mineral specimens are single crystals, while some are polycrystalline aggregates of either natural or synthetic origin. Still others are really ore rocks composed primarily of one mineral (e.g., MG05, PR07, PR08).

The minerals in appendixes 1 through 3 are classified by the system of Deer, Howie, and Zussman [118] (see Preface to Appendixes, p. 62).

The silicate minerals are classified according to the structural arrangement of the individual silica tetrahedra (SiO_4):

(a) Ortho- and ring silicates: independent tetrahedra ($-SiO_4$) and double tetrahedra ($-Si_2O_7$)

(b) Single-chain silicates: infinite, one-dimensional, single-strand chains of tetrahedra ($-SiO_3$)

(c) Double-chain silicates: infinite, one-dimensional, double-strand chains of tetrahedra ($-Si_4O_{11}$)

(d) Sheet or layered silicates: infinite, two-dimensional sheets of tetrahedra ($-Si_2O_5$)

(e) Framework silicates: ($-S_iO_2$)

The nonsilicates are classified according to chemical composition:

(a) Oxides

(b) Sulfides

(c) Sulfates

(d) Carbonates

(e) Halides

(f) Carbon

5.4. APPENDIX 1, EXPLANATION

Appendix 1 includes data on the properties of rocks and minerals at or near room temperature and atmospheric pressure. All the measurements were taken at temperatures from 0^oC to 30^oC and pressures from 0 to 50 bars (1 bar = 0.98692 atmospheres = 1×10^6 dynes/cm^2 = 1.01971 kg/cm^2). Readings with an apostrophe added were taken at 25 to 50 bars.

The density (RHO) and, when available, the porosity (POR) are included. Verification of the anticipated inverse dependence of velocity upon porosity is possible for certain rocks (SS33-SS38), but for other specimens (PX01-PX05 and SS21-SS32) the dependence is less clear.

The mean atomic weight (M/p) has been calculated by Birch [104] from the chemical analyses of some of the rocks in his study. These values of M/p are applicable also to certain specimens in Simmons [35] and Verma [94] (see OV01, GT03, GT04). Further values of M/p could be calculated from the chemical analyses of appendix 7 and added to appendix 1. Still others could be calculated from the petrographic analyses of appendix 6 and the representative M/p values for minerals given by Birch [104] and Anderson and Schreiber [93].

Both compressional (VP1) and shear (VS1) sound velocities are given for the rocks. A second shear velocity (VS2) for minerals is included when available. In certain cases (notably in the work of Alexandrov and Ryzhova [119-121], Ryzhova [122], and Ryzhova and Alexandrov [123]) the directions of polarization of the shear modes are presented in the original paper but are not included here.

In appendixes 1 through 5, geographical origin (or catalog number for the Russian collection) is given for each specimen. In certain cases, descriptive or mineralogical adjectives are appended. The indexing system is used to aid in cross referencing rock data, petrographic and/or chemical analyses, and sources of data. Each rock and mineral type is assigned a two-letter index (see Preface to Appendixes, p 63) and a number is attached to this letter index. Each index refers to an individual specimen and/or a separate source of data. The only duplication is that Birch [124] quoted mean compressional velocities for serpentinites (SE15, SE16, SE17, SE18) from the data of Birch [33] for the same serpentinites (SE10, SE11, SE13, SE12, respectively).

Directional notation included in appendixes 1 through 5 indicates the direction of propagation of the sound wave through the specimen. X, Y, and Z refer to mutually perpendicular directions which have no specific relation to rock or crystal orientation. PAR and PERP refer to propagation directions either parallel or perpendicular to some structural feature of the rock such as foliation, bedding, schistosity, banding, or crystal alignment. The symbols [001] . . . [010], etc., refer to directions of zone axes along which the velocities have been measured in single crystals. Alexandrov and Ryzhova [119-121] and Ryzhova [122] have used an orthogonal system of coordinates for their velocity determinations, as pointed out by Christensen [125]. This transition for the crystals of the monoclinic system results in measurements of velocities in directions parallel to the c and b crystallographic axes and inclined (β^{o} - 90^{o}) to the a axis (see HO01, HO02, AE01, MI01, AZ01, AB05, OL02, OL03, OL04, LA01, LA02, LA03). The feldspars, which are triclinic (except orthoclase), are treated as having monoclinic symmetry by the Russian authors since α and γ are close to 90^{o} ($\pm 5^{o}$). Measurements of velocities in the layered silicates (see MU01, BI01, CH01, CH02, PH01, TC01) indicate that all the velocities

in the X-Y plane are equivalent where the Z axis is perpendicular to the (001) cleavage. This is in agreement with the observation that β is commonly close to 90° for minerals of the mica group [117], and these minerals are treated by the Russian authors as possessing hexagonal symmetry. Thus the [010] velocities are representative of the values in any direction in the X-Y plane which is parallel to the (001) cleavage. Nephelite (NE01, NE02) is a member of the hexagonal system and the notation used by the Russians ([100], [011]) is not the proper one for this class. These directions should be treated as any two mutually perpendicular directions in the plane of the a crystallographic axis. Even after these corrections, some ambiguity remains in the work on single crystals, since the energy propagation is not always found to be perpendicular to the faces of the specimen because of the tensorial character of the crystal properties [126].

A few remarks on data selection are appropriate. In general, the data from all of the rocks in a paper were presented, but in the work of Hirasawa [127] only the velocities of representative specimens were chosen; for the schists, specimens were chosen which best illustrate the extreme anisotropy mentioned by the author in his abstract. Christensen's [125] metagabbro was omitted, as were the data on the terrigeneous muds and globegerina ooze of Laughton [128], certain poorly consolidated shales of Hughes and his colleagues, and the volcanics of Iida and Kumazawa [45, 46] (see further comment below).

For the data found in foreign publications in which the velocity anisotropy was significant, all the values were presented since much of the work is not well known nor easily accessible in the United States. For the rocks of Woeber et al. [129], the mean velocities are given unless the anisotropy exceeded 10%. For the suite of rocks studied by Birch [33] and Simmons [35, 130], the anisotropy frequently disappeared at elevated pressures and rarely exceeded 2% to 3% for the oversaturated and saturated rocks at 10 kb [104]. All three values were reported for the dunites, serpentinites, bronzitites, pyroxenites, and harzburgites of these papers. For the gneisses and schists, we took the velocities either parallel and perpendicular to the foliation or the two extreme values if no indication was given as to orientation. For Christensen's [125] metamorphic rocks, all three mutually perpendicular velocities were presented regardless of degree of anisotropy. From Tooley [131], only selected means of the velocities in marble were presented since the author has stated in a personal communication that "thermally-induced structural damage makes this marble elastically isotropic."

5.5. APPENDIXES 2 AND 3, EXPLANATION AND COMMENTS

Appendixes 2 and 3 include data on the variation of the compressional and shear sound velocities with pressure. All measurements were taken at temperatures between 0° and 30°C.

The pressure range is from atmospheric pressure (1 bar) to 10 kb (9869 atmospheres). The pressures of the column headings are accurate within 3%. The special symbols which follow certain readings refer to pressures other than those of the column headings; these are fully explained on the first pages of appendixes 2 and 3. This notation may seem somewhat cumbersome, but it was considered necessary to enable presentation of all of the available data.

The pressures are hydrostatic unless otherwise indicated. "Axial pressure" (see LS28, LS44, SS57, SS63, SS66) refers to the pressure of uniaxial compression along the direction of propagation. Tocher [34] has observed that uniaxial compression parallel to the direction of propagation has approximately the same effect on the compressional velocity as hydrostatic pressure; compression perpendicular to the direction of propagation does not seem to affect the compressional velocity appreciably (see fig. 16). "Differential pressure" ($P_e - P_i$) of Gardner et al. [132] (see SS52) refers to the pressure difference between externally applied hydrostatic pressure and the internal pore pressure for sedimentary rocks. "Net overburden pressure" ($P_e - nP_i$) of Banthia et al. [133] (see SS48, SS51) refers to the differential pressure when a factor n (less than unity) reduces the effect of the pore pressure. For the rocks from Birch and Bancroft [134] and Ide [135] the values of the dynamic shear modulus were used to calculate the shear velocity, assuming the density to be constant with temperature and pressure.

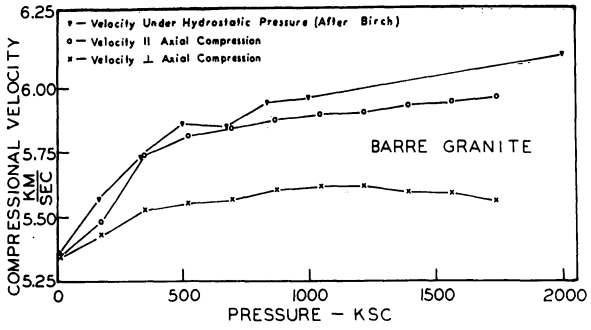

FIGURE 16. VARIATION OF COMPRESSIONAL VELOCITY OF BARRE GRANITE AS A FUNCTION OF AXIAL COMPRESSION AND HYDROSTATIC PRESSURE [34]

Both the compressional and the shear sound velocities of rocks and minerals generally increase with increasing pressure (see fig. 17 and 18). The rapid increase at low pressures is due to a decrease in porosity as shown by Birch and Hughes, closing of cracks and defects [88, 136], and an increase in the mechanical contact between the grains [137] (see fig. 19). At higher pressures, the velocity increase results from changes in the intrinsic properties of the rock

such as finite compression of the crystals. For certain specimens (see LS01, LS21, LS22, LS23, SS45, OB02, QU02), the sound velocity is observed to decrease when the pressure exceeds a certain value (see fig. 20).

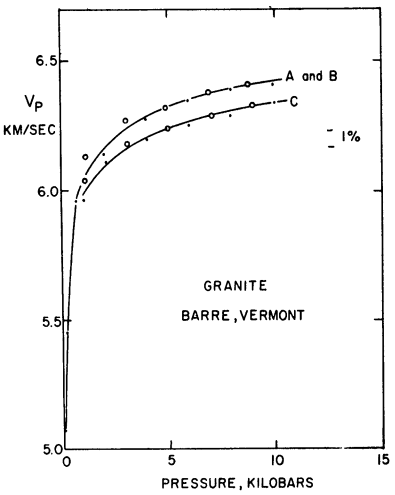

FIGURE 17. COMPRESSIONAL VELOCITY OF BARRE GRANITE AS A FUNCTION OF HYDROSTATIC PRESSURE. Dots indicate measurements with increasing pressure, circles with decreasing pressure. [33]

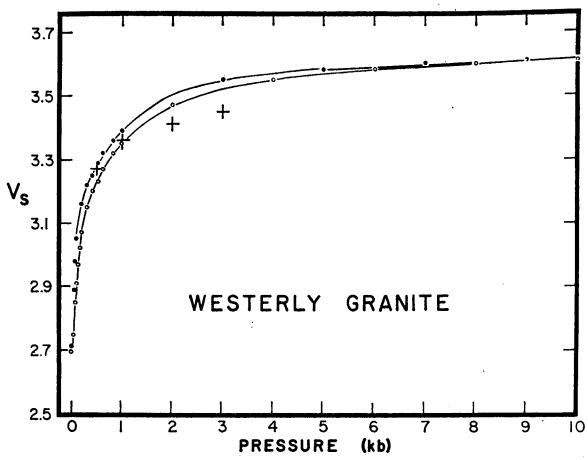

FIGURE 18. SHEAR VELOCITY OF WESTERLY GRANITE AS A FUNCTION OF HYDROSTATIC PRESSURE. The lower curve was obtained with increasing pressure, the upper curve with decreasing pressure. Crosses represent data from reference 133. [34]

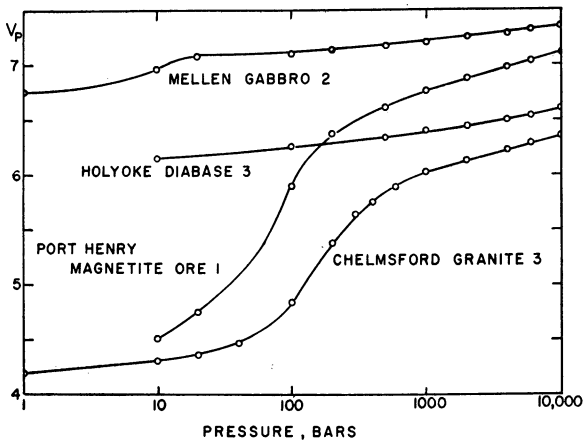

FIGURE 19. COMPRESSIONAL VELOCITY OF VARIOUS ROCKS AS A FUNCTION OF HYDROSTATIC PRESSURE. V_p is plotted against log P here to emphasize the behavior below 1 kb. [33]

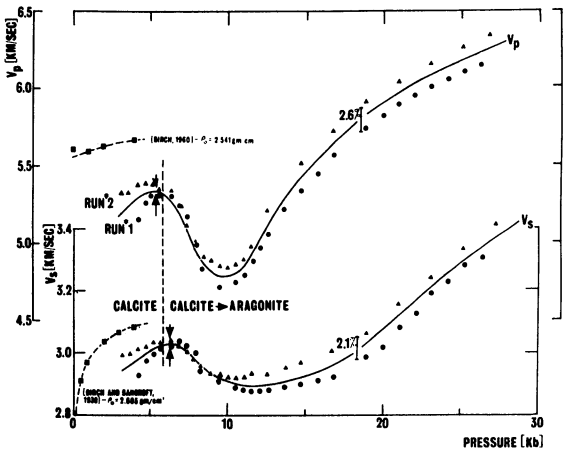

FIGURE 20. COMPRESSIONAL AND SHEAR VELOCITIES OF SOLENHOFEN LIMESTONE AS A FUNCTION OF HYDROSTATIC PRESSURE. The anomalous decrease of V above 5-6 kb is shown. [107]

For the limestones, Ahrens and Katz [107] have attributed this velocity inversion to a phase transition from calcite to aragonite with a concomitant density increase. Using the Solenhofen limestone specimen of Ahrens and Katz, Gordon and Vaisnys [138] have measured the compressional velocity at pressures up to 10 kb and observed no velocity decrease; the authors suggest that the velocity decreases observed by Ahrens and Katz are associated with the onset of the diffusionless calcite I to calcite II transformation. Simmons [36] has substantiated the occurrence of the velocity inversion for limestone without prescribing the mechanism.* A different approach to the problem is provided by the data in appendix 9. The arithmetic mean longitudinal (compressional) velocity of aragonite (5.840) is indeed lower than that of calcite (6.259-6.333), but the Voigt-Reuss limiting bounds are seen to overlap in every case. The arithmetic mean shear velocity, on the other hand, is higher for aragonite (3.657) than for calcite (3.264-3.423) with the bounds again overlapping. This overlapping, the small differences in predicted velocities, and the disagreement of the predicted and observed [107] shear-velocity behavior all lead us to doubt that a clear answer to the problem is presently available. The changes of velocity associated with phase changes has been discussed by Birch [104]. These changes will undoubtedly become even more significant when considering pressures in the shock-wave domain.

5.6. APPENDIXES 4 AND 5, EXPLANATION AND COMMENTS

Appendixes 4 and 5 include data on the variation of compressional and shear sound velocities with temperature. The temperature range is from room temperature (0^{o} to 25^{o}C) to 600^{o}C. Due to the limited amount of data, the rocks and minerals are presented in alphabetical order by index instead of by petrographical and mineralogical groups as in appendixes 1 through 3.

The pressure of each measurement is also indicated. It should be noted that Hughes and his colleagues measured velocity vs. pressure at constant values of temperature (see fig. 21), but never actually measured velocity vs. temperature at constant pressure. Simmons [36] refers to the work of Ide [6] as the first indication that measurements of elastic properties of rocks vs. temperature at atmospheric pressure destroys the rock and provides only irreproducible data (see fig. 22). Birch [112] pointed out that due to looseness of grains, cracks, porosity, and other rock defects, the only valid measurements of velocity vs. temperature are

*Professor Birch (private communication, January 1966) informs us that the work of Wang at Harvard clearly indicates that the transition in calcium carbonate rocks is not calcite to aragonite, but one of the diffusionless transformations of Bridgman [147].

those conducted at elevated pressures (see fig. 23). Even when this approach is used, it is important to demonstrate the lack of hysteresis [36]. In view of these considerations, only those measurements conducted at pressures greater than 1 kb were included in appendixes 4 and 5; specifically, the work of certain Japanese and Indian investigators has been omitted.

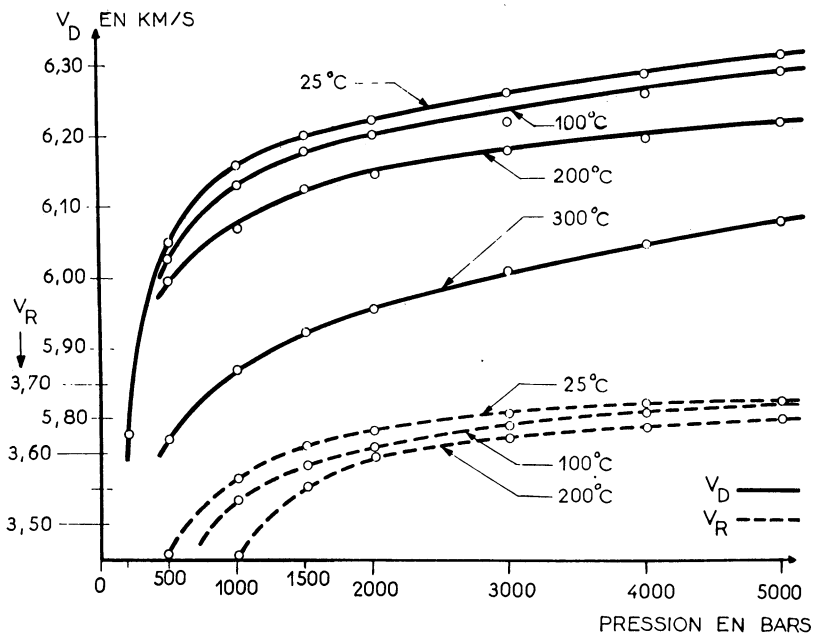

FIGURE 21. COMPRESSIONAL (V_D) AND SHEAR (V_R) VELOCITIES AS A FUNCTION OF HYDROSTATIC PRESSURE AT VARIOUS TEMPERATURES [139]

This criterion of elevated pressures is not necessary for work on single crystals of gem quality or on polycrystalline aggregates in which departures from homogeneity are negligible. Schreiber and Anderson [63] have measured the sound velocity vs. temperature for a synthetic specimen of MgO and also for polycrystalline Al_2O_3 (AA02) over the same range, -80^oC to $+25^oC$. The precision of the interferometric methods enables them to detect even small changes in velocity within this narrow temperature range (see fig. 24). Using Förster's dynamic resonance method, Soga has been able to obtain data on the elastic moduli of synthetic polycrystalline aggregates (grain size $<40\ \mu$, porosity $<1\%$) of MgO and Al_2O_3 (same as MS01-03, AA02-03) at temperatures in excess of 1000^oC [19]. This extension of the temperature range more clearly delineates the temperature gradients of the elastic moduli.

Measurements of the velocity vs. temperature for fused silica (QU05, QU06) at atmospheric pressure were included to show the marked contrast in behavior between silica and

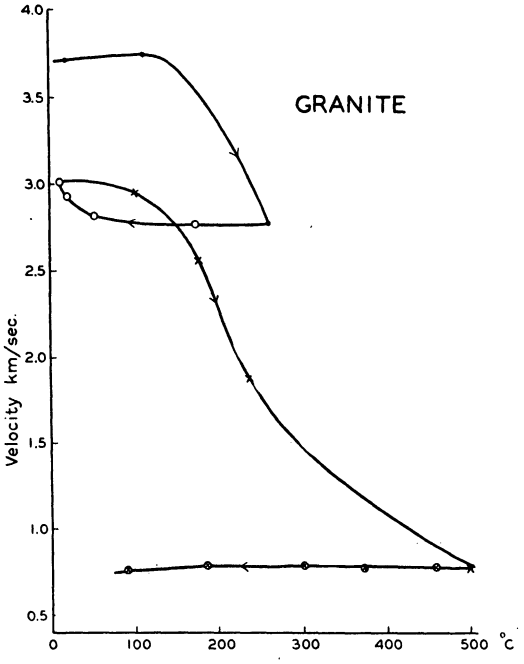

FIGURE 22. EFFECT OF THERMAL CYCLING AT ROOM PRESSURE ON THE COMPRESSIONAL VELOCITY OF QUINCY GRANITE. Reproduced by permission of the University of Chicago Press from J. M. Ide, Journal of Geology, Vol. 45, 1937 [6].

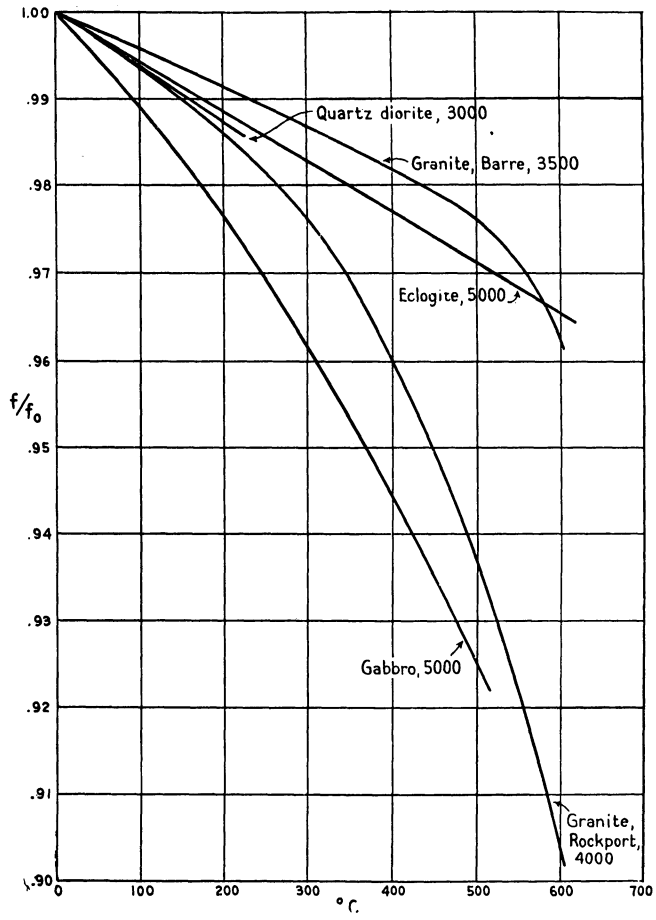

FIGURE 23. RELATIVE FREQUENCY OF THE RESONANT SHEAR-MODE VIBRATIONS IN CYLINDERS OF CERTAIN ROCKS AS A FUNCTION OF TEMPERATURE. Measurements were taken at the elevated pressures (in kilograms per square centimeter) indicated. [8]

rocks (see fig. 25 and 26). This anomalous increase of velocity with temperature was first noticed by Iida [140]. Iida and Kumazawa [46] have attempted to relate the anomalous behavior of their volcanic rocks to the amount and polymorph (cristobalite or quartz) of free silica in the rocks; this explanation is dubious since the experiments were conducted at atmospheric pressure and the velocities are so extremely low as to be questionable.

5.7. APPENDIXES 6 AND 7, EXPLANATION

Appendixes 6 and 7 include the petrographic modal analyses and the chemical analyses available for the rocks in appendixes 1 through 5.

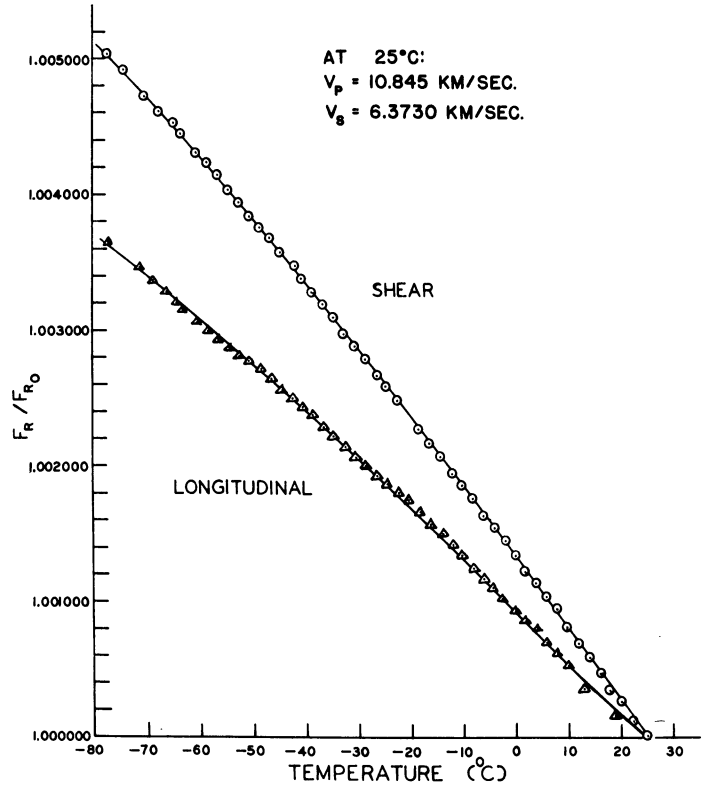

FIGURE 24. RELATIVE FREQUENCY OF THE PSEUDO-RESONANCE MODES IN POLYCRYSTALLINE Al_2O_3 AS A FUNCTION OF TEMPERATURE [63]

The rocks and minerals are presented in alphabetical order by index. Inset entries indicate that the analysis also applies to these specimens, although the specimens are not necessarily identical. (They often are different cores of the same rock or different rocks from the same locality.)

The references for the analyses are included at the end of appendixes 6 and 7. These are not necessarily references to the original source, but to the papers from which we obtained the analyses. In certain cases, notably with respect to the Daly collection at Harvard, the analyses are old but are quoted from recent papers of Birch [17, 104] and apply as well to rocks studied earlier. All of this should be evident in the cross-indexing system.

5.8. APPENDIX 8, EXPLANATION

Appendix 8 lists the references for the velocities of appendixes 1 through 5. More complete references with titles included are given in the bibliography. This appendix has been included to enable easy reference to the source of the data.

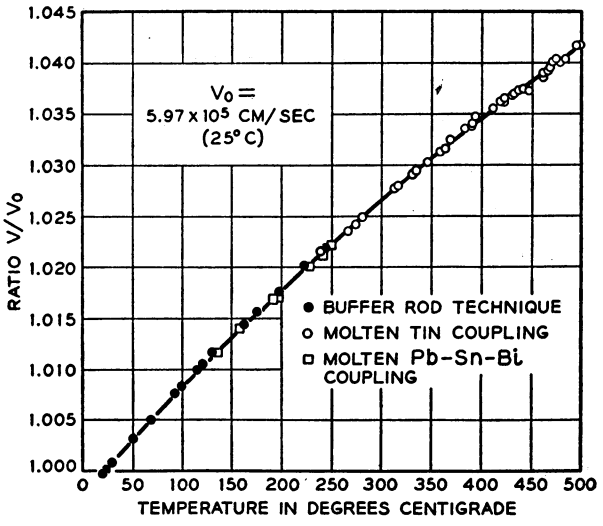

FIGURE 25. COMPRESSIONAL VELOCITY OF FUSED SILICA AS A FUNCTION OF TEMPERATURE AT ROOM PRESSURE [58]

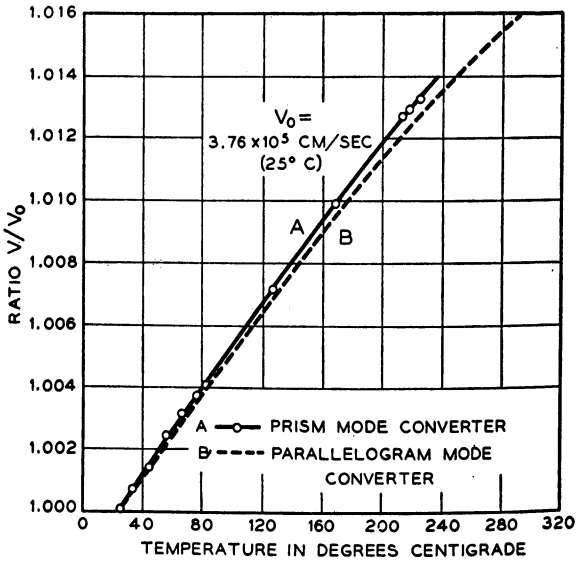

FIGURE 26. SHEAR VELOCITY OF FUSED SILICA AS A FUNCTION OF TEMPERATURE AT ROOM PRESSURE [58]

5.9. APPENDIX 9, EXPLANATION AND COMMENTS

Appendix 9 includes data on the properties of isotropic polycrystalline aggregates of certain minerals as calculated from the measured elastic constants and/or compliances of single crystals. These calculated properties correspond to a homogeneous isotropic elastic solid with random orientation of crystal grains and zero porosity. Simmons [141] has recently published an excellent and comprehensive compilation of the available single-crystal data and computed the isotropic elastic moduli. This work is an invaluable reference for investigators in the field and we do not wish to duplicate this work. We have included in appendix 9 only the data on the naturally occurring minerals, certain of which are of particular interest to the geophysicist or the geologist in the study of the composition of the interior of the earth. The methods employed in these calculations are described in detail by Anderson [68] and are only summarized here.

Hill [142] derived a method for calculating the elastic moduli for polycrystalline aggregates, pointing out from energy considerations that the two classical approximations of Voigt [143] and Reuss [144] were limits and suggesting an explanation of the fact that measured values were intermediate.

Voigt averaged over all crystal orientations using the assumption that the strain is uniform throughout a grain. Reuss did the averaging by assuming the stress to be uniform

throughout a grain. Hill showed that the Voigt approximation tends to make the elastic moduli larger than they should be so that the Reuss approximation tends to make them smaller, so that the true isotropic values of K and μ are given by the equations in section 3.7.

Another important elastic constant relating single crystals and polycrystalline aggregates is the elastic constant, c_a, used in calculating the Debye temperature θ. The Debye temperature is an important parameter of a solid. It is found in equations describing properties that arise from atomic vibrations and in theories involving phonons.

One of the standard methods of calculating the Debye temperature is from elastic-constant data, since θ is proportional to the sound velocity (averaged) by the equation

$$\theta = \frac{h}{k}\left(\frac{3p}{4\pi}\frac{N\rho}{M}\right)^{1/3}\sqrt{\frac{c_a}{\rho}}$$

where h/k have the usual meanings of quantum mechanics, N is Avogadro's number, ρ is the density, M is the molecular weight of the solid, and p is the number of atoms in the molecule (p = 2 for NaCl, 3 for CaF_2).

The value $\sqrt{c_a/\rho}$ is often called the mean sound velocity, V_m. For isotropic materials, the relationship of V_m to the compressional sound velocity and the shear sound velocity is given by

$$V_m = \left[\frac{1}{3}\left(\frac{2}{V_s^3} + \frac{1}{V_p^3}\right)\right]^{-1/3}$$

In this case, the results are valid for truly isotropic materials such as glass and for polycrystalline materials for which the shear and compressional sound velocities V_s and V_p are invariant with direction.

Application to crystal classes with lower symmetry than isotropy is hindered by the problem of finding V_m. Since θ is a scalar, it follows the V_m must also be a scalar, and herein lies the difficulty of this method. The stress is a tensor quantity, and for each direction in a crystal there are three velocities, each of which is a complicated function of the stress components. The expression for V_m is [95]:

$$V_m = \left(\frac{1}{3}\sum_{i=1}^{3}\int_V \frac{1}{V_i^3}\frac{d\Omega}{4\pi}\right)^{-1/3}$$

This integral is solved by numerical methods as follows: The three sound velocities, V_1, V_2, V_3, are found for an arbitrary direction and then stored; the process is repeated for a

large sample of directions throughout all directions in space; and a numerical summation using Simpson's rule is made in place of the volume integral.

This method is the rigorous way to find the mean sound velocity, but it is impractical to use except with high-speed computers. The solution of the equation requires knowledge of the elastic constants of the crystal. Alternatively, the mean sound velocity may be predicted from the isotropic moduli. The Voigt and Reuss moduli are used to calculate compressional and shear velocities which are in turn averaged to obtain the Hill velocities:

$$\bar{V}_p = \frac{1}{2}(V_{pV} + V_{pR})$$

$$\bar{V}_s = \frac{1}{2}(V_{sV} + V_{sR})$$

These isotropic velocities can then be used to predict the mean sound velocity:

$$\bar{V}_m = \sqrt{\frac{c_a}{\rho}} = \left[\frac{1}{3}\left(\frac{2}{\bar{V}_s^3} + \frac{1}{\bar{V}_p^3}\right)\right]^{-1/3}$$

whose value is close to the value obtained from the numerical integration (V_m).

In appendix 9, the collected single-crystal data are used in an IBM 7090 program designed to compute the isotropic moduli using the Voigt and Reuss approximations and to compute the mean sound velocity, V_m, using numerical integration.

The following are read into the computer program as input data: the elastic constants, C_{ij}, or the elastic compliances, S_{ij}; the density; the molecular weight of the crystal; the limits of integration (for a cubic crystal the limits correspond to one-fourth of the sphere); and the increment of angles in the numerical integration (usually 5^o).

The elastic compliances are computed from the elastic constants, or vice versa, by a subroutine which inverts any n × n matrix of reasonable size.

After the mean sound velocity V_m is computed and the Debye temperature θ is calculated from it, the Voigt and Reuss values of the bulk modulus K and the shear modulus μ are determined. From K and μ, the other moduli and the various sound velocities are obtained for each approximation from the equations:

Young's modulus: $$E = \frac{9K\mu}{3K + \mu}$$

Longitudinal modulus: $$\rho V_p^2 = K + 4\mu/3$$

Poisson's ratio: $$\sigma = \frac{3K - 2\mu}{2(3K + \mu)}$$

Longitudinal (compressional) velocity: $$V_p = \left(\frac{K + 4\mu/3}{\rho}\right)^{1/2}$$

Shear velocity: $$V_s = (\mu/\rho)^{1/2}$$

Bulk velocity: $$C_o = (K/\rho)^{1/2}$$

Mean (average) velocity: $$\overline{V}_m = \left[\frac{1}{3}\left(\frac{2}{\overline{V}_s^3} + \frac{1}{\overline{V}_p^3}\right)\right]^{-1/3}$$

The arithmetic means of all of these quantities are also given in appendix 9.

A comparison of the mean sound velocity determined from the numerical integration, V_m, with that predicted from the isotropic moduli, $\overline{V}_m$, offers a check on the validity of the Hill scheme. In each case, a percentage error is calculated:

$$\Delta = \frac{\overline{V}_m - V_m}{V_m}$$

Values of Δ less than a few percent increase our confidence in the validity of the Hill scheme for determining the isotropic moduli of polycrystalline aggregates from the elastic constants of single crystals.

In appendix 9, the source of the single-crystal data and the temperatures at which the measurements were taken are indicated for each entry. The elastic constants for the magnetite specimens CU193701 and CU193702 (p. 149) are identical. Clark and Strakna [145] obtained their values from Doraiswami [146]; this duplication was overlooked until the appendixes were in final form.

6
PREFACE TO APPENDIXES

PETROGRAPHIC CLASSIFICATION OF ROCKS IN APPENDIXES 1-3

IGNEOUS ROCKS

	EUCRYSTALLINE	DYSCRYSTALLINE
OVERSATURATED ROCKS	GRANITE	RHYOLITE
	QUARTZ MONZONITE	QUARTZ LATITE
	GRANODIORITE	DACITE
	QUARTZ DIORITE--TONALITE	
	QUARTZ GABBRO	
SATURATED ROCKS	SYENITE	TRACHYTE
		LATITE
	DIORITE	ANDESITE
	ALBITITE-OLIGOCLASITE	KERATOPHYRE
	GABBRO--NORITE DIABASE	BASALT
	ANORTHOSITE	TRAP
UNDERSATURATED ROCKS	FELDSPATHOIDAL SYENITES	

ULTRAMAFIC ROCKS

- DUNITE
- PERIDOTITE
  - HARZBURGITE
- PYROXENITE
  - BRONZITITE
- SERPENTINITE
  - CHRYSOTILE
  - ANTIGORITE
- PORPHYRY

FRAGMENTAL ROCKS

- VOLCANIC BRECCIA
- TUFF
- BASALTIC SCORIA

GLASSES

- OBSIDIAN
- DIABASE GLASS

METAMORPHIC ROCKS

- SCHIST
- SLATE
- GNEISS
- CHARNOCKITE
- MARBLE
- QUARTZITE
- AMPHIBOLITE
- ECLOGITE

SEDIMENTARY ROCKS

DETRITAL ROCKS

- SANDSTONE
- GREYWACKE
- SHALE
- KAOLIN

CHEMICAL AND ORGANIC ROCKS

- LIMESTONE
- CHALK
- DOLOMITE

STRUCTURAL CLASSIFICATION OF MINERALS IN APPENDIXES 1-3

ORTHO- AND RING SILICATES

OLIVINE GROUP
- OLIVINE
- MONTICELLITE

GARNET GROUP
- GARNET
  - GROSSULARITE
  - ALMANDITE-PYROPE

AL2SIO5 GROUP
- SILLIMANITE

OTHERS
- ZIRCON
- IDOCRASE
- STAUROLITE

SINGLE CHAIN SILICATES

PYROXENE GROUP
- DIOPSIDE
- AUGITE
- AEGIRITE
- JADEITE

PYROXENOID GROUP
- WOLLASTONITE

DOUBLE CHAIN SILICATES

AMPHIBOLE GROUP
- ANTHOPHYLLITE
- TREMOLITE
- HORNBLENDE

SHEET OR LAYERED SILICATES
- MUSCOVITE
- PHLOGOPITE
- BIOTITE
- TALC
- CLINOCHLORE
  - LEICHTENBERGITE

FRAMEWORK SILICATES

SIO2 GROUP
- QUARTZ
- FUSED SILICA
- OPAL

ALKALI FELDSPARS
- ORTHOCLASE
- MICROCLINE
  - AMAZONITE

PLAGIOCLASE FELDSPARS
- ALBITE
- OLIGOCLASE
- LABRADORITE
- BYTOWNITE

FELDSPATHOIDAL GROUP
- NEPHELITE

NON-SILICATES

OXIDES
- MAGNESIA
- ALUMINA
- HEMATITE
- LIMONITE
- SPINEL
- MAGNETITE

SULFIDES
- PYRITE
- PYRRHOTITE
- GALENA

SULFATES
- ANHYDRITE

CARBONATES
- CALCITE
- ARAGONITE
- MAGNESITE

HALIDES
- HALITE

CARBON
- GRAPHITE

CODE INDEX FOR ROCKS AND MINERALS IN APPENDIXES 1-8

AA	ALUMINA (CORUNDUM)
AB	ALBITITE
AD	ANDESITE
AE	AEGIRITE
AH	ANHYDRITE
AM	AMPHIBOLITE
AN	ANORTHOSITE
AP	ANTHOPHYLLITE
AR	ARAGONITE
AU	AUGITE
AZ	AMAZONITE
BA	BASALT
BI	BIOTITE
BR	BRONZITITE
BY	BYTOWNITE
CA	CALCITE
CH	CLINOCHLORE
CK	CHARNOCKITE
CL	CHALK
DB	DIABASE
DC	DACITE
DO	DOLOMITE
DP	DIOPSIDE
DT	DIORITE
DU	DUNITE
EC	ECLOGITE
GA	GALENA
GD	GRANODIORITE
GN	GNEISS
GP	GRAPHITE
GR	GRANITE
GT	GARNET
GY	GREYWACKE
HA	HALITE
HB	HARZBURGITE
HE	HEMATITE
HO	HORNBLENDE
ID	IDOCRASE
JD	JADEITE
KA	KAOLIN
LA	LABRADORITE
LM	LIMONITE
LS	LIMESTONE
LT	LATITE
MA	MARBLE
MG	MAGNETITE
MI	MICROCLINE
MN	MAGNESITE
MO	MONTICELLITE
MS	MAGNESIA (PERICLASE)
MU	MUSCOVITE
NE	NEPHELITE
NG	NORITE AND GABBRO
OB	OBSIDIAN
OL	OLIGOCLASITE AND OLIGOCLASE
OR	ORTHOCLASE
OV	OLIVINE
PE	PERIDOTITE
PH	PHLOGOPITE
PO	PORPHYRY
PR	PYRITE
PT	PYRRHOTITE
PX	PYROXENITE
QD	QUARTZ DIORITE
QG	QUARTZ GABBRO
QL	QUARTZ LATITE
QM	QUARTZ MONZONITE
QU	QUARTZ (AND SILICA AND OPAL)
QZ	QUARTZITE
RH	RHYOLITE
SC	SCHIST
SE	SERPENTINITE (INCL. ANTIGORITE AND CHRYSOTILE)
SH	SHALE
SI	SILLIMANITE
SL	SLATE
SN	SPINEL
SS	SANDSTONE
ST	STAUROLITE
SY	SYENITE
TA	TRACHYTE
TC	TALC
TP	TRAP
TR	TREMOLITE
TU	TUFF
VB	VOLCANIC BRECCIA
WO	WOLLASTONITE
ZR	ZIRCON

Appendix 1

PROPERTIES OF ROCKS AT STANDARD TEMPERATURES AND PRESSURES

(SOURCES OF DATA LISTED IN APPENDIX 8)
(DATA AT ROOM TEMPERATURE AND PRESSURE UNLESS OTHERWISE SPECIFIED
' PRESSURE=25-50 BARS. RHO=DENSITY. POR=POROSITY IN PERCENT. M/P=MEAN ATOMIC WEIGHT. VP1=COMPRESSIONAL VELOCITY IN KM./SEC. VS1=SHEAR VELOCITY. VS2=SECOND SHEAR VELOCITY--FOR MINERALS)

ROCKS

IGNEOUS ROCKS

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
OVERSATURATED							
GRANITE	2.619	.	20.9	4.1	.	.	GR25
WESTERLY,R.I.							
GRANITE	2.66	.	.	5.76	.	.	GR03
WESTERLY,R.I.							
GRANITE	2.636	.	20.9		2.77	.	GR37
WESTERLY,R.I.							
GRANITE	2.64				2.28		GR80
WESTERLY,R.I.							
GRANITE	2.64				2.68		GR85
WESTERLY,R.I.							
GRANITE	2.621	.	20.9	5.1	.	.	GR26
QUINCY,MASS.							
GRANITE SURFACE	2.61				2.78		GR81
100 FT.	2.59				3.26		GR83
235 FT.	2.64				2.75		GR82
QUINCY,MASS.							
GRANITE	2.64				2.53		GR78
QUINCY,MASS.							
GRANITE	2.624	.	20.6	5.0	.	.	GR27
ROCKPORT,MASS.							
GRANITE	2.638	.	20.6		3.07		GR38
ROCKPORT,MASS.							
GRANITE	2.62				2.55		GR79
ROCKPORT,MASS.							
GRANITE	2.63				2.66		GR84
ROCKPORT,MASS.							
GRANITE	2.626	.	20.8	4.2	.	.	GR29
CHELMSFORD,MASS.							
GRANITE	2.655	.	.	5.1	.	.	GR31
BARRE,VT.							
GRANITE	2.665	.	20.8		2.79	.	GR40
BARRE,VT.							
GRANITE X	2.66			4.77	2.70		GR87
Y	2.66			4.22	2.83		GR87
Z	2.66			5.09	2.89		GR87
WOODBURY,VT.							

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
GRANITE	2.625	.	20.7	3.7	.	.	GR28
STONE MT.,GA.							
GRANITE	2.639	.	20.7		2.43	.	GR39
STONE MT.,GA.							
GRANITE	2.662	.	.	5.9	.	.	GR32
SACRED HEART,MINN.							
GRANITE	2.610			5.52'	3.04'		GR42
BEAR MT.,TEX.							
GRANITE RED	.	.	.	4.39	.	.	GR22
COLORADO							
GRANITE GREY	.	.	.	4.95	.	.	GR23
COLORADO							
GRANITE ALTERED	.	.	.	4.03	.	.	GR24
COLORADO							
GRANITE				5.64	2.87		GR41
BARRIEFIELD,ONT.							
GRANITE	2.672	.	.	5.7	.	.	GR33
BARRIEFIELD,ONT.							
GRANITE	2.683	.	.	5.7	.	.	GR36
LATCHFORD,ONT.							
GRANITE	2.679	.	.	6.1	.	.	GR35
ENGLEHART,ONT.							
GRANITE	.	.	.	4.64	3.07	.	GR06
USSR 137							
GRANITE	2.62	0.41	.	4.56	.	.	GR07
USSR 137							
GRANITE	.	.	.	4.95	2.90	.	GR04
USSR 247							
GRANITE	.	.	.	5.30	3.50	.	GR05
USSR 248							
GRANITE				5.50	3.63		GR77
USSR 249							
GRANITE	2.58	.	.	4.60	.	.	GR08
USSR 732							
GRANITE	2.62	.	.	5.00	2.93	.	GR09
USSR 1776							
GRANITE PAR	2.620	.	.	6.57	.	.	GR18
PERP	2.623	.	.	5.98	.	.	GR18
KONDAVIDU,INDIA							
GRANITE PAR	.	.	.	6.21	2.89	.	GR19
PERP	.	.	.	6.41	3.02	.	GR19
INDIA 1							
GRANITE PAR	.	.	.	6.02	2.82	.	GR20
PERP	.	.	.	6.13	2.95	.	GR20
INDIA 2							
GRANITE PAR	.	.	.	5.77	2.63	.	GR21
PERP	.	.	.	6.08	2.93	.	GR21
INDIA 3							
GRANITE	2.80			7.16	2.37		GR86
HYDERABAD,INDIA							
GRANITE A	2.676	.	.	5.7	.	.	GR34
HYDERABAD,INDIA							
GRANITE B	2.654	.	.	5.4		.	GR30
HYDERABAD,INDIA							

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
GRANITE PINK	2.732	.	.	7.14	.	.	GR10
PINK	2.74	.	.	6.40	.	.	GR11
PINK	2.68	.	.	5.85	.	.	GR12
PINK	2.606	.	.	6.58	.	.	GR13
GREY	2.82	.	.	6.41	.	.	GR14
GREY	2.66	.	.	6.20	.	.	GR15
GREEN	2.76	.	.	7.08	.	.	GR16
	2.7	.	.	6.4	3.3	.	GR17
HYDERABAD,INDIA							
GRANITE	2.8	.	.	5.69	.	.	GR01
HIDAKA,JAPAN							
GRANITE	2.6	.	.	5.92	.	.	GR02
HIDAKA,JAPAN							
GRANITE-1	2.54			4.86			GR88
FUKUI, JAPAN							
GRANITE-7	2.45			5.38			GR89
KYOTO, JAPAN							
GRANITE 1	2.86	.	.	5.75	3.27	.	GR60
2	2.77	.	.	5.77	3.50	.	GR61
3	2.79	.	.	5.38	3.16	.	GR62
4	2.76	.	.	5.89	3.37	.	GR63
5	2.77	.	.	5.63	3.16	.	GR64
6	2.65	.	.	4.91	2.89	.	GR65
7	2.78	.	.	4.45	2.70	.	GR66
8	2.77	.	.	4.86	3.00	.	GR67
9	2.71	.	.	4.56	2.78	.	GR68
10	2.70	.	.	5.40	3.05	.	GR69
11	2.68	.	.	4.83	2.96	.	GR70
12	2.62	.	.	5.02	3.10	.	GR71
13	2.94	.	.	5.30	3.03	.	GR72
14	2.87	.	.	5.18	2.88	.	GR73
15	2.77	.	.	4.09	2.51	.	GR73
16	2.70	.	.	5.71	3.55	.	GR74
17	2.70	.	.	4.77	2.81	.	GR75
18	2.77	.	.	4.62	2.85	.	GR76
JAPAN SUITE							
RHYOLITE	2.39			4.10	2.46		RH02
CHAFFEE CO.,COLO.							
RHYOLITE X	2.05			3.47	1.95		RH03
Y	2.05			3.19	2.06		RH03
Z	2.05			3.16	1.94		RH03
CASTLE ROCK,COLO.							
RHYOLITE	2.75			6.99	3.19		RH01
SUJARGARH (BIKANEER),INDIA							
QTZ. MONZONITE	2.628			5.26'	2.89'		QM03
WESTERLY,R.I.							
QUARTZ MONZONITE	2.65			5.82	3.46		QM04
WESTERLY, R.I.							
QTZ. MONZONITE	2.644	.	.	5.1	.	.	QM02
PORTERVILLE,CAL.							
QTZ. MONZONITE	2.652	.	.	.	3.16	.	QM01
PORTERVILLE,CAL.							

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
QUARTZ LATITE X	2.46			3.89	2.23		QL01
Y	2.46			3.50	2.14		QL01
Z	2.46			3.76	2.32		QL01
CHAFFEE CO.,COLO.							
GRANODIORITE	2.705	.	.	4.4	.	.	GD01
BUTTE,MONTANA							
GRANODIORITE	2.63	.	.	.	3.14	.	GD02
WESTON,MASS.							
QUARTZ DIORITE	2.906	.	.	5.5	.	.	QD03
DEDHAM,MASS.							
QUARTZ DIORITE	2.928	.	.	.	3.39	.	QD05
DEDHAM,MASS.							
QUARTZ DIORITE	2.798	.	.	5.1	.	.	QD02
SAN LUIS REY QUAD.,CAL.							
TONALITE	2.763	.	.	5.1	.	.	QD01
VAL VERDE,CAL.							
TONALITE	2.76	.	.	.	3.12	.	QD04
VAL VERDE,CAL.							
DACITE	2.67			6.50	3.33		DC01
BOULDER,COLO.							
QUARTZ GABBRO	2.99			6.46	3.50		QG01
SALEM, MASS.							
SATURATED							
SYENITE	2.780	.	22.1	5.7	.	.	SY02
SUDBURY,ONTARIO							
SYENITE	2.79				2.43		SY03
PENINSULA STATION,ONTARIO							
SYENITE	2.72	.	.	5.00	2.99	.	SY01
USSR 31							
TRACHYTE	2.60			5.18	2.83		TA02
HAWAII							
TRACHYTE	2.61			4.94	2.49		TA03
HAWAII							
TRACHYTE	2.62			6.00	3.32		TA04
BANNOCKBURN TWP.,ONTARIO							
TRACHYTE-TUFF X	2.42			3.96	2.59		TA05
Y	2.42			4.74	2.72		TA05
Z	2.42			4.65	2.66		TA05
CRIPPLE CREEK,COLO.							
LATITE X	2.45			4.10	2.38		LT01
Y	2.45			3.70	2.10		LT01
Z	2.45			3.51	2.15		LT01
CHAFFEE CO.,COLO.							
DIORITE	3.025	.	.	.	3.06		DT01
SALEM,MASS.							
DIORITE	2.91			5.34	3.24		DT02
JACKSON, WYO.							
ALBITITE	2.615	.	.	6.07	.	.	AB01
SYLMAR,PA.							
ALBITITE	2.615	.	.	.	3.43	.	AB02
SYLMAR,PA.							
ALBITITE	2.62	.	.	.	3.32	.	AB03
SYLMAR,PA.							

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
OLIGOCLASITE	2.687	.	.	6.40	.	.	OL01
SYLMAR,PA.							
ANDESITE	2.618			5.23'	2.73'		AD04
SALIDA,COLO.							
ANDESITE	2.70			5.66	3.22		AD08
SAN JUAN CO., COLO.							
ANDESITE	2.68			5.41	3.33		AD07
BOULDER CO.,COLO.							
ANDESITE	.	.	.	5.36	.	.	AD01
COLORADO							
ANDESITE-HORN. X	2.32			2.71	1.75		AD05
Y	2.32			2.77	1.80		AD05
Z	2.32			2.50	1.64		AD05
MT. SHASTA,CAL.							
ANDESITE	.	.	.	5.23	.	.	AD03
ANDESITE-VESICULAR	2.57			5.46	3.04		AD06
CHAFFEE CO.,COLO.							
ANDESITE BRECCIA	2.73			4.76	3.17		AD09
OURAY, COLO.							
KERATOPHYRE	2.612	.	.	6.16	.	.	AD02
WALES							
GABBRO	3.054	.	21.8	5.8	.	.	NG07
FRENCH CREEK,PA.							
GABBRO	3.033				3.27		NG18
FRENCH CREEK,PA.							
GABBRO	3.05				3.30		NG21
FRENCH CREEK,PA.							
GABBRO	2.931	.	21.8	6.8	.	.	NG05
MELLEN,WISC.							
GABBRO	2.90				3.37		NG19
MELLEN,WISC.							
GABBRO	2.874	.	.	.	3.59	.	NG08
SAN MARCOS,CAL.							
GABBRO	2.96			6.07			NG16
USSR 38							
GABBRO	2.96			6.46			NG15
USSR 82							
GABBRO	2.8	.	.	6.88	.	.	NG02
HIDAKA,JAPAN							
NORITE	3.057			6.18'	3.24'		NG10
ESSEX CO.,N.Y.							
NORITE	2.86				3.16		NG17
SUDBURY,ONTARIO							
NORITE	2.85				3.62		NG20
SUDBURY,ONTARIO							
NORITE	2.978	.	.	6.6	.	.	NG06
PRETORIA,TRANSVAAL							
NORITE	2.984	.	.	.	3.56	.	NG09
PRETORIA,TRANSVAAL							
NORITE	2.93	.	.	6.50	.	.	NG01
USSR 466							
NORITE	2.95	.	.	6.4	.	.	NG04
USSR 466							
NORITE	3.08	.	.	6.60	.	.	NG03
KONDAPALLI,INDIA							

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
ANORTHOSITE TAHAWUS,N.Y.	2.678	.	.	6.73	.	.	AN01
ANORTHOSITE WHITEFACE MT.,N.Y.	2.712	.	.	6.28	.	.	AN05
ANORTHOSITE STILLWATER,MONT.	2.770	.	.	6.5	.	.	AN02
ANORTHOSITE STILLWATER,MONT.	2.750	.	.	.	3.56	.	AN06
ANORTHOSITE STILLWATER,MONT.	2.74	.	.	.	3.59	.	AN07
ANORTHOSITE-GABBRO DULUTH, MINN.	2.75			6.73	3.69		AN09
ANORTHOSITE NEW GLASCOW,QUE.	2.708	.	21.1	6.54	.	.	AN04
ANORTHOSITE BUSHVELD,TRANSVAAL	2.807	.	21.3	5.7	.	.	AN03
DIABASE MT. TOM, MASS.	2.97			5.96	3.38		DB23
DIABASE HOLYOKE,MASS.	2.977	.	22.0	6.25	.	.	DB09
DIABASE VINAL HAVEN,ME.	2.96				3.76		DB21
DIABASE VINAL HAVEN,ME.	2.962				3.76		DB18
DIABASE FREDERICK,MD.	3.012	.	22.0	6.76	.	.	DB11
DIABASE FREDERICK,MD.	3.017	.	22.0	.	3.71	.	DB13
DIABASE FREDERICK,MD.	3.013				3.67		DB19
DIABASE CENTREVILLE,VA.	2.976	.	22.0	6.14	.	.	DB08
DIABASE CENTREVILLE,VA.	2.984	.	22.0	.	3.49	.	DB12
DIABASE KEWEENAWAN,SUDBURY.ONT.	3.003	.	22.2	6.4	.	.	DB10
DIABASE KEWEENAWAN,ONTARIO	2.989				3.52		DB20
DIABASE NIPISSING,COBALT,ONT.	2.964	.	21.8	6.55	.	.	DB07
DIABASE USSR 3	.	.	.	6.33	3.75	.	DB01
DIABASE USSR 3	3.04	0.4	.	6.37	.	.	DB02
DIABASE USSR 3	3.08	.	.	6.3	.	.	DB03
DIABASE USSR 288	2.85	.	.	5.61	3.16	.	DB04
DIABASE 3 PRIBRAM,CZECH.	2.903	.	.	6.51	.	.	DB16
DIABASE 7 PRIBRAM,CZECH.	2.879	.	.	6.47	.	.	DB17
DIABASE HYDERABAD,INDIA	3.12			6.62	3.31		DB22

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
DIABASE PAR	3.086	.	.	7.84	.	.	DB06
PERP	2.995	.	.	6.91	.	.	DB06
HYDERABAD,INDIA							
DIABASE	3.12	.	.	5.15	.	.	DB05
HYDERABAD,INDIA							
BASALT	2.97			6.48	3.58		BA22
SOMERSET CO., N.J.							
BASALT	2.67			5.37	3.07		BA19
CHAFFEE CO., COLO.							
BASALT	2.73			5.56	2.95		BA20
JEFFERSON CO., COLO.							
BASALT	2.82	2.06	.	.	2.53	.	BA05
GUADALUPE MOHOLE SITE							
BASALT	.	.	.	5.53	3.34	.	BA03
USSR 4							
BASALT	2.88	0.47	.	5.57	.	.	BA04
USSR 4							
BASALT	2.63	.	.	5.57	3.40	.	BA02
USSR							
BASALT	2.91	.	.	5.68	.	.	BA01
INDIA							
BASALT-OLIVINE	2.0			4.80	2.56		BA07
HAWAII							
BASALT-OLIVINE	2.30			4.65	2.50		BA08
HAWAII							
BASALT-OLIVINE	2.36			5.50	3.10		BA09
HAWAII							
BASALT-OLIVINE	2.60			5.52	2.76		BA11
HAWAII							
BASALT-OLIVINE	2.44			2.99	1.75		BA18
WASHINGTON							
BASALT-OLIVINE	2.83			5.74	3.39		BA21
BOULDER CO., COLO.							
BASALT-OLIVINE	3.00			5.92	3.55		BA23
LINTZ, GERMANY							
BASALT-THOLEIITIC	2.40			4.82	2.35		BA12
HAWAII							
BASALT-THOLEIITIC	2.40			4.64	2.26		BA13
HAWAII							
BASALT-ANKARAMITE	2.40			5.08	3.02		BA10
HAWAII							
BASALT-ANKARAMITE	2.51			5.10	2.38		BA16
HAWAII							
BASALT-MUGEARITE	2.31			3.50	1.68		BA15
HAWAII							
BASALT-ALKALIC	2.33			4.24	2.07		BA17
HAWAII							
BASALT-VESICULAR	2.00			3.05			BA14
HAWAII							
TRAP	3.02	.	.	6.4	.	.	TP01
DECCAN,GULBERGA,INDIA							
TRAP PAR	2.767	.	.	8.61	.	.	TP02
PERP	2.777	.	.	6.97	.	.	TP02
DECCAN,GULBERGA,INDIA							

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
TRAP PAR	2.863	.	.	8.58	.	.	TP03
PERP	2.886	.	.	6.93	.	.	TP03
DECCAN,RUTLAM,INDIA							
TRAP	3.10			6.87	3.19		TP04
DECCAN,IGADPURI (BOMBAY),INDIA							
UNDERSATURATED							
SYENITE-SODALITE	2.52			6.45	2.79		SY04
KISHENGARH (RAJASTHAN),INDIA							
SYENITE-NEPHELINE	2.70			6.16	2.75		SY05
SIVAMALAI (MADRAS),INDIA							
ULTRAMAFIC							
DUNITE X	3.258	.	20.9	6.4	.	.	DU07
Y	3.274	.	20.9	8.0	.	.	DU07
Z	3.269		20.9	6.5			DU07
BALSAM GAP,N.C.							
DUNITE	3.275				4.12		DU19
BALSAM GAP,N.C.							
DUNITE X	3.25			6.52	3.59		DU20
Y	3.25			6.66	3.84		DU20
Z	3.25			5.88	3.65		DU20
JACKSON CO., N.C.							
DUNITE X	3.306	.	.	7.90	.	.	DU08
Y	3.302	.	.	7.34	.	.	DU08
Z	3.304			7.85			DU08
ADDIE,N.C.							
DUNITE ALTERED	3.00	.	.	6.31	.	.	DU04
ALTERED	2.962	.	.	5.46		.	DU04
	3.244	.	21.0	7.0	.	.	DU05
WEBSTER,N.C.							
DUNITE	3.264	.	21.0	.	4.01	.	DU11
WEBSTER,N.C.							
DUNITE X	3.312	.	20.9	8.3	.	.	DU09
Y	3.310	.	20.9	7.2	.	.	DU09
Z	3.314		20.9	7.6			DU09
TWIN SISTERS MT.,WASH.							
DUNITE	3.326	.	20.9	.	4.60	.	DU13
TWIN SISTERS MT.,WASH.							
DUNITE PAR	3.262	.	.	8.27	.	.	DU01
PERP	3.211	.	.	7.55	.	.	DU01
MT. DUN,NEW ZEALAND							
DUNITE X	3.255	.	21.1	7.9	.	.	DU06
Y	3.257	.	21.1	7.2	.	.	DU06
Z	3.262		21.1	7.3			DU06
MT. DUN,NEW ZEALAND							
DUNITE	3.270	.	21.1	.	4.17	.	DU12
MT.DUN,NEW ZEALAND							
DUNITE X	3.777	.	24.3	7.0	.	.	DU10
Y	3.717	.	24.3	6.6	.	.	DU10
Z	3.737		24.3	6.6			DU10
MOOIHOEK MINE,TRANSVAAL							
DUNITE	3.760	.	24.3	.	3.68	.	DU14
MOOIHOEK MINE,TRANSVAAL							

ROCK		RHO	POR	M/P	VP1	VS1	VS2	INDEX
DUNITE	X	3.1	.	.	7.40	.	.	DU03
	Y	3.1	.	.	7.32	.	.	DU03
	Z	3.1	.	.	7.53	.	.	DU03
NEW GUINEA								
DUNITE	X	3.3	.	.	7.80	4.0	.	DU02
	Y	3.3			7.97			DU02
	Z	3.3	.	.	8.26	.	.	DU02
JAPAN 8A								
DUNITE					7.9			DU21
JAPAN								
PERIDOTITE	X	2.67			4.07	2.50		PE13
	Y	2.67			4.06	2.31		PE13
	Z	2.67			4.00	2.25		PE13
MURFREESBORO, ARK.								
PERIDOTITE		3.35	.	.	8.50	.	.	PE08
PERIDOTITE 25 SERP		3.16	.	.	7.78	.	.	PE09
PERIDOTITE 50 SERP		2.97	.	.	7.06	.	.	PE10
PERIDOTITE 75 SERP		2.85	.	.	6.38	.	.	PE11
PERIDOTITE 100SERP		2.60	.	.	5.68	.	.	PE12
PERIDOTITE		3.28	.	.	7.40	4.02	.	PE04
USSR 455								
PERIDOTITE		3.28	.	.	6.8	.	.	PE01
USSR 455								
PERIDOTITE		3.21			6.97	3.66		PE03
USSR 462								
PERIDOTITE		3.34	.	.	7.7	.	.	PE02
USSR 609								
PERIDOTITE	X	3.3	.	.	7.92	4.2	.	PE05
	Y	3.3	.	.	8.24	.	.	PE05
	Z	3.3			7.83			PE05
JAPAN 8								
PERIDOTITE	X	3.2	.	.	8.08	4.0	.	PE06
	Y	3.2	.	.	7.74	.	.	PE06
	Z	3.2	.	.	8.37	.	.	PE06
JAPAN 9								
PERIDOTITE	X	3.3	.	.	7.50	.	.	PE07
	Y	3.3	.	.	7.73	.	.	PE07
	Z	3.3	.	.	7.25	.	.	PE07
JAPAN 12								
HARZBURGITE	X	3.380	.	.	6.7	.	.	HB01
	Y	3.371	.	.	7.3	.	.	HB01
	Z	3.356			6.6			HB01
BUSHVELD, TRANSVAAL								
PYROXENITE	X	3.239			6.7			PX06
	Y	3.244	.	.	6.4	.	.	PX06
	Z	3.259	.	.	7.2	.	.	PX06
SONOMA CO., CAL.								
PYROXENITE		2.93			6.45	3.27		PX07
HAWAII								

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
PYROXENITE	3.24	0.37	.	7.14	3.90	.	PX01
USSR 457							
PYROXENITE	3.15	0.21	.	6.75	3.50	.	PX05
USSR 468							
PYROXENITE	3.29	0.32	.	7.62	4.14	.	PX02
USSR 469							
PYROXENITE	3.22	0.41	.	5.90	3.26	.	PX03
USSR 470							
PYROXENITE	3.24	0.42	.	6.75	3.60	.	PX04
USSR 472							
BRONZITITE X	3.283	.	21.2	7.20	.	.	BR01
Y	3.284	.	21.2	7.58	.	.	BR01
Z	3.271		21.2	7.48			BR01
STILLWATER,MONTANA							
BRONZITITE	3.287	.	21.2	.	4.45	.	BR03
STILLWATER,MONT.							
BRONZITITE	3.27	.	.	.	4.50	.	BR04
STILLWATER,MONT.							
BRONZITITE	3,272				4.50		BR06
STILLWATER,MONT.							
BRONZITITE X	3.304	.	21.0	6.2	.	.	BR02
Y	3.264	.	21.0	5.0	.	.	BR02
Z	3.297		21.0	5.9			BR02
BUSHVELD,TRANSVAAL							
BRONZITITE	3.289				4.37		BR07
BUSHVELD,TRANSVAAL							
SERPENTINITE X	2.768			6.18'			SE14
Y	2.887			7.05'			SE14
Z	2.792			6.70'			SE14
MIDDLEFIELD,MASS.							
SERPENTINITE	2.798	.	.	6.4	.	.	SE13
LUDLOW,VT.							
SERPENTINITE	2.798			6.4			SE17
LUDLOW,VT.							
SERPENTINITE	2.806	.	.	.	3.61	.	SE09
LUDLOW,VT.							
SERPENTINITE	2.710	.	.	5.8	.	.	SE12
CAL.							
SERPENTINITE	2.710			5.8			SE18
CALIF.							
SERPENTINITE	2.718	.	.	.	3.12	.	SE08
CAL.							
SERPENTINITE	2.70	0.4	.	6.13	.	.	SE06
USSR 240							
SERPENTINITE	.	.	.	6.60	.	.	SE05
USSR							
SERPENTINE 10	2.6	.	.	5.80	.	.	SE01
IWAUCHIDAKE,JAPAN							
SERPENTINE 11 X	2.5	.	.	5.08	.	.	SE03
Y	2.5	.	.	4.60	.	.	SE03
Z	2.5	.	.	4.95	.	.	SE03
NITTO MINE,JAPAN							
SERPENTINE 14	2.6	.	.	5.54	.	.	SE02
TARI,JAPAN							

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
SERPENTINE 15 X	2.7	.	.	4.81	.	.	SE04
Y	2.7	.	.	3.34	.	.	SE04
Z	2.7	.	.	4.08	.	.	SE04
HAMATONBETSU,JAPAN							
CHRYSOTILE X	2.598	.	.	5.5	.	.	SE10
Y	2.603	.	.	5.8	.	.	SE10
Z	2.601			5.5			SE10
THETFORD,QUE.							
CHRYSOTILE	2.601			5.6			SE15
THETFORD,QUE.							
CHRYSOTILE	2.602	.	.	.	2.71	.	SE07
THETFORD,QUE.							
ANTIGORITE X	2.620	.	.	4.0	.	.	SE11
Y	2.603	.	.	5.7	.	.	SE11
Z	2.618			4.5			SE11
LUDLOW,VT.							
ANTIGORITE	2.614			4.7			SE16
LUDLOW,VT.							
PORPHYRY	2.92	.	.	6.52	3.81	.	PO01
USSR 290							
FRAGMENTAL ROCKS							
VOLCANIC BRECCIA	2.19			4.22	2.49		VB01
PARK CO.,COLO.							
TUFF X	1.38			1.41	0.83		TU01
Y	1.38			1.36	0.82		TU01
Z	1.38			1.51	0.97		TU01
SAN LUIS OBISPO,CAL.							
BASALTIC SCORIA X	2.23			3.73	2.21		BA24
Y	2.23			4.53	2.69		BA24
Z	2.23			4.72	2.63		BA24
KLAMATH FALLS,ORE.							
GLASSES							
OBSIDIAN	2.376	.	.	5.80	.	.	OB01
MODOC,CAL.							
OBSIDIAN	2.440				3.53		OB02
MODOC,CALIF.							
OBSIDIAN	2.35			5.82	3.57		OB03
LAKE CO.,ORE.							
DIABASE GLASS	2.750	.	.	6.30	.	.	DB15
GENERAL ELECTRIC CO.							

METAMORPHIC ROCKS

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
SCHIST-TALC	2.914	.	.	4.9	.	.	SC01
CHESTER,VT.							
SCHIST-ACTIN X	3.217	.	.	5.62	.	.	SC02
Y	3.199	.	.	7.32	.	.	SC02
CHESTER,VT.							

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
SCHIST-PAR	2.800	.	.	6.5	.	.	SC03
PERP	2.796	.	.	4.6	.	.	SC03
WOODSVILLE,VT.							
SCHIST-CHLORITE X	2.877	.	.	5.9	.	.	SC04
Y	2.897	.	.	3.3	.	.	SC04
CHESTER,VT.							
SCHIST	2.95	.	.	.	3.34	.	SC12
FRAMINGHAM,MASS.							
SCHIST 1	2.70	.	.	.	3.02	.	SC13
FRAMINGHAM,MASS.							
SCHIST 2	2.73	.	.	.	2.76	.	SC14
FRAMINGHAM,MASS.							
SCHIST	2.82	.	.	6.16	2.05	.	SC11
SCHIST PAR	.	.	.	6.20	.	.	SC10
PERP	.	.	.	6.20	.	.	SC10
USSR							
SCHIST PAR	.	.	.	7.45	2.67	.	SC07
PERP	.	.	.	8.16	2.83	.	SC07
INDIA 1							
SCHIST PAR	.	.	.	7.74	2.61	.	SC08
PERP	.	.	.	8.03	2.74	.	SC08
INDIA 2							
SCHIST PAR	.	.	.	5.82	2.53	.	SC09
PERP	.	.	.	6.42	2.65	.	SC09
INDIA 3							
SCHIST	.	.	.	5.96	2.85	.	SC06
HYDERABAD,INDIA							
SCHIST	2.97			5.96	2.85		SC22
HYDERABAD,INDIA							
SCHIST	2.97	.	.	4.89	2.20	.	SC05
YELLANDLAPAD,INDIA							
SCHIST-QTZ PAR	2.78			4.56			SC23
PERP	2.78			2.65			SC23
JAPAN 5							
SCHIST-QTZ PAR	2.74			6.30			SC24
PERP	2.74			2.52			SC24
JAPAN 52							
SCHIST-EP-QTZ PAR	2.44			5.99			SC25
PERP	2.44			4.36			SC25
JAPAN 114							
SCHIST-MG-QTZ PAR	3.79			6.39			SC26
PERP	3.79			5.56			SC26
JAPAN 115							
SCHIST-GREEN PAR	2.93			5.52			SC27
PERP	2.93			3.90			SC27
JAPAN 30							
SCHIST-GREEN PAR	3.16			6.24			SC28
PERP	3.16			4.88			SC28
JAPAN 34							
SCHIST-GREEN PAR	2.88			6.14			SC29
PERP	2.88			4.62			SC29
JAPAN 118							
SLATE X	.	.	.	4.95	.	.	SL04
Y	.	.	.	6.28	.	.	SL04
EVERETT,MASS.							

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
SLATE	2.67	.	.	.	2.89	.	SL05
EVERETT,MASS.							
SLATE X	2.741	.	.	4.97	.	.	SL06
Y	2.734	.	.	5.81	.	.	SL06
MEDFORD,MASS.							
SLATE	3.07	.	.	5.62	2.27	.	SL01
HYDERABAD,INDIA							
SLATE	2.64	.	.	4.21	2.08	.	SL02
BIHAR,INDIA							
SLATE	2.60	.	.	5.22	2.99	.	SL03
KURNOOL,INDIA							
GNEISS PAR	2.642	.	20.8	3.7	.	.	GN15
PERP	2.646	.	20.8	2.9	.	.	GN15
PELHAM,MASS.							
GNEISS PAR	2.64				1.85		GN29
PERP	2.64				1.73		GN29
PELHAM,MASS.							
GNEISS PERP	2.64				2.35		GN30
PELHAM,MASS.							
GNEISS	2.91	.	.	.	3.42	.	GN17
SOLOMON'S POND,MASS.							
GNEISS PAR	2.768	.	.	4.9	.	.	GN14
PERP	2.762	.	.	3.6	.	.	GN14
BETHLEHEM,N.H.							
GNEISS PAR	2.684	.	.	5.6	.	.	GN13
PERP	2.664	.	.	4.5	.	.	GN13
HELL GATE,N.Y.							
GNEISS PAR	2.65	.	.	.	2.49	.	GN16
PERP	2.65	.	.	.	2.62	.	GN16
HELL GATE,N.Y.							
GNEISS PAR	2.684	.	.	6.29	.	.	GN08
PERP	2.788	.	.	5.48	.	.	GN08
UXBRIDGE,ENGLAND							
GNEISS	2.87	.	.	3.87	2.20	.	GN09
USSR 286							
GNEISS	2.70	.	.	3.44	2.15	.	GN10
USSR 287							
GNEISS	2.84	.	.	6.1	.	.	GN12
USSR 460							
GNEISS	2.68	.	.	5.2	.	.	GN11
USSR 740							
GNEISS	2.83	.	.	6.77	.	.	GN01
INDIA							
GNEISS	2.74	.	.	6.74	3.13	.	GN02
HYDERABAD,INDIA							
GNEISS	2.80	.	.	7.55	3.08	.	GN03
BIHAR,INDIA							
GNEISS	2.76	.	.	7.12	2.95	.	GN04
TRIHINOPOLY,INDIA							
GNEISS PAR				6.24	2.63		GN05
PERP	.	.	.	7.87	2.65	.	GN05
INDIA 1							
GNEISS PAR	.	.	.	6.13	2.37	.	GN06
PERP	.	.	.	6.93	2.47	.	GN06
INDIA 2							

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
GNEISS PAR	.	.	.	6.08	2.32	.	GN07
PERP	.	.	.	6.62	2.39	.	GN07
INDIA 3							
CHARNOCKITE	2.60	.	.	7.13	3.12	.	CK01
KONDAPALLI, INDIA							
CHARNOCKITE	2.64	.	.	7.58	3.26	.	CK02
PALLAVARAM, INDIA							
CHARNOCKITE AK1	2.61	.	.	6.1	3.1	.	CK03
AK2	2.68	.	.	6.0	3.0	.	CK04
IK1	2.66	.	.	6.3	3.1	.	CK05
IK2	2.83	.	.	6.3	3.2	.	CK06
BK1	2.68	.	.	6.5	3.3	.	CK07
BK2	2.67	.	.	6.4	3.4	.	CK08
UK1	3.12	.	.	6.7	3.7	.	CK09
UK2	3.36	.	.	6.6	3.7	.	CK10
UK3	3.07	.	.	6.6	3.5	.	CK11
KONDAPALLI, INDIA							
CHARNOCKITE	2.740	.	.	6.15	.	.	CK12
PALLAVARAM, INDIA							
CHARNOCKITE AP1	2.63	.	.	6.0	3.1	.	CK13
AP2	2.42	.	.	6.1	3.0	.	CK14
BP1	3.06	.	.	6.3	3.2	.	CK15
BP2	3.06	.	.	6.2	3.2	.	CK16
BP3	3.05	.	.	6.4	3.2	.	CK17
BP4	3.01	.	.	6.4	3.3	.	CK18
BP5	2.99	.	.	6.5	3.3	.	CK19
PALLAVARAM, INDIA							
CHARNOCKITE	2.64			7.58	3.27		CK20
MADRAS, INDIA							
MARBLE X	2.705	.	.	4.7			MA09
Y	2.703	.	.	5.9	.	.	MA09
Z	2.704			4.8			MA09
DANBY, VT.							
MARBLE PERP	2.71				2.05		MA58
PAR	2.71				2.85		MA58
PROCTOR, VT.							
MARBLE	2.71				2.71		MA57
PROCTOR, VT.							
MARBLE	2.71			5.34	2.83		MA60
TATE, GA.							
MARBLE PERP C				5.96	3.96		MA11
PAR C				6.08	3.87		MA11
YULE, COLO.							
MARBLE 37	2.66	.	.	6.33	3.51	.	MA48
38	2.58	.	.	5.90	3.28	.	MA49
39	2.75	.	.	5.70	3.20	.	MA50
40	2.59	.	.	5.53	2.99	.	MA51
41	2.62	.	.	5.25	2.92	.	MA52
42	2.88	.	.	4.68	2.43	.	MA53
43	2.82	.	.	5.31	2.75	.	MA54
44	2.64	.	.	6.62	3.31	.	MA55
45	2.75	.	.	5.20	2.53	.	MA56
ITALY							
MARBLE	2.93	.	.	5.61	3.47	.	MA03
RAJAPUTANA, INDIA							

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
MARBLE FINE	2.72	.	.	7.11	2.66	.	MA01
MEDIUM	2.74	.	.	7.05	2.64	.	MA01
COARSE	2.74	.	.	6.78	2.59	.	MA01
MAKRANA, INDIA							
MARBLE	2.86	.	.	7.07	3.40	.	MA05
RAMAGUNDAM, INDIA							
MARBLE PAR	2.85	.	.	6.46	.	.	MA06
PERP	2.84	.	.	5.57	.	.	MA06
JUBBALPORE, INDIA							
MARBLE PAR	2.71	.	.	6.41	.	.	MA07
PERP	2.70	.	.	4.33	.	.	MA07
RAJAPUTANA, INDIA							
MARBLE	2.88			7.33	2.74		MA59
MANDITOG (HYDERABAD), INDIA							
MARBLE	2.88	.	.	6.83	3.81	.	MA02
HYDERABAD, INDIA							
MARBLE	2.80	.	.	7.33	2.74	.	MA04
MANDITOG, INDIA							
MARBLE 35	2.39	.	.	5.38	3.00	.	MA46
RYUKYU ISLANDS							
MARBLE 36	2.70	.	.	6.00	3.30	.	MA47
KOREA							
MARBLE 1	2.66	.	.	5.62	3.26	.	MA12
2	2.73	.	.	5.97	3.32	.	MA13
3	2.80	.	.	5.34	2.96	.	MA14
4	2.93	.	.	6.08	3.73	.	MA15
5	2.76	.	.	5.48	2.92	.	MA16
6	2.76	.	.	6.14	3.22	.	MA17
7	2.73	.	.	5.09	2.80	.	MA18
8	2.73	.	.	5.89	2.96	.	MA19
9	2.79	.	.	5.85	3.46	.	MA20
10	2.74	.	.	5.89	2.83	.	MA21
11	2.72	.	.	6.02	3.54	.	MA22
12	2.68			3.75	2.02		MA23
13	2.66	.	.	5.11	3.12	.	MA24
14	2.83	.	.	5.25	3.13	.	MA25
15	2.66	.	.	6.15	3.84	.	MA26
16	2.72	.	.	6.05	3.48	.	MA27
17	2.70	.	.	6.37	3.31	.	MA28
18	2.80	.	.	5.92	3.64	.	MA29
19	2.76	.	.	6.48	3.92	.	MA30
20	2.76	.	.	6.34	3.43	.	MA31
21	2.76	.	.	5.98	3.04	.	MA32
22	2.72	.	.	5.80	3.07	.	MA33
23	2.79	.	.	6.10	3.70	.	MA34
24	2.72	.	.	5.41	3.15	.	MA35
25	2.82	.	.	5.67	3.10	.	MA36
26	2.74	.	.	6.94	3.86	.	MA37
27	2.70	.	.	6.16	3.76	.	MA38
28	2.69	.	.	6.10	3.70	.	MA39
29	2.62	.	.	6.01	3.50	.	MA40
30	2.70	.	.	6.19	3.75	.	MA41
31	2.72	.	.	6.23	3.38	.	MA42
32	2.72	.	.	5.72	3.18	.	MA43
33	2.73	.	.	6.02	3.10	.	MA44
34	2.80	.	.	5.14	2.72	.	MA45
JAPAN SUITE							

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
QUARTZITE	2.647	.	.	5.6	.	.	QZ03
MONTANA							
QUARTZITE PAR	.	.	.	4.80	.	.	QZ01
PERP	.	.	.	3.30	.	.	QZ01
USSR 1							
QUARTZITE PAR	.	.	.	5.90	.	.	QZ02
PERP	.	.	.	5.90	.	.	QZ02
USSR 2							
QUARTZITE				5.55	3.40		QZ15
USSR 22							
QUARTZITE	2.716	.	.	5.70	.	.	QZ04
INDIA 7							
QUARTZITE	2.64	.	.	6.60	2.75	.	QZ05
GUNTUR,INDIA 2							
QUARTZITE	2.56	.	.	5.61	3.03	.	QZ06
WARANGAL,INDIA							
QUARTZITE	2.54	.	.	5.06	2.70	.	QZ07
KARIMMAGAR,INDIA							
QUARTZITE	.	.	.	5.62	3.03	.	QZ08
MANDITOG,INDIA							
QUARTZITE	2.56			5.61	3.03		QZ16
MANDITOG (HYDERABAD),INDIA							
QUARTZITE	2.61	.	.	6.11	3.08	.	QZ09
YELLANLAPAD,INDIA 8							
QUARTZITE	2.56	.	.	6.15	3.08	.	QZ10
KHAMMAM,INDIA 5							
AMPHIBOLITE X	3.108	.	.	6.09	.	.	AM04
Y	3.124	.	.	7.31	.	.	AM04
MADISON CO.,MONT.							
AMPHIBOLITE	3.070	.	.	.	3.90	.	AM05
MADISON CO.,MONT.							
AMPHIBOLITE	2.95			6.80	3.53		AM11
HAWAII							
AMPHIBOLITE	.	.	.	7.40	.	.	AM02
USSR 1							
AMPHIBOLITE	3.05	.	.	6.20	3.45	.	AM01
USSR 289							
AMPHIBOLITE X	3.0	.	.	7.22	.	.	AM03
Y	3.0	.	.	4.98	.	.	AM03
Z	3.0	.	.	6.16	.	.	AM03
HIDAKA,JAPAN							
ECLOGITE	3.441	.	22.2	7.31	.	.	EC10
HEALDSBURG,CAL.							
ECLOGITE	3.44	.	22.2	.	4.26	.	EC03
HEALDSBURG,CAL.							
ECLOGITE	3.360	.	.	.	3.83	.	EC06
OCCIDENTAL,CAL.							
ECLOGITE	2.81			5.97	2.94		EC15
HAWAII							
ECLOGITE	2.71			5.69	2.77		EC16
HAWAII							
ECLOGITE	3.376	.	21.7	5.2	.	.	EC09
SUNNMORE,NORWAY							
ECLOGITE	3.577	.	.	.	4.07	.	EC04
NORWAY 1552							

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
ECLOGITE	3.578	.	.	.	3.70	.	EC05
NORWAY 1553							
ECLOGITE	3.36			7.84			EC02
SCOTLAND							
ECLOGITE 1	3.338	.	.	6.6	.	.	EC14
2	3.376	.	.	7.17	.	.	EC08
KIMBERLEY DIST.,O.F.S.							
ECLOGITE	3.328	.	.	6.64	.	.	EC07
TANGANYIKA							
ECLOGITE X	3.2	.	.	7.39	.	.	EC01
Y	3.2	.	.	6.64	.	.	EC01
Z	3.2	.	.	7.60	.	.	EC01
HIDAKA,JAPAN							

SEDIMENTARY ROCKS

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
SANDSTONE	2.61	.	.	.	3.04	.	SS07
BROOKLINE,MASS.							
SANDSTONE	2.64				3.36		SS47
ALLENTOWN,PA.							
SANDSTONE	2.66				3.39		SS46
ALLENTOWN,PA.							
SANDSTONE	2.659	.	.	3.9	.	.	SS13
CATSKILL,N.Y.							
SANDSTONE	2.543	5.1	.	3.67	.	.	SS11
CAPLEN DOME,GALVESTON CO.,TEX.							
SANDSTONE	2.514	9.	.	3.73	.	.	SS12
TRAVIS PEAK,MARION CO.,TEX.							
SANDSTONE	.	.	.	4.65	2.76	.	SS02
SANDSTONE RED	.	.	.	4.31	.	.	SS03
GOLDEN,COLO.							
SANDSTONE WHITE	.	.	.	3.18	.	.	SS04
GOLDEN,COLO.							
SANDSTONE					1.78'		SS51
AUSTIN							
SANDSTONE		20			2.16'		SS14
BANDERA							
SANDSTONE					2.10'		SS49
BANDERA							
SANDSTONE	2.66	.	.	5.15	1.97	.	SS01
BARAKER							
SANDSTONE		20			1.74'		SS15
BEREA							
SANDSTONE					1.83'		SS48
BEREA							
SANDSTONE					1.92'		SS52
BEREA							
SANDSTONE	2.51	8.5		4.15'			SS44
MCKEE							
SANDSTONE		17			2.05'		SS16
SEMINOLE							

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
SANDSTONE STEVEN SAND	2.08	21.9		2.42'			SS43
SANDSTONE TENSLEEP	2.31	13.7		3.73'			SS42
SANDSTONE TENSLEEP		13			1.75'		SS17
SANDSTONE TORPEDO					2.04'		SS50
SANDSTONE TORPEDO		17			1.99'		SS18
SANDSTONE WEBER		8			2.30'		SS19
SANDSTONE USSR 94				3.30	2.15		SS41
SANDSTONE USSR 204	2.18	7.7	.	2.94	1.89	.	SS08
SANDSTONE USSR 205				2.95	1.90		SS39
SANDSTONE USSR 208	2.14	15.	.	3.22	1.92	.	SS09
SANDSTONE USSR 209	2.15	7.9	.	3.13	1.94	.	SS10
SANDSTONE USSR 213	2.70	.	.	4.85	3.03	.	SS05
SANDSTONE USSR 213				4.90	3.07		SS40
SANDSTONE	.	20.	.	2.64	.	.	SS33
	.	17.6	.	3.10	.	.	SS34
	.	11.2	.	3.63	.	.	SS35
	.	10.5	.	3.66	.	.	SS36
	.	6.0	.	3.84	.	.	SS37
	.	0.3	.	4.00	.	.	SS38
FRANCE							
SANDSTONE	2.44	.	.	4.09	.	.	SS06
INDIA							
SANDSTONE	2.61	1.12	.	6.85	2.19	.	SS21
	2.47	9.75	.	4.51	2.13	.	SS22
	2.63	5.17	.	6.19	2.62	.	SS23
	2.62	4.00	.	6.03	2.38	.	SS24
	2.64	1.35	.	6.54	2.40	.	SS25
	2.60	9.38	.	6.03	2.13	.	SS26
	2.62	3.87	.	5.83	2.54	.	SS27
	2.50	7.88	.	4.99	2.49	.	SS28
	2.62	2.58	.	6.05	2.36	.	SS29
	2.62	0.58	.	6.10	2.05	.	SS30
	2.59	5.57	.	5.61	2.40	.	SS31
	2.62	2.31	.	6.47	2.26	.	SS32
INDIA							
GREYWACKE	2.679	.	.	5.4	.	.	GY01
NEW ZEALAND							
GREYWACKE	2.705	.	.	5.4	.	.	GY02
QUEBEC							
GREYWACKE 6	2.749	.	.	6.19	3.90	.	GY03
PRIBRAM,CZECH.							
GREYWACKE U2-U7	2.688	.	.	6.06	3.61	.	GY04
PRIBRAM,CZECH.							

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
SHALE	3.07			5.62	2.27		SH03
HYDERABAD, INDIA							
SHALE	2.78	.	.	5.79	1.97	.	SH01
INDIA							
SHALE	3.07	.	.	4.93	.	.	SH02
KAOLIN	1.62	.	.	3.12	1.64	.	KA01
KAOLIN	1.58			1.44	0.93		KA02
DRYBRANCH, GA.							
LIMESTONE	2.69	.	.	3.15	.	.	LS03
NAZARETH, PA.							
LIMESTONE	.	.	.	3.85	.	.	LS04
INDIANA							
LIMESTONE	.	.	.	5.12	2.87	.	LS19
USSR							
LIMESTONE	2.62	1.8	.	4.78	.	.	LS20
USSR 246							
LIMESTONE	.	.	.	5.54	.	.	LS18
DACHSTEIN, AUSTRIA							
LIMESTONE	2.656	.	.	5.97	2.88	.	LS01
SOLENHOFEN, BAVARIA							
LIMESTONE	2.543	.	.	5.5	.	.	LS02
SOLENHOFEN, BAVARIA							
LIMESTONE	2.581			5.56			LS45
SOLENHOFEN, BAVARIA							
LIMESTONE	2.605				2.75		LS41
SOLENHOFEN, BAVARIA							
LIMESTONE		4.0			2.62'		LS27
SOLENHOFEN, BAVARIA							
LIMESTONE	2.67	.	.	.	3.14	.	LS29
	2.59	.	.	.	2.9	.	LS30
	.	.	.	6.14	.	.	LS31
	.	.	.	5.88	.	.	LS32
R	2.485	.	.	5.38	2.98	.	LS33
8068	2.517	.	.	5.55	3.05	.	LS34
S4	2.558	4.5	.	5.65	3.07	.	LS35
O	2.582	.	.	5.84	3.17	.	LS36
A5	2.591	3.6	.	5.90	3.13	.	LS37
S10	2.599	3.3	.	5.96	3.15	.	LS38
F	2.661	.	.	6.12	3.22	.	LS39
SOLENHOFEN, BAVARIA							
LIMESTONE	2.80	.	.	7.07	3.40	.	LS05
RAMAGUNDAM, INDIA							
LIMESTONE	2.84	.	.	6.36	3.08	.	LS06
PIDUGURALLA, INDIA							
LIMESTONE	2.81			6.26	3.07		LS07
VINDHYA PRADESH, INDIA							
LIMESTONE	2.86	.	.	6.24	3.02	.	LS08
MADHYA PRADESH, INDIA							
LIMESTONE	3.00	.	.	6.21	3.10	.	LS09
BHIMA, INDIA							
LIMESTONE PAR	2.700	.	.	6.18	.	.	LS10
PERP	2.721	.	.	5.10	.	.	LS10
BHIMA, INDIA							

ROCK	RHO	POR	M/P	VP1	VS1	VS2	INDEX
LIMESTONE PAR	2.697	.	.	6.72	.	.	LS11
PERP	2.647	.	.	4.17	.	.	LS11
KURNOOL,INDIA							
LIMESTONE PAR	.	.	.	6.59	3.09	.	LS12
PERP	.	.	.	7.37	3.26		LS12
INDIA 1							
LIMESTONE PAR	.	.	.	6.78	3.26	.	LS13
PERP	.	.	.	7.01	3.42	.	LS13
INDIA 2							
LIMESTONE PAR	.	.	.	6.53	3.16	.	LS14
PERP	.	.	.	6.85	3.29	.	LS14
INDIA 3							
LIMESTONE	2.68	.	.	5.98	3.46	.	LS15
SHAHABAD,INDIA 4							
LIMESTONE 1	2.82	.	.	6.40	3.20	.	LS40
2	2.66	.	.	5.89	2.94	.	LS16
CUDDAPAH,INDIA							
LIMESTONE	2.780	.	.	6.25	.	.	LS17
INDIA 8-11							
LIMESTONE	3.00			6.24	3.02		LS42
HYDERABAD,INDIA							
CHALK	1.67	.	.	3.04	1.58	.	CL01
DOLOMITE	2.844	.	.	5.6	.	.	DO02
RUTLAND,VT.							
DOLOMITE	2.845			6.06'			DO05
DUNHAM,WILLIAMSTOWN,MASS.							
DOLOMITE	2.83	.	.	.	3.52	.	DO03
BETHLEHEM,PA.							
DOLOMITE	2.82				3.58		DO06
BETHLEHEM,PA.							
DOLOMITE	2.58	.	.	4.69	2.72	.	DO01
USSR 1745							
DOLOMITE				4.56			DO07

MINERALS

ORTHO- AND RING SILICATES

MINERAL	RHO	POR	M/P	VP1	VS1	VS2	INDEX
OLIVINE GROUP							
OLIVINE 100	3.324	.	20.9	9.87	4.88	4.87	OV01
010	.	.	20.9	7.73	4.88	4.42	OV01
001	.	.	20.9	8.65	5.00	4.54	OV01
BURMA							
MONTICELLITE	3.014			7.10'			MO02
CRESTMORE,CAL.							
MONTICELLITE	2.975	.	.	.	3.85	.	MO01
CRESTMORE,CAL.							

MINERAL	RHO	POR	M/P	VP1	VS1	VS2	INDEX
GARNET GROUP							
GARNET 100	4.247	.	24.9	8.51	4.74	.	GT03
110	.	.	24.9	8.47	.	.	GT03
BRAZIL 1							
GARNET 100	4.183	.	24.3	8.54	4.75	.	GT04
110	.	.	24.3	8.51	.	.	GT04
BRAZIL 2							
GROSSULARITE	3.561	.	22.8	6.3	.	.	GT01
CONNECTICUT							
ALMAND.-PYROPE	3.950	.	24.1	5.9	.	.	GT02
AL2SIO5 GROUP							
SILLIMANITE X	3.189			9.04'			SI02
Y	3.179			9.55'			SI02
Z	3.194			9.60'			SI02
WILLIAMSTOWN,AUSTRALIA							
SILLIMANITE	3.187	.	.	.	4.93	.	SI01
WILLIAMSTOWN,AUSTRALIA							
OTHERS							
ZIRCON 100	4.564	.	.	4.03	1.88	1.76	ZR01
001	4.604	.	.	3.15	1.73	1.73	ZR01
110	4.596	.	.	3.54	1.71	2.65	ZR01
111	4.650	.	.	3.14	.	.	ZR01
IDOCRASE	3.144			5.52'			ID02
CRESTMORE,CAL.							
IDOCRASE	3.140	.	.	.	3.13	.	ID01
CRESTMORE,CAL.							
STAUROLITE 100	3.385	.	.	10.07	4.54	5.26	ST01
010	3.367	.	.	7.42	3.72	5.18	ST01
001	3.325	.	.	6.66	3.66	4.56	ST01
110	3.358	.	.	5.19	.	.	ST01

SINGLE CHAIN SILICATES

MINERAL	RHO	POR	M/P	VP1	VS1	VS2	INDEX
PYROXENE GROUP							
DIOPSIDE X	3.08			3.36	3.11		DP01
Y	3.08			5.83	4.07		DP01
Z	3.08			7.48	3.96		DP01
QUEBEC							
AUGITE X	3.26			5.30	3.47		AU01
Y	3.26			2.96	1.97		AU01
Z	3.26			2.95			AU01
NEW YORK							

MINERAL		RHO	POR	M/P	VP1	VS1	VS2	INDEX
PYROXENE GROUP (CONT.)								
AEGIRITE	001	3.50	.	.	8.21	3.72	4.23	AE01
	110	.	.	.	7.60	4.07	3.95	AE01
	010	.	.	.	7.20	3.97	3.48	AE01
	101	.	.	.	6.75	4.43	3.60	AE01
	100	.	.	.	7.30	3.68	3.78	AE01
	011	.	.	.	8.30	4.65	3.86	AE01
USSR								
JADEITE		3.33	.	.	8.60	5.04	.	JD01
BURMA								
JADEITE		3.331	.	20.4	8.45	.	.	JD03
BURMA								
JADEITE		3.180	.	20.4	7.6	.	.	JD04
JAPAN								
JADEITE		3.203	.	20.4	.	4.65	.	JD02
JAPAN								
PYROXENOID GROUP								
WOLLASTONITE		2.873			5.03'			WO01

DOUBLE CHAIN SILICATES

MINERAL		RHO	POR	M/P	VP1	VS1	VS2	INDEX
AMPHIBOLE GROUP								
ANTHOPHYLLITE	001	.	.	.	5.67	2.73	2.75	AP01
	010	.	.	.	8.64	2.70	5.10	AP01
NAZYAMSKY MTS.,S.URALS,USSR								
TREMOLITE	X	2.86			6.25	3.83		TR01
	Y	2.86				3.02		TR01
	Z	2.86			6.08	4.25		TR01
NEW YORK								
HORNBLENDE	001	3.124	.	.	7.85	3.16	4.29	HO01
	110	.	.	.	6.50	3.56	3.92	HO01
	010	.	.	.	7.16	4.52	3.53	HO01
	101	.	.	.	7.11	3.65	3.62	HO01
	100	.	.	.	6.11	3.43	3.18	HO01
	011	.	.	.	7.55	4.20	3.30	HO01
USSR 1								
HORNBLENDE	001	.	.	.	8.13	3.03	4.40	HO02
	110	.	.	.	7.01	3.87	3.77	HO02
	010	.	.	.	7.54	4.45	3.72	HO02
	101	.	.	.	6.18	3.98	4.05	HO02
	100	.	.	.	6.45	3.78	3.46	HO02
	011	.	.	.	7.80	4.48	3.48	HO02
USSR 2								
HORNBLENDE	X	3.32			7.17	3.05		HO03
	Y	3.32			5.85	3.14		HO03
	Z	3.32			6.06	3.79		HO03
ONTARIO								

SHEET OR LAYERED SILICATES

MINERAL	RHO	POR	M/P	VP1	VS1	VS2	INDEX
MUSCOVITE 001	2.79	.	.	4.44	2.03	2.05	MU01
010	.	.	.	8.03	2.06	2.01	MU01
USSR							
PHLOGOPITE 001	2.81	.	.	4.28	1.46	1.47	PH01
010				7.96	1.48	5.19	PH01
USSR							
BIOTITE 001	3.05	.	.	4.21	1.38	1.38	BI01
010	.	.	.	7.80	1.34	5.06	BI01
USSR							
TALC 001	.	.	.	3.73	.	.	TC01
010				9.00		5.08	TC01
USSR							
CLINOCHLORE 001	.	.	.	5.88	2.03	2.03	CH01
010	.	.	.	8.09		4.52	CH01
SHISHIMSKY MTS.,S.URALS,USSR							
LEICHTENBERGITE	.	.	.	6.72	2.16	2.16	CH02
	.	.	.	8.34	2.05	5.11	CH02
SHISHIMSKY MTS.,S.URALS,USSR							

FRAMEWORK SILICATES

MINERAL	RHO	POR	M/P	VP1	VS1	VS2	INDEX
SIO2 GROUP							
QUARTZ X	.	.	.	5.38	.	.	QU01
Y	.	.	.	5.41	.	.	QU01
Z	.	.	.	6.52	.	.	QU01
FUSED SILICA	2.20	.	.	5.96	3.76	.	QU04
FUSED SILICA	2.20			5.97	3.76		QU05
FUSED SILICA	2.213	.	.	5.97	.	.	QU02
FUSED QUARTZ				6.10			QU06
OPAL	.	.	.	5.26	.	.	QU03
ALKALI FELDSPARS							
ORTHOCLASE X	.	.	.	3.70	.	.	OR01
Y	.	.	.	5.72	.	.	OR01
Z	.	.	.	3.80	.	.	OR01

MINERAL		RHO	POR	M/P	VP1	VS1	VS2	INDEX
ALKALI FELDSPARS (CONT.)								
MICROCLINE	001	2.56	.	.	6.95	2.93	2.37	MI01
	110	.	.	.	7.14	3.44	2.88	MI01
	010	.	.	.	8.15	2.14	3.83	MI01
	101	.	.	.	5.20	3.55	3.04	MI01
	100	.	.	.	5.10	3.75	3.04	MI01
	011	.	.	.	6.30	4.96	3.20	MI01
N.KARELIA,USSR								
MICROCLINE	001	2.571			6.43'			MI02
	010	2.570			7.67'			MI02
	100	2.571			4.65'			MI02
LABRADOR								
MICROCLINE	X	2.57			4.75	2.97		MI03
	Y	2.57			5.57	3.05		MI03
	Z	2.57			7.49	3.38		MI03
ONTARIO								
AMAZONITE	001	.	.	.	6.43	2.73	2.37	AZ01
	010	.	.	.	6.81	2.31	3.49	AZ01
	100	.	.	.	4.59	3.47	2.25	AZ01
USSR								
PLAGIOCLASE FELDSPARS								
ALBITE	001	2.61	.	.	7.13	3.19	2.56	AB05
	110	.	.	.	6.38	3.69	2.74	AB05
	010	.	.	.	7.26	2.58	3.56	AB05
	101	.	.	.	5.31	3.40	2.95	AB05
	100	.	.	.	5.42	5.45	3.30	AB05
	011	.	.	.	6.20	4.63	3.10	AB05
USSR								
ALBITE	X	.	.	.	4.38	.	.	AB06
	Y	.	.	.	6.68	.	.	AB06
ALBITE	X	2.63			6.23	3.10		AB07
	Y	2.63			6.73	3.55		AB07
	Z	2.63			6.42	2.70		AB07
ONTARIO								
OLIGOCLASE	001	2.64	.	.	6.88	3.19	2.58	OL02
	110	.	.	.	6.81	3.72	2.78	OL02
	010	.	.	.	7.87	2.71	3.66	OL02
	101	.	.	.	6.60	3.07	3.13	OL02
	100	.	.	.	5.68	3.70	2.95	OL02
	011	.	.	.	6.45	4.53	3.36	OL02
CHUPA,WHITE SEA,USSR								
OLIGOCLASE	001	2.64	.	.	7.18	3.24	2.59	OL03
	110	.	.	.	8.55	3.72	2.86	OL03
	010	.	.	.	7.41	2.84	3.58	OL03
	101	.	.	.	5.48	3.48	3.06	OL03
	100	.	.	.	5.62	3.55	3.35	OL03
	011	.	.	.	6.30	4.62	3.26	OL03
USSR								

MINERAL		RHO	POR	M/P	VP1	VS1	VS2	INDEX
PLAGIOCLASE FELDSPARS (CONT.)								
OLIGOCLASE	001	2.64	.	.	7.17	3.27	2.65	OL04
	110	.	.	.	6.67	3.76	2.90	OL04
	010	.	.	.	7.55	2.70	3.61	OL04
	101	.	.	.	5.50	3.52	3.10	OL04
	100	.	.	.	5.70	3.60	3.37	OL04
	011	.	.	.	6.35	4.70	3.29	OL04
USSR								
LABRADORITE	001	2.68	.	.	7.53	3.49	2.83	LA01
	110	.	.	.	7.38	4.14	2.89	LA01
	010	.	.	.	7.71	2.76	3.53	LA01
	101	.	.	.	7.05	3.65	2.96	LA01
	100	.	.	.	6.10	3.72	3.59	LA01
	011	.	.	.	6.48	4.89	3.63	LA01
GOLOVINO,UKRAINE,USSR								
LABRADORITE	001	2.68	.	.	7.30	3.40	2.70	LA02
	110	.	.	.	6.98	3.84	2.95	LA02
	010	.	.	.	7.80	2.78	3.63	LA02
	101	.	.	.	7.25	3.65	3.14	LA02
	100	.	.	.	6.06	3.72	3.44	LA02
	011	.	.	.	6.55	4.76	3.44	LA02
USSR								
LABRADORITE	001	2.69	.	.	7.33	3.40	2.72	LA03
	110	.	.	.	7.10	3.90	3.02	LA03
	010	.	.	.	8.00	2.80	3.65	LA03
	101	.	.	.	7.38	3.67	3.17	LA03
	100	.	.	.	6.10	3.74	3.50	LA03
	011	.	.	.	6.64	4.80	3.48	LA03
USSR								
BYTOWNITE	X	2.71			6.69	3.49		BY01
	Y	2.71			7.37	3.38		BY01
	Z	2.71			6.73	3.54		BY01
MINNESOTA								
FELDSPATHOID GROUP								
NEPHELITE	001	.	.	.	7.12	3.72	.	NE01
	100	.	.	.	5.61	2.83	3.72	NE01
	011	.	.	.	6.25	3.92	3.26	NE01
1 VISHNEVYE MTS.,URALS,USSR								
NEPHELITE	001	.	.	.	6.90	3.63	.	NE02
	100	.	.	.	5.35	2.53	3.63	NE02
	011	.	.	.	6.00	3.90	3.12	NE02
2 BALYKTACH-KHEM RIVER,USSR								

NON-SILICATES

MINERAL	RHO	POR	M/P	VP1	VS1	VS2	INDEX
OXIDES							
MAGNESIA	3.580	.	.	9.77	5.96	.	MS01
BERKELEY SYNTHETIC							
MAGNESIA	3.580	.	.	9.78	5.97	.	MS02
BERKELEY SYNTHETIC							
MAGNESIA	3.572	.	.	9.67	6.00	.	MS03
AVCO D64B SYNTHETIC							
ALUMINA	3.822	.	.	10.45	.	.	AA01
AD 99 SYNTHETIC							
ALUMINA	3.972	0.35		10.85	6.37		AA02
G.E. LUCALOX							
ALUMINA	3.941	1.13		10.74	6.34		AA03
AVCO 1495A							
HEMATITE	5.5	.	.	7.1	.	.	HE01
HEMATITE X	4.93			6.85	3.91		HE02
Y	4.93			7.04	3.84		HE02
Z	4.93			6.58	3.78		HE02
MICHIGAN							
LIMONITE X	3.55			5.28	2.95		LM01
Y	3.55			5.37	2.96		LM01
Z	3.55			5.42	3.00		LM01
ALABAMA							
SPINEL 100	3.63	.	.	9.10	6.61	.	SN01
				10.30			SN01
SYNTHETIC							
MAGNETITE	4.54	.	30.9	5.9	.	.	MG01
TRANSVAAL							
MAGNETITE	4.532	.	.	2.3	.	.	MG02
TAHAWUS,N.Y.							
MAGNETITE	4.866	.	.	3.8	.	.	MG03
PORT HENRY,N.Y.							
MAGNETITE X	4.81			4.07	2.09		MG04
Y	4.81			4.12	1.57		MG04
Z	4.81			4.34	2.25		MG04
NEWYORK							
MAGNETITE ORE	3.85			5.29			MG05
JAPAN 108							
SULFIDES							
PYRITE 100	5.016	.	.	8.72	4.67	4.67	PR02
110	.	.	.	7.94	5.92	4.67	PR02
LEADVILLE,COLO.							
PYRITE X	4.81			7.63	4.76		PR06
Y	4.81			7.68	4.72		PR06
Z	4.81			7.76	4.87		PR06
COLORADO							

MINERAL	RHO	POR	M/P	VP1	VS1	VS2	INDEX
SULFIDES (CONT.)							
PYRITE 110	4.929	.	.	7.91	5.90	4.67	PR03
1 GLENDON,N.C.							
PYRITE 100	4.929	.	.	8.51	4.59	4.57	PR04
110	.	.	.	7.76	5.70	4.58	PR04
2 GLENDON,N.C.							
PYRITE	4.85	.	.	.	3.81	.	PR01
NORANDA MINES,QUE.							
PYRITE 100	.	.	.	8.49	.	.	PR05
110	.	.	.	7.23	.	.	PR05
NEPAL							
PYRITE ORE	4.51			7.46			PR07
JAPAN 96							
PYRITE ORE	4.20			6.31			PR08
JAPAN 104							
PYRRHOTITE X	4.55			4.70	2.78		PT01
Y	4.55			4.66	2.71		PT01
Z	4.55			4.71	2.78		PT01
ONTARIO							
GALENA 100	7.564	.	.	1.88	.	.	GA01
110	7.560	.	.	3.51	.	.	GA01
111	7.565	.	.	3.93	.	.	GA01
210	7.563	.	.	3.04	.	.	GA01
CHEROKEE CO.,KANSAS							
SULFATES							
ANHYDRITE	2.928	.	.	4.8	.	.	AH01
ANHYDRITE X				6.20			AH02
Y				6.34			AH02
Z				6.21			AH02
CARBONATES							
CALCITE X	2.705	.	.	7.12	4.15	3.58	CA01
Z	2.704	.	.	5.44	3.55	.	CA01
CALCITE X	.	.	.	7.03	.	.	CA02
Y	.	.	.	6.59	.	.	CA02
Z	.	.	.	4.80	.	.	CA02
ARAGONITE	2.917	.	.	5.7	.	.	AR01
MEXICO							
MAGNESITE	2.802			6.92'			MN02
MAGNESITE	^.848	.	.	.	4.05	.	MN01
HALIDES							
HALITE	.	.	.	4.68	.	.	HA01
CARBON							
GRAPHITE X	2.16			3.30	1.77		GP01
Y	2.16			2.93	1.97		GP01
Z	2.16			2.94	1.84		GP01
CEYLON							

Appendix 2

COMPRESSIONAL VELOCITY VERSUS PRESSURE (10 bars to 10 kb)

(SOURCES FOR DATA ARE LISTED IN APPENDIX 8)
(VELOCITY UNITS=KM./SEC. COLUMN HEADINGS ARE PRESSURES IN UNITS OF KILOBARS)
(ALL MEASUREMENTS AT TEMPERATURES OF 0-30 DEGREES CENTIGRADE)

EXPLANATION OF SPECIAL SYMBOLS IN APPENDIXES 2-3

(ALL PRESSURES ARE + OR - 3 PERCENT)

SYMBOL	EXPLANATION
.01	PRESSURE=0.000-0.025 KILOBARS
'	PRESSURE=0.025-0.050 KILOBARS
)	PRESSURE=0.070 KILOBARS
/	PRESSURE=0.170 KILOBARS
=	PRESSURE=0.200 KILOBARS
))	PRESSURE=0.300 KILOBARS
(	PRESSURE=0.345 KILOBARS
((	PRESSURE=0.400 KILOBARS
**	PRESSURE=0.470 KILOBARS
*	PRESSURE=0.600 KILOBARS
//	PRESSURE=0.900 KILOBARS
$	PRESSURE=9.000 KILOBARS
+	ADD 0.5 KILOBARS TO COLUMN HEADING
-	SUBTRACT 0.5 KILOBARS FROM COLUMN HEADING
++	ADD 1.0 KILOBARS TO COLUMN HEADING
--	SUBTRACT 1.0 KILOBARS FROM COLUMN HEADING

(SYMBOLS IMMEDIATELY FOLLOW THE READINGS TO WHICH THEY APPLY)

ROCKS

IGNEOUS ROCKS

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
OVERSATURATED													
GRANITE	2.619	4.1		5.63	5.84	5.97		6.10		6.16		6.23	GR25
WESTERLY,R.I.													
GRANITE	2.615	.	5.90=	5.98	6.06	6.12	6.14	6.18	6.22	.	.	.	GR44
WESTERLY,R.I.													
GRANITE	2.621	5.1	.	6.04	6.11	6.20	.	6.30	.	6.37	.	6.45	GR26
QUINCY,MASS.													
GRANITE	2.629	.	5.92=	6.06	6.21	6.30	6.34	6.38	6.40	.	.	.	GR43
QUINCY,MASS.													
GRANITE	2.624	5.0	.	5.96	6.18	6.29	.	6.39	.	6.43	.	6.51	GR27
ROCKPORT,MASS													
GRANITE	2.626	4.2	.	5.64	5.91	6.09	.	6.22	.	6.28	.	6.35	GR29
CHELMSFORD,MASS.													
GRANITE	2.625	3.7	.	5.42	5.94	6.16	.	6.27	.	6.33	.	6.40	GR28
STONE MT.,GA.													

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
GRANITE	2.662	5.9			6.24	6.28		6.34		6.38		6.45	GR32
SACRED HEART,MINN.													
GRANITE	2.672	5.7	.	6.21	6.29	6.35	.	6.42	.	6.46	.	6.51	GR33
BARRIEFIELD, ONT.													
GRANITE	.	5.64	5.88	6.22	6.34	6.38	6.41	6.43	6.45	.	.	.	GR41
BARRIEFIELD,ONT.													
GRANITE	2.679	6.1	.	6.28	6.33	6.37	.	6.43	.	6.48	.	6.57	GR35
ENGLEHART,ONT.													
GRANITE	2.683	5.7	.	6.13	6.19	6.25	.	6.30	.	6.34	.	6.41	GR36
LATCHFORD,ONT.													
GRANITE	2.655	5.1	.	5.86	6.06	6.15	.	6.25	.	6.32	.	6.39	GR31
BARRE,VT.													
GRANITE	2.634		5.77=6.05		6.16	6.22	6.26	6.29	6.31				GR45
WOODBURY,VT.													
GRANITE	2.610	5.52	5.80/6.11		6.23	.	.	.	.	.	.	.	GR42
BEAR MT.,TEX.													
GRANITE PINK	2.636	.	6.14=6.29		6.34	6.43	6.47	6.50	6.52	6.54	.	.	GR46
LLANO CO.,TEX.													
GRANITE GREY	2.609	.	5.78=5.96		6.10	6.19	6.23	6.25	6.28	6.30	6.34	.	GR47
LLANO CO.,TEX.													
GRANITE A	2.676	5.7			6.42	6.46		6.51		6.55		6.61	GR34
HYDERABAD,INDIA													
GRANITE B	2.654	5.4	.	6.26	6.31	6.38	.	6.44	.	6.49	.	6.56	GR30
HYDERABAD,INDIA													
GRANITE	2.62	4.64	4.86=5.11		*5.36	.	.	.	.	.	.	.	GR06
USSR 137													
GRANITE	2.62	4.56							6.06				GR07
USSR 137													
GRANITE	.	4.95	.	5.30	5.48	5.55-	5.55-	5.55-	.	.	.		GR04
USSR 247													
GRANITE	.	5.30	.	5.70	5.84	5.84-	.	.	.	.	.		GR05
USSR 248													
GRANITE	.	5.50	.	.	6.09	6.09	6.09	6.08	.	.	.		GR77
USSR 249													
GRANITE	2.58	4.60			6.1	6.3				6.3			GR08
USSR 732													
GRANITE	2.62	5.00			5.46//								GR09
USSR 1776													
QTZ MONZONITE	2.628	5.26	5.62/5.90		6.00	.	.	.					QM03
WESTERLY,R.I.													
QTZ MONZONITE	2.644	5.1			5.95	6.07		6.22		6.28		6.37	QM02
PORTERVILLE,CAL.													
GRANODIORITE	2.705	4.4			6.27	6.35		6.43		6.48		6.56	GD01
BUTTE, MONT.													
QTZ DIORITE	2.906	5.5			6.46	6.53		6.60		6.65		6.71	QD03
DEDHAM,MASS.													
QTZ DIORITE	2.798	5.1			6.43	6.52		6.60		6.64		6.71	QD02
SAN LUIS REY QUAD., CAL.													
TONALITE	2.763	5.1			6.33	6.43		6.49		6.54		6.60	QD01
VAL VERDE,CAL.													
SATURATED													
SYENITE	2.780	5.7			6.58	6.63		6.70		6.73		6.79	SY02
SUDBURY, ONTARIO													
TRACHYTE	2.712		5.41=5.48		5.55	5.67	5.73	5.76	5.78				TA01

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
DIORITE	3.025	5.78'	5.97/	6.24	6.30	.	.	.	.	.	.	.	DT01
SALEM,MASS.													
ALBITITE	2.615	6.07		6.18	6.24	6.31		6.40		6.45		6.52	AB01
SYLMAR,PA.													
OLIGOCLASITE	2.687	6.40			6.62	6.65		6.68		6.72		6.76	OL01
SYLMAR,PA.													
ANDESITE	2.618	5.23'	5.24/	5.27	5.31	.	.	.	.	.	.	.	AD04
SALIDA,COLO.													
GABBRO	3.054	5.8		6.74	6.93	7.02		7.11		7.17		7.23	NG07
FRENCH CREEK,PA.													
GABBRO	2.931	6.8		7.04	7.07	7.09		7.13		7.16		7.21	NG05
MELLEN,WISC.													
GABBRO	2.885		6.45=6.61		6.69	6.76	6.78	6.81	6.83	6.84			NG12
DULUTH,MINN.													
GABBRO	2.993		6.69=6.79		6.88	6.95	6.98	7.01	7.03	7.05			NG11
SAN MARCOS,CAL.													
GABBRO	2.933	.	6.60=6.67		6.74	6.80	6.84	6.86	6.88	6.89	.		NG13
GABBRO	2.96	6.07	.	.	6.53	6.53	6.53	6.52	.	.	.	.	NG16
USSR 38													
GABBRO	2.98	6.46	.	.	6.80	6.80	6.80	6.80	.	.	.	.	NG15
USSR 82													
NORITE	3.057	6.18'	6.50/	6.76	6.88	.	.	.	.	.	.	.	NG10
ESSEX CO.,N.Y.													
NORITE	2.978	6.6		7.02	7.07	7.11		7.16		7.20		7.28	NG06
PRETORIA,TRANS.													
NORITE	2.95	6.4	.	.	6.7	7.0	.	.	.	7.2++	.	7.2++	NG04
USSR 466													
NORITE	2.93	6.50	.	.	6.70	.	.	6.75	.	.	.		NG01
USSR 466													
ANORTHOSITE	2.768	6.73	.	.	6.86	6.90	.	6.94	.	6.97	.	7.02	AN01
TAHAWUS,N.Y.													
ANORTHOSITE	2.712	6.28	.	6.61	6.69	6.75	.	6.82	.	6.85	.	6.91	AN05
WHITEFACE MT.,N.Y.													
ANORTHOSITE	2.770	6.5			6.97	7.01		7.05		7.07		7.10	AN02
STILLWATER,MONT.													
ANORTHOSITE	2.708	6.54		6.64	6.69	6.73		6.78		6.81		6.85	AN04
NEW GLASCOW,QUE.													
ANORTHOSITE	2.807	5.7		6.92	6.98	7.05		7.13		7.16		7.21	AN03
BUSHVELD,TRANSVAAL													
DIABASE	2.976	6.14	.	.	6.70	6.76	.	6.82	.	6.86	.	6.93	DB08
CENTREVILLE,VA.													
DIABASE	2.977	6.25	.	6.40	6.43	6.47	.	6.52	.	6.56	.	6.63	DB09
HOLYOKE,MASS.													
DIABASE	3.012	6.76	.	.	6.77	6.80	.	6.84	.	6.88	.	6.92	DB11
FREDERICK,MD.													
DIABASE	2.964	6.55	.	.	6.64	6.67	.	6.71	.	6.75	.	6.82	DB07
NIPISSING,COBALT,ONT.													
DIABASE	3.003	6.4	.	6.67	6.72	6.76	.	6.81	.	6.84	.	6.91	DB10
KEWEENAWAN,SUDBURY,ONT.													
DIABASE	3.04	6.33	6.40=6.58*		6.67	.	.	.	.	.	.	.	DB01
USSR 3													
DIABASE	3.04	6.37	.	.	.	.	.	.	6.95	.	.	.	DB02
USSR 3													
DIABASE	3.08	6.3	.	.	.	.	.	7.0	.	.	.	.	DB03
USSR 3													

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
DIABASE 3	2.903	6.51	.	6.69	6.81	6.88	6.91						DB16
PRIBRAM,CZECH.													
DIABASE 7	2.879	6.47	.	6.65	6.72	6.77	6.81	6.84					DB17
PRIBRAM,CZECH.													
BASALT	2.586		5.41=5.57		5.66	5.75	5.79	5.80	5.81	5.82			BA06
CHAFFEE CO.,COLO.													
BASALT	2.88	5.53	5.70=5.84*5.92										BA03
USSR 4													
BASALT	2.88	5.57							6.19				BA04
USSR 4													
BASALT	2.63	4.77		5.57//									BA02
USSR													
ULTRAMAFIC													
DUNITE ALTERED	3.00	6.31	.	.	6.54	6.62	.	6.72	.	6.80	.	6.93	DU04
ALTERED	2.962	5.46	.	.	6.07	6.18	.	6.28	.	6.40	.	6.62	DU04
	3.244	7.0			7.54	7.59		7.65		7.69		7.78	DU05
WEBSTER,N.C.													
DUNITE X	3.258	6.4		7.52	7.54	7.70		7.85		7.91		8.00	DU07
Y	3.274	8.0		8.38	8.42	8.49		8.57		8.63		8.69	DU07
Z	3.258	6.4		7.52	7.54	7.70		7.85		7.91		8.00	DU07
BALSAM GAP,N.C.													
DUNITE	3.198		7.40=7.54		7.63	7.77	7.82	7.86	7.91				DU16
BALSAM GAP,N.C.													
DUNITE X	3.306	7.90		8.23	8.30	8.35		8.41		8.44		8.51	DU08
Y	3.302	7.34			7.56	7.61		7.73		7.82		7.91	DU08
Z	3.304	7.85		8.07	8.12	8.19		8.29		8.34		8.41	DU08
ADDIE,N.C.													
DUNITE X	3.312	8.3		8.73	8.78	8.85		8.88		8.90		8.95	DU09
Y	3.310	7.2		7.74	7.83	7.92		7.97		8.00		8.07	DU09
Z	3.314	7.6		7.86	7.97	8.04		8.12		8.16		8.23	DU09
TWIN SISTERS MT.,WASH.													
DUNITE	3.160		8.60)		8.87		8.94	8.96	8.98				DU15
TWIN SISTERS MT.,WASH.													
DUNITE X	3.255	7.9		8.14	8.20	8.25		8.30		8.35		8.43	DU06
Y	3.257	7.2		7.54	7.61	7.66		7.73		7.81		7.91	DU06
Z	3.262	7.3		7.38	7.45	7.48		7.54		7.60		7.66	DU06
MT. DUN,NEW ZEALAND													
DUNITE X	3.777	7.0		7.40	7.42	7.46		7.50		7.53		7.57	DU10
Y	3.717	6.6	.	6.87	6.90	6.98	.	7.06	.	7.10	.	7.19	DU10
Z	3.737	6.6		7.12	7.15	7.20		7.26		7.28		7.33	DU10
MOOIHOEK MINE,TRANS.													
PERIDOTITE	3.28	6.8			7.3+	7.5				7.6	7.8	8.0++	PE01
USSR 455													
PERIDOTITE	3.28	7.40	.	.	7.70	.	.	7.70	.	.	.		PE04
USSR 455													
PERIDOTITE	3.21	6.97	.	.	7.83	.	.	8.02	.	.	.		PE03
USSR 462													
PERIDOTITE	3.34	7.7	.	.	.	8.0	.	.	.	8.2++	.		PE02
USSR 609													
HARZBURGITE X	3.380	6.7		7.61	7.65	7.70		7.73		7.77		7.82	HB01
Y	3.371	7.3		7.84	7.89	7.91		7.96		8.01		8.05	HB01
Z	3.356	6.6		7.76	7.80	7.82		7.87		7.91		7.97	HB01
BUSHVELD,TRANSVAAL													

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
PYROXENITE X	3.239	6.7			7.72	7.79		7.87		7.94		8.00	PX06
Y	3.244	6.4			7.45	7.52		7.65		7.72		7.82	PX06
Z	3.259	7.2			8.03	8.06		8.11		8.14		8.20	PX06
SONOMA CO., CAL.													
PYROXENITE	3.24	7.14			7.40			7.46					PX01
USSR 457													
PYROXENITE	3.15	6.75			7.05			7.05					PX05
USSR 468													
PYROXENITE	3.29	7.62			7.87			8.00					PX02
USSR 469													
PYROXENITE	3.22	5.90			6.72			7.05					PX03
USSR 470													
PYROXENITE	3.24	6.75			7.67			7.67					PX04
USSR 472													
BRONZITITE X	3.283	7.20			7.60	7.64		7.70		7.73		7.82	BR01
Y	3.284	7.58			7.67	7.71		7.77		7.81		7.89	BR01
Z	3.271	7.48			7.59	7.61		7.68		7.71		7.79	BR01
STILLWATER, MONT.													
BRONZITITE X	3.304	6.2		7.45	7.50	7.57		7.66		7.71		7.80	BR02
Y	3.264	5.0		7.46	7.56	7.71		7.88		8.00		8.13	BR02
Z	3.297	5.9		7.30	7.40	7.53		7.70		7.85		8.12	BR02
BUSHVELD, TRANSVAAL													
SERPENTINITE	2.710	5.8			6.02	6.08		6.15		6.21		6.31	SE12
CALIF.													
SERPENTINITE	2.710	5.8			6.02	6.08		6.15					SE18
CALIF.													
SERPENTINITE	2.798	6.4			6.51	6.57		6.67		6.74		6.84	SE13
LUDLOW, VT.													
SERPENTINITE	2.798	6.4			6.51	6.57		6.67					SE17
LUDLOW, VT.													
SERPENTINITE X	2.768	6.18	6.21	6.33*	6.37	6.42	.	6.50	.	6.58	6.63	6.68	SE14
Y	2.807	7.05	7.06	7.08*	7.10	7.14		7.18		7.22	7.25	7.27	SE14
Z	2.792	6.70	6.71	6.74*	6.76	6.80		6.85		6.89	6.93	6.97	SE14
MIDDLEFIELD, MASS.													
SERPENTINITE	2.70	6.13							7.36				SE06
USSR 240													
SERPENTINITE B	2.433		5.0	5.16	5.24	5.34		5.46					SE19
PUERTO RICO													
SERPENTINITE B	2.510		4.5	4.68	4.75	4.88		5.06					SE20
PUERTO RICO													
SERPENTINITE B	2.536		4.7	4.86	4.91	5.01		5.17					SE21
PUERTO RICO													
SERPENTINITE A	2.599		5.8	5.82	5.86	5.90		5.99					SE22
PUERTO RICO													
SERPENTINITE A	2.589		5.1	5.24	5.28	5.36		5.48					SE23
PUERTO RICO													
SERPENTINITE A	2.744		6.17	6.19	6.20	6.23		6.30					SE24
PUERTO RICO													
SERPENTINITE A	2.732		6.1	6.18	6.21	6.26		6.33					SE25
PUERTO RICO													
SERPENTINITE A	2.725		6.1	6.07	6.09	6.12		6.19					SE26
PUERTO RICO													

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
CHRYSOTILE X	2.598	5.5			5.60	5.66		5.73		5.79		5.91	SE10
Y	2.603	5.8			5.83	5.88		5.96		6.03		6.15	SE10
Z	2.601	5.5			5.59	5.65		5.71		5.78		5.93	SE10
THETFORD,QUE.													
CHRYSOTILE	2.601	5.6			5.67	5.73		5.80					SE15
THETFORD,QUE.													
ANTIGORITE X	2.620	4.0		6.00	6.16	6.28		6.41		6.46		6.57	SE11
Y	2.603	5.7		6.94	6.99	7.15		7.26		7.29		7.33	SE11
Z	2.618	4.5		6.06	6.22	6.33		6.44		6.49		6.56	SE11
LUDLOW,VT.													
ANTIGORITE	2.614	4.7			6.46	6.59		6.70					SE16
LUDLOW,VT.													
GLASSES													
OBSIDIAN	2.376	5.80	.	.	.	5.78	.	5.73	.	5.70	.	5.62	OB01
MODOC,CAL.													
DIABASE GLASS	2.750	6.30	.	.	.	.	.	.	.	.	.	6.30	DB15
GENERAL ELECTRIC CO.													

METAMORPHIC ROCKS

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
SCHIST PAR	2.800	6.5	.	.	6.77	6.80	.	6.84	.	6.87	.	6.91	SC03
PERP	2.796	4.6	.	.	6.05	6.10	.	6.17	.	6.22	.	6.31	SC03
WOODSVILLE,VT.													
SCHIST-CHLOR	2.877	5.9	.	.	7.17	7.23	.	7.30	.	7.32	.	7.36	SC04
	2.897	3.3	.	.	6.52	6.61	.	6.70	.	6.75	.	6.82	SC04
CHESTER QUARRY,VT.													
SCHIST-TALC	2.914	4.9	.	.	6.30	6.50	.	6.71	.	6.82	.	6.97	SC01
CHESTER QUARRY,VT.													
SCHIST-ACTIN	3.217	5.62	.	.	6.62	6.75	.	6.84	.	6.92	.	7.01	SC02
	3.199	7.32	.	.	7.68	7.79	.	7.89	.	7.94	.	8.00	SC02
CHESTER QUARRY,VT.													
SCHIST X	2.75	.	5.4	6.3	*6.44	6.58	.	6.70	.	6.74	6.77	6.82	SC18
Y	2.76	.	5.3	6.2	*6.44	6.54	.	6.64	.	6.71	6.76	6.77	SC18
Z	2.76	.	5.0	5.61	*5.71	5.84	.	5.95	.	6.05	6.11	6.17	SC18
THOMASTON,CONN.													
SCHIST 1X	2.99	.	5.0	6.2	*6.53	6.72	.	7.07	.	7.27	7.41	7.50	SC19
1Y	2.95	.	5.6	6.55	*6.78	7.01	.	7.17	.	7.29	7.35	7.48	SC19
1Z	3.07	.	4.6	5.8	*6.12	6.61	.	6.92	.	7.03	7.19	7.26	SC19
TORRINGTON,CONN.													
SCHIST 2X	2.73	.	5.8	6.53	*6.73	6.92	.	7.04	.	7.17	7.23	7.27	SC20
2Y	2.84	.	5.0	6.05	*6.26	6.54	.	6.75	.	6.87	6.92	7.00	SC20
2Z	2.73	.	4.6	5.57	*5.74	5.87	.	6.02	.	6.02	6.12	6.20	SC20
TORRINGTON,CONN.													
SCHIST X	2.75	.	5.9	6.74	*6.87	6.97	.	7.16	.	7.20	7.23	7.25	SC21
Y	2.76	.	5.6	6.41	*6.54	6.66	.	6.77	.	6.85	6.89	6.93	SC21
Z	2.75	.	.	5.25	*5.41	5.54	.	5.63	.	5.70	5.78	5.85	SC21
LITCHFIELD,CONN.													

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
SLATE X	2.734	5.81	.	.	6.05	6.13	.	6.23	.	6.29	.	6.39	SL06
Y	2.741	4.97			5.40	5.56		5.71		5.80		5.96	SL06
MEDFORD,MASS.													
SLATE X	2.77	.	6.28	6.35	*6.37	6.41	.	6.48	.	6.54	6.59	6.66	SL08
Y	2.75	.	6.29	6.33	*6.36	6.40	.	6.46	.	6.51	6.57	6.63	SL08
Z	2.77	.	4.94	5.04	*5.09	5.15	.	5.29	.	5.41	5.50	5.59	SL08
POULTNEY,VT.													
GNEISS PAR	2.642	3.7	.	5.82	6.04	6.18	.	6.30	.	6.35	.	6.43	GN15
PERP	2.646	2.9	.	5.54	5.83	5.96	.	6.09	.	6.15	.	6.25	GN15
PELHAM,MASS.													
GNEISS PAR	2.684	5.6	.	6.25	6.31	6.39	.	6.47	.	6.53	.	6.61	GN13
PERP	2.664	4.5	.	5.76	5.83	5.94	.	6.05	.	6.10	.	6.26	GN13
HELL GATE,N.Y.													
GNEISS PAR	2.768	4.9	.	.	6.14	6.22	.	6.30	.	6.36	.	6.43	GN14
PERP	2.762	3.6	.	.	5.74	5.87	.	6.01	.	6.08	.	6.13	GN14
BETHLEHEM,N.H.													
GNEISS 1X	2.643	.	4.7	5.7	*5.92	6.12	.	6.23	.	6.29	6.34	6.37	GN23
1Y	2.621	.	5.0	5.9	*6.07	6.18	.	6.29	.	6.32	6.37	6.41	GN23
1Z	2.665	.	4.6	5.7	*5.91	6.05	.	6.15	.	6.21	6.24	6.29	GN23
TORRINGTON,CONN.													
GNEISS 2X	2.661	.	4.5	5.5	*5.79	6.04	.	6.22	.	6.29	6.35	6.39	GN24
2Y	2.651	.	4.5	5.7	*5.91	6.09	.	6.22	.	6.27	6.31	6.35	GN24
2Z	2.650	.	4.6	5.7	*5.85	6.04	.	6.09	.	6.15	6.21	6.25	GN24
TORRINGTON,CONN.													
GNEISS 3X	2.742	.	5.1	5.9	*6.19	6.32	.	6.44	.	6.48	6.54	6.58	GN25
3Y	2.745	.	4.7	5.8	*6.06	6.33	.	6.42	.	6.48	6.53	6.57	GN25
3Z	2.777	.	5.4	6.1	*6.19	6.32	.	6.43	.	6.50	6.53	6.56	GN25
TORRINGTON,CONN.													
GNEISS 4X	2.819	.	4.6	5.7	*6.02	6.32	.	6.52	.	6.60	6.68	6.72	GN26
4Y	2.877	.	4.7	5.8	*6.08	6.28		6.45		6.52	6.57	6.63	GN26
4Z	2.776		5.1	5.8	*5.98	6.14		6.23		6.29	6.34	6.38	GN26
TORRINGTON,CONN.													
GNEISS 5X	2.845	.	5.5	6.1	*6.29	6.35	.	6.47	.	6.54	6.58	6.63	GN27
5Y	2.850	.	5.7	5.81	*5.88	5.99	.	6.16	.	6.36	6.49	6.58	GN27
5Z	2.848	.	5.2	5.9	*5.98	6.09	.	6.18	.	6.24	6.29	6.33	GN27
TORRINGTON,CONN.													
GNEISS 6X	2.76	.	5.4	6.0	*6.17	6.34	.	6.49	.	6.55	6.60	6.65	GN28
6Y	2.75	.	5.2	5.9	*6.05	6.24	.	6.44	.	6.52	6.57	6.63	GN28
6Z	2.76	.	4.1	4.9	*5.16	5.43	.	5.66	.	5.81	5.90	5.99	GN28
GOSHEN,CONN.													
GNEISS	2.84	6.1			6.4	+6.5	6.6			6.6	6.7	6.8	GN12
USSR 460													
GNEISS	2.68	5.2	.	.	6.1	+ .	6.3	.	.	6.4	.	6.5	GN11
USSR 740													
CHARNOCKITE	2.740	6.15			6.24	6.30		6.36		6.40		6.46	CK12
PALLAVARAM,INDIA													
MARBLE	.	.	5.87)	6.25(	6.55	6.65	+6.67	6.67	6.66	.	.		MA08
DANBY,VT.													
MARBLE X	2.705	4.7	.	.	6.48	6.53	.	6.58	.	6.59	.	6.60	MA09
Y	2.703	5.9	.	.	6.69	6.76	.	6.81	.	6.84	.	6.87	MA09
Z	2.704	4.8			6.65	6.69		6.77		6.80		6.81	MA09
DANBY,VT.													
MARBLE PERP C	.	5.96	6.48=	6.63	*6.68		.	.	.	.	.	.	MA11
PAR C	.	6.08	6.55=	6.66	*6.67		.	.	.	.	.	.	MA11
YULE,COLO.													

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
QUARTZITE	2.647	5.6	.	.	6.11	6.15	.	6.22	.	6.26	.	6.35	QZ03
MONTANA													
QUARTZITE X	2.63	.	5.2	5.83*	5.98	6.07	.	6.16	.	6.21	6.24	6.28	QZ12
Y	2.62	.	5.6	5.97*	6.05	6.12	.	6.17	.	6.21	6.26	6.28	QZ12
Z	2.63	.	5.6	6.01*	6.11	6.18	.	6.25	.	6.29	6.31	6.33	QZ12
CLARENDON SPRINGS,VT.													
QUARTZITE X	2.68	.	5.4	6.17*	6.27	6.35	.	6.43	.	6.49	6.51	6.55	QZ13
Y	2.66	.	5.2	6.06*	6.16	6.23	.	6.29	.	6.35	6.39	6.43	QZ13
Z	2.68	.	5.1	5.78*	5.86	5.93	.	6.01	.	6.07	6.12	6.17	QZ13
THOMASTON,CONN.													
QUARTZITE	.	5.55	.	.	5.85	6.00	6.00-	.	.	.	.	.	QZ15
USSR 22													
AMPHIBOLITE	3.108	6.09			6.61	6.65		6.72		6.77		6.83	AM04
	3.124	7.31			7.50	7.54		7.59		7.63		7.66	AM04
MADISON CO.,MONT.													
AMPHIBOLITE 1X	3.05		7.0	7.2 *	7.21	7.26		7.37		7.42	7.46	7.49	AM07
1Y	3.04		6.9	7.09*	7.13	7.20		7.28		7.33	7.38	7.42	AM07
1Z	3.04		5.6	6.14*	6.29	6.45		6.60		6.68	6.73	6.76	AM07
BANTAM,CONN.													
AMPHIBOLITE 2X	3.03	.	5.8	6.7 *	6.97	7.25	.	7.47	.	7.52	7.58	7.61	AM08
2Y	3.02	.	6.2	6.8 *	6.92	7.08	.	7.22	.	7.26	7.29	7.33	AM08
2Z	3.03	.	4.5	5.7 *	6.01	6.27	.	6.44	.	6.51	6.55	6.59	AM08
BANTAM,CONN.													
AMPHIBOLITE 1X	3.11	.	6.8	7.2 *	7.29	7.45	.	7.61	.	7.73	7.77	7.82	AM09
1Y	3.15	.	6.0	6.9 *	7.10	7.32	.	7.52	.	7.60	7.65	7.69	AM09
LITCHFIELD,CONN.													
AMPHIBOLITE 2X	3.25	.	6.4	6.9 *	7.15	7.40	.	7.66	.	7.75	7.81	7.83	AM10
2Y	3.30	.	6.4	7.1 *	7.25	7.49	.	7.65	.	7.72	7.77	7.80	AM10
2Z	3.24	.	5.8	6.7 *	6.87	7.07	.	7.24	.	7.32	7.36	7.39	AM10
LITCHFIELD,CONN.													
ECLOGITE	3.441	7.31	.	.	7.69	7.81	.	7.89	.	7.94	.	8.01	EC10
HEALDSBURG,CAL.													
ECLOGITE	3.376	5.2	.	.	7.13	7.30	.	7.46	.	7.54	.	7.69	EC09
SUNNMORE,NORWAY													
ECLOGITE 1	3.338	6.6		7.49	7.56	7.65		7.79		7.85		7.92	EC14
2	3.376	7.17	.	7.65	7.68	7.73	.	7.79	.	7.82	.	7.87	EC08
KIMBERLEY DIST. ,O.F.S													
ECLOGITE	3.328	6.64	.	7.30	7.38	7.46	.	7.57	.	7.62	.	7.71	EC07
TANGANYIKA													

SEDIMENTARY ROCKS

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
SANDSTONE	2.659	3.9	.	5.0	5.27	5.44	.	5.63	.	5.75	.	(5.85)	SS13
CATSKILL,N.Y.													
SANDSTONE	2.543	3.67	4.04	4.58	4.87	5.11	5.13	5.28	5.36				SS11
CAPLEN DOME,GALVESTON CO.,TEXAS													
SANDSTONE	2.514	3.73	4.11	5.09	5.37	5.46	5.50	5.53	5.55				SS12
TRAVIS PEAK,MARION CO.,TEXAS													
SANDSTONE (POR=3.3)				5.61**									SS58
ORISKANY,PENNSYLVANIA													

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
SANDSTONE 1(POR=19.0)	2.56'	3.41=	3.67((										SS65
2			3.41))			(AXIAL PRESSURE)							SS66
BEREA,OHIO													
SANDSTONE	2.14		4.58	4.69	4.74	4.72	4.70	4.69					SS45
ST.PETER,KLONDIKE,MO.													
SANDSTONE	2.31	3.73'	4.05	4.89	5.03								SS42
TENSLEEP,LONGS CREEK,WYO.													
SANDSTONE (POR=15.3)			3.93((										SS55
TENSLEEP,WYOMING													
SANDSTONE 1 (POR=7.4)			4.45((										SS56
2			4.29			(AXIAL PRESSURE)							SS57
FOX HILLS,WYOMING													
SANDSTONE (POR=23.5)			3.53))										SS59
JELM,WYOMING													
SANDSTONE (POR=29.7)			3.05))										SS60
TEAPOT,WYOMING													
SANDSTONE (POR=2.3)			4.91**										SS61
SUNDANCE,WYOMING													
SANDSTONE (POR=12.5)			3.51((										SS62
CHUGWATER,WYOMING													
SANDSTONE 1(POR=17.4)	3.78/	3.93=	4.11((					(AXIAL PRESSURE)					SS63
2		3.43=	3.81((										SS64
TORPEDO,OKLAHOMA													
SANDSTONE	2.08	2.42'	2.71	3.62	3.81	.	.						SS43
STEVEN SAND,KERN CO.,CAL.													
SANDSTONE	2.51	4.15'	4.45	5.42	5.56	.	.	.	.	.			SS44
MCKEE													
SANDSTONE	.	3.30	.	.	3.70	3.75	3.75-3.75		.	.	.	.	SS41
USSR 94													
SANDSTONE	2.18	2.94	.	.	3.30	.	.	3.52	.	.	.	.	SS08
USSR 204													
SANDSTONE	.	2.95	.	.	3.25	3.43	3.50	3.53	.	.	.	.	SS39
USSR 205													
SANDSTONE	2.14	3.22	.	.	3.46	.	.	.	.	.	.	.	SS09
USSR 208													
SANDSTONE	2.15	3.13	.	.	3.42	.	.	.	.	.	.	.	SS10
USSR 209													
SANDSTONE	.	4.90	.	4.95	5.05	5.20	5.30	5.30	.	.	.	.	SS40
USSR 213													
GREYWACKE	2.679	5.4	.	5.63	5.76	5.87	.	5.98	.	6.04	.	6.13	GY01
NEW ZEALAND													
GREYWACKE	2.705	5.4	.	.	5.92	6.04	.	6.14	.	6.20	.	6.28	GY02
QUEBEC													
GREYWACKE 6	2.749	6.19	.	6.21	6.23	6.27	6.30	6.33	.				GY03
PRIBRAM,CZECH.													
GREYWACKE U2-7	2.688	6.06	.	6.14	6.19	6.23	6.26	6.28	.	.			GY04
PRIBRAM,CZECH.													
LIMESTONE	2.688	.	.	.	.		5.40	.	5.45	5.40	5.10	4.95	LS23
MANLIUS,RAVENA,N.Y.													
LIMESTONE PAR.	2.739	.	5.74	5.90	5.98	6.06	6.11	6.14	6.17	.	.		LS21
PERP	2.731	.	6.05'	6.13	6.17	6.28	6.32	6.39	6.37	.	.		LS21
UPTON CO.,TEXAS													
LIMESTONE 1(POR=0.47)				6.61**									LS43
2				5.93**				(AXIAL PRESSURE)					LS44
CALICO													

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
LIMESTONE	2.656	5.97	6.00	6.03	6.05	6.08	6.11	6.12	6.13	.			LS01
SOLENHOFEN,BAVARIA													
LIMESTONE	2.543	5.5	.	.	5.59	5.54	.	5.56	.	.	.	.	LS02
SOLENHOFEN,BAVARIA													
LIMESTONE	2.602	.	.	.	.		5.20	.	5.30	5.30	4.85	4.75	LS22
SOLENHOFEN,BAVARIA													
LIMESTONE 1		5.06/5.64(		(5.67*									LS24
2				5.57(				(AXIAL PRESSURE)					LS28
SOLENHOFEN,BAVARIA													
LIMESTONE	2.581	5.56							5.76				LS45
SOLENHOFEN,BAVARIA													
LIMESTONE	2.62	4.78	.	.	.	.	.	.	6.45	.	.	.	LS20
USSR 246													
LIMESTONE	.	5.12	5.44=5.67*		5.82	.	.	.	.	.	.	.	LS19
USSR													
DOLOMITE	2.844	5.6	.	.	6.98	7.03	.	7.09	.	7.14	.	7.22	DO02
RUTLAND,VT.													
DOLOMITE	2.845	6.06'	6.30	6.77	6.93	7.06	.	7.17	.	7.23	7.30	7.36	DO05
DUNHAM,WILLIAMSTOWN,MASS.													
DOLOMITE	2.58	4.69	.	4.92*	.	.	.	.	.	.	.	.	DO01
USSR 1745													

MINERALS

ORTHO- AND RING SILICATES

MINERAL	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
OLIVINE GROUP													
MONTICELLITE	3.014	7.10'	7.13	7.23*	7.27	7.31	.	7.36	.	7.40	7.45	7.50	MO02
CRESTMORE,CAL.													
GARNET GROUP													
GROSSULARITE	3.561	6.3	.	.	8.41	8.55	.	8.72	.	8.83	.	8.99	GT01
CONNECTICUT													
ALMAND.-PYROPE	3.950	5.9	.	.	7.81	7.91	.	7.99	.	8.01	.	8.07	GT02
AL2SIO5 GROUP													
SILLIMANITE X	3.189	9.04'	9.09	9.22*	9.25	9.30	.	9.35	.	9.39	9.42	9.45	SI02
Y	3.179	9.55'	9.57	9.67*	9.71	9.75		9.80		9.85	9.88	9.91	SI02
Z	2.194	9.60'	9.62	9.66*	9.70	9.75		9.79		9.81	9.82	9.84	SI02
WILLIAMSTOWN,AUSTRALIA													
OTHERS													
IDOCRASE	3.144	5.52'	5.62	6.21*	6.54	6.95	.	7.27	.	7.40	7.47	7.54	ID02
CRESTMORE,CAL.													

SINGLE CHAIN SILICATES

MINERAL	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
PYROXENE GROUP													
JADEITE BURMA	3.33	8.60	.	.	.	.	.	8.86+	.	.	.	9.01	$JD01
JADEITE BURMA	3.331	8.45	.	.	8.67	8.69	.	8.72	.	8.75	.	8.78	JD03
JADEITE JAPAN	3.180	7.6	.	.	8.21	8.22	.	8.23	.	8.24	.	8.28	JD04
PYROXENOID GROUP													
WOLLASTONITE	2.873	5.03'	5.67	6.98	7.21	7.42	.	7.56	.	7.64	7.68	7.71	WO01

FRAMEWORK SILICATES

MINERAL	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
SIO2 GROUP													
FUSED SILICA	2.213	5.97	.	.	.	.	.	.	.	.	.	5.53	QU02
ALKALI FELDSPARS													
MICROCLINE 001	2.571	6.43'	6.73	7.28*	7.43	7.53	.	7.58	.	7.60	7.60	7.62	MI02
010	2.570	7.67'	7.82	8.21*	8.25	8.29	.	8.33	.	8.37	8.40	8.45	MI02
100	2.571	4.65'	4.83	5.12*	5.18	5.22	.	5.28	.	5.31	5.35	5.38	MI02
LABRADOR													

NON-SILICATES

OXIDES													
MAGNESIA BERKELEY SYNTHETIC	3.580	9.77				9.78	9.79						MS01
ALUMINA AD-99-SYNTHETIC	3.822	10.45										10.55	AA01
ALUMINA G.E. LUCALOX	3.972	10.85		10.85	10.85	10.86	10.86						AA02
HEMATITE	5.0	7.1	.	.	7.72	7.73	.	7.74	.	7.76	.	7.80	HE01
MAGNETITE TRANSVAAL	4.54	5.9	.	.	6.32	6.41	.	6.52	.	6.58	.	6.67	MG01
MAGNETITE TAHAWUS,N.Y.	4.532	2.3	.	.	6.65	6.75	.	6.85	.	6.92	.	6.98	MG02
MAGNETITE PORT HENRY,N.Y.	4.866	3.8	.	.	6.77	6.90	.	6.99	.	7.04	.	7.11	MG03
SULFATES													
ANHYDRITE	2.928	4.8	.	.	6.00	6.06	.	6.15	.	6.19	.	6.27	AH01
CARBONATES													
ARAGONITE MEXICO	2.917	5.7	.	.	5.82	5.85	.	5.90	.	5.93	.	5.97	AR01
MAGNESITE	2.802	6.92'	6.97	7.08*	7.11	7.19	.	7.27	.	7.33	7.39	7.45	MN02

Appendix 3

SHEAR VELOCITY VERSUS PRESSURE (10 bars to 10 kb)

(SOURCES FOR DATA ARE LISTED IN APPENDIX 8)
(VELOCITY UNITS=KM./SEC. COLUMN HEADINGS ARE PRESSURES IN UNITS OF KILOBARS)
(ALL MEASUREMENTS AT TEMPERATURES OF 0-30 DEGREES CENTIGRADE)

EXPLANATION OF SPECIAL SYMBOLS IN APPENDIXES 2-3

(ALL PRESSURES ARE + OR - 3 PERCENT)

SYMBOL	EXPLANATION
.01	PRESSURE=0.000-0.025 KILOBARS
'	PRESSURE=0.025-0.050 KILOBARS
)	PRESSURE=0.070 KILOBARS
/	PRESSURE=0.170 KILOBARS
=	PRESSURE=0.200 KILOBARS
))	PRESSURE=0.300 KILOBARS
(	PRESSURE=0.345 KILOBARS
((	PRESSURE=0.400 KILOBARS
**	PRESSURE=0.470 KILOBARS
*	PRESSURE=0.600 KILOBARS
//	PRESSURE=0.900 KILOBARS
$	PRESSURE=9.000 KILOBARS
+	ADD 0.5 KILOBARS TO COLUMN HEADING
-	SUBTRACT 0.5 KILOBARS FROM COLUMN HEADING
++	ADD 1.0 KILOBARS TO COLUMN HEADING
--	SUBTRACT 1.0 KILOBARS FROM COLUMN HEADING

(SYMBOLS IMMEDIATELY FOLLOW THE READINGS TO WHICH THEY APPLY)

ROCKS

IGNEOUS ROCKS

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
OVERSATURATED													
GRANITE	2.636	2.77		3.27	3.36	3.44		3.51		3.54		3.58	GR37
WESTERLY,R.I.													
GRANITE	2.615	.	3.50=	3.52	3.55	3.57	3.58	3.59	3.59	.	.		GR44
WESTERLY R.I.													
GRANITE	2.64	2.28	.	3.28	3.37	.	.	.	.	.	.	.	GR80
WESTERLY,R.I.													
GRANITE								3.47					GR56
WESTERLY,R.I.													
GRANITE	2.629	.	3.34=	3.43	3.44	3.46	3.47	3.48	3.50	.	.		GR43
QUINCY,MASS.													
GRANITE	2.64	2.53	.	3.45	3.53	.	.	3.61	.	.	.	.	GR78
QUINCY,MASS.													
GRANITE								3.61					GR53
QUINCY,MASS.													

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
GRANITE	2.638	3.07		3.47	3.54	3.61		3.68		3.71		3.77	GR38
ROCKPORT,MASS.													
GRANITE	2.62	2.55	.	3.42	3.50	.	.	3.58	.	.	.	.	GR79
ROCKPORT,MASS.													
GRANITE	2.62	.	.	.	.	.	.	3.48	.	.	.	.	GR50
ROCKPORT,MASS.													
GRANITE								3.59					GR52
ROCKPORT,MASS.													
GRANITE	2.62	.	.	.	.	.	.	.	3.60	.	.	.	GR49
CHELMSFORD,MASS.													
GRANITE								3.59					GR55
CHELMSFORD,MASS.													
GRANITE								3.47					GR54
LYNNFIELD,MASS.													
GRANITE	2.665	2.79		3.35	3.48	3.52		3.64		3.67		3.70	GR40
BARRE,VT.													
GRANITE	2.65	.	.	.		.	3.59+	.	.	.	.	.	GR48
BARRE,VT.													
GRANITE								3.59					GR57
BARRE,VT.													
GRANITE	2.634	.	3.31=	3.46	3.56	3.63	3.66	3.67	3.68	.	.		GR45
WOODBURY,VT.													
GRANITE	2.639	2.43		3.36	3.53	3.66		3.74		3.76		3.80	GR39
STONE MT.,GA.													
GRANITE PINK	2.636	.	3.27=	3.35	3.35	3.39	3.38	3.36	3.37	3.39	.		GR46
LLANO CO.,TEX.													
GRANITE GREY	2.609	.	3.42=	3.55	3.58	3.59	3.60	3.61	3.61	3.61	3.62		GR47
LLANO CO.,TEX.													
GRANITE	2.610	3.04'	3.23/	3.40	3.47	.	.	.					GR42
BEAR MT.,TEX.													
GRANITE		2.87	2.96	3.11	3.16	3.21	3.22	3.23	3.23				GR41
BARRIEFIELD,ONT.													
GRANITE								3.55					GR58
BARRIEFIELD,ONT.													
GRANITE								3.61					GR59
LATCHFORD,ONT.													
GRANITE								3.59					GR51
ENGLEHART,ONT.													
GRANITE	2.62	3.07	3.13=	3.17*	3.23	.	.	.	.	.	.		GR06
USSR 137													
GRANITE	.	2.90	.	3.16	3.30	3.40	3.40-	3.40-	.	.	.	.	GR04
USSR 247													
GRANITE	.	3.50	.	3.57	3.63	3.63-	.	.	.	.	.	.	GR05
USSR 248													
GRANITE	.	3.63	.	.	3.85	3.85	3.85	3.85+	.	.	.	.	GR77
USSR 249													
GRANITE	2.62	2.93			3.05//								GR09
USSR 1776													
QTZ MONZONITE	2.628	2.89'	3.09/	3.20	3.23	.	.	.	.	.	.	.	QM03
WESTERLY,R.I.													
QTZ MONZONITE	2.652	3.16		3.55	3.63	3.71		3.78		3.81		3.86	QM01
PORTERVILLE,CAL.													

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
GRANODIORITE WESTON,MASS.	2.63	3.14		3.45	3.51	3.56	3.58	3.58	3.58	3.59	3.59	3.60	$GD02
GRANODIORITE MASS.								3.58					GD03
GRANODIORITE QUEBEC								3.56					GD04
QUARTZ DIORITE SAN LUIS REY QUAD.,CAL.	2.81	.	.	.	.		3.59	.	.	.	.	.	QD06
QTZ DIORITE DEDHAM,MASS.	2.928	3.39		3.65	3.69	3.74		3.78		3.81		3.84	QD05
TONALITE VAL VERDE,CAL.	2.76	3.12		3.45	3.55	3.60	3.63	3.64	3.65	3.65	3.66		QD04
TONALITE VAL VERDE,CAL.								3.64					QD07
SATURATED													
SYENITE PENINSULA ST.,ONT.	2.79	2.43	.	3.26	3.31	3.34	3.35	3.36	.	.	.	.	SY03
TRACHYTE	2.712		3.05	=3.08	3.09	3.10	3.11	3.11	3.11				TA01
DIORITE SALEM,MASS.	3.025	3.06	3.17	/3.30	3.33	.	.	.	.				DT01
ALBITITE SYLMAR,PA.	2.615	3.43		3.54	3.57	3.61		3.65		3.68		3.73	AB02
ALBITITE SYLMAR PA.	2.62	3.32		3.37	3.39	3.42	3.43	3.44					AB03
ALBITITE SYLMAR,PA.	2.62	.	.	.	.		3.50	.	.				AB04
ANDESITE SALIDA,COLO.	2.618	2.73	2.78	/2.83	2.84	.	.	.	.	.	.	.	AD04
GABBRO FRENCH CREEK,PA.	3.033	3.27	.	3.83	3.91	.	.	3.98	.	.	.	.	NG18
GABBRO MELLEN,WISC.	2.90	3.37	.	3.67	3.68	.		3.71	.	.	.	.	NG19
GABBRO MELLEN,WISC.	2.90	.	.	.	.	.	.	.	3.76				NG14
GABBRO DULUTH,MINN.	2.885	.	3.42	=3.45	3.47	3.52	3.52	3.53	3.53	3.54			NG12
GABBRO	2.933	.	3.56	=3.59	3.65	3.69	3.71	3.71	3.71	3.72	.		NG13
GABBRO SAN MARCOS,CAL.	2.993	.	3.47	=3.48	3.50	3.51	3.51	3.52	3.53	3.54	.		NG11
GABBRO SAN MARCOS,CAL.	2.874	3.59		3.70	3.73	3.76		3.79		3.82		3.84	NG08
NORITE ESSEX CO.,N.Y.	3.057	3.24	3.38	/3.58	3.63	.	.	.	.	.	.		NG10
NORITE SUDBURY,ONT.	2.86	3.16	.	3.61	3.64	.	.	3.71	.	.	.	.	NG17
NORITE PRETORIA,TRANS.	2.984	3.56		3.81	3.84	3.86		3.89		3.90		3.94	NG09
ANORTHOSITE STILLWATER,MONT.	2.750	3.56		3.65	3.69	3.72		3.76		3.77		3.81	AN06
ANORTHOSITE STILLWATER,MONT.	2.74	3.59			3.67	3.68	3.68	3.68	3.69	3.69	3.70	3.70	$AN07
ANORTHOSITE STILLWATER,MONT.	2.74	.	.	.	.	.	.	.	.	.	3.71-	.	AN08

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
DIABASE	2.962	3.76	.	3.83	3.84	.	.	3.88	.	.	.	.	DB18
VINAL HAVEN,ME.													
DIABASE	2.984	3.49	.	3.64	3.68	3.72	.	3.75	.	3.77	.	3.80	DB12
CENTREVILLE,VA.													
DIABASE	3.017	3.71	.	3.75	3.77	3.79	.	3.81	.	3.82	.	3.85	DB13
FREDERICK,MD.													
DIABASE	3.013	3.67	.	3.77	3.79	.	.	3.83	.	.	.	.	DB19
FREDERICK,MD.													
DIABASE	2.96	.	.	.	.	.	3.85	.	.	.	.	.	DB14
FREDERICK,MD.													
DIABASE	2.989	3.52	.	3.65	3.71	.	.	.	.	.	.	.	DB20
KEWEENAWAN,ONTARIO													
DIABASE 3	2.903	3.61	.	3.64	3.66	3.68	3.69	3.70	.	.			DB16
PRIBRAM,CZECH.													
DIABASE 7	2.879	3.49	.	3.55	3.58	3.60	3.61	3.61	.	.			DB17
PRIBRAM,CZECH.													
DIABASE	3.04	3.75	3.79=3.82*3.87			.	.	.	.	.	.	.	DB01
USSR 3													
BASALT	2.586		3.21=3.23	3.25	3.26	3.26	3.27	3.27	3.27				BA06
CHAFFEE CO.,COLO.													
BASALT	2.82	2.53	2.57	2.60/									BA05
GUADALUPE MOHOLE SITE													
BASALT	2.88	3.34	3.36=3.39*3.42			.	.	.	.	.	.		BA03
USSR 4													
BASALT	2.63	3.10			3.40//								BA02
USSR													
ULTRAMAFIC													
DUNITE	3.198	.	3.79=3.88		3.99	4.10	4.13	4.15	4.17	.	.		DU16
BALSAM GAP,N.C.													
DUNITE	3.275	4.12	.	4.44	4.48	4.53		4.55	.	.	.	.	DU19
BALSAM GAP,N.C.													
DUNITE	3.265									4.40			DU18
BALSAM GAP,N.C.													
DUNITE	3.264	4.01		4.25	4.28	4.30		4.33		4.36		4.40	DU11
WEBSTER,N.C.													
DUNITE	3.160	.	4.19)	.	4.46	.	4.55	4.53	4.53				DU15
TWIN SISTERS MT.,WASH.													
DUNITE	3.326	4.60		4.67	4.69	4.72		4.77		4.79		4.83	DU13
TWIN SISTERS MT., WASH.													
DUNITE	3.270	4.17		4.34	4.37	4.41		4.45		4.48		4.54	DU12
MT. DUN,NEW ZEALAND													
DUNITE	3.250										4.41+		DU17
MT.DUN,NEW ZEALAND													
DUNITE	3.760	3.68		3.76	3.77	3.80		3.83		3.86		3.90	DU14
MOOIHOEK MINE,TRANS.													
PERIDOTITE	3.28	4.02	.	.	4.18	.	.	4.22	.	.	.		PE04
USSR 455													
PERIDOTITE	3.21	3.66	.	.	3.95	.	.	4.00	.	.	.		PE03
USSR 462													

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
PYROXENITE USSR 457	3.24	3.90			4.05			4.06					PX01
PYROXENITE USSR 468	3.15	3.50			3.58			3.66					PX05
PYROXENITE USSR 469	3.29	4.14			4.22			4.22					PX02
PYROXENITE USSR 470	3.22	3.26			3.66			3.80					PX03
PYROXENITE USSR 472	3.24	3.60			3.75			3.75					PX04
BRONZITITE STILLWATER, MONT.	3.287	4.48		4.54	4.56	4.58		4.62		4.63		4.66	BR03
BRONZITITE STILLWATER, MONT.	3.27	4.50			4.57	4.58	4.59	4.59	4.60	4.60	4.61	4.62	BR04
BRONZITITE STILLWATER, MONT.	3.272	4.50	.	4.54	4.55			4.58	.	.	.	.	BR06
BRONZITITE STILLWATER, MONT.	3.27										4.58		BR05
BRONZITITE BUSHVELD, TRANSVAAL	3.289	4.37	.	4.50	4.50	.		4.55	.	.	.	.	BR07
SERPENTINITE LUDLOW, VT.	2.806	3.61		3.69	3.70	3.73		3.77		3.80		3.83	SE09
SERPENTINITE CAL.	2.718	3.12		3.17	3.18	3.20		3.23		3.24		3.28	SE08
CHRYSOTILE THETFORD, QUE.	2.602	2.71		2.79	2.81	2.82		2.85		2.87		2.90	SE07
GLASSES													
OBSIDIAN MODOC, CAL.	2.440	3.53	.	.	.			3.49	.	.	.	.	OB02

METAMORPHIC ROCKS

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
SCHIST-CHLOR FRAMINGHAM, MASS.	2.95	3.34	.	3.49	3.55	3.63	3.69	3.73	3.76	.	.	.	SC12
SCHIST-CHLOR FRAMINGHAM, MASS.	.	.	.	.	.	.	.	3.73	.	.	.	.	SC16
SCHIST 1 FRAMINGHAM, MASS.	2.70	3.02	.	3.47	3.61	3.71	3.76	3.78	.	.	.	.	SC13
SCHIST-1 FRAMINGHAM, MASS.	.	.	.	.	.	.	.	3.73	.	.	.	.	SC15
SCHIST 2 FRAMINGHAM, MASS.	2.73	2.76	.	3.42	3.57	3.63	3.66	3.68	3.69	.	.	.	SC14
SCHIST-CHLOR QUEBEC	.	.	.	.	.	.	.	3.65	.	.	.	.	SC17
SLATE EVERETT, MASS.	2.67	2.89	.	.	2.98	3.07	3.14	3.19	.	.	.	.	SL05
SLATE EVERETT, MASS.			.	.	.	.	.	3.19	.	.	.	.	SL07

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
GNEISS PAR	2.64	1.85	.	3.24	3.46	.	.	.	.	.	.	.	GN29
PERP	2.64	1.73	.	3.15	3.32	.		3.56	.	.	.	.	GN29
PELHAM,MASS.													
GNEISS		.	.	.	.	.	.	3.43	.	.	.	.	GN22
PELHAM,MASS.													
GNEISS	2.91	3.42	.	3.51	3.54	3.57	.	.	.	.	.	.	GN17
SOLOMON'S POND,MASS.													
GNEISS		.	.	.	.	.	.	3.59	.	.	.	.	GN19
SOLOMON'S POND,MASS.													
GNEISS PAR	2.65	2.49	.	3.29	3.47	3.55	.	.	.	.	.	.	GN16
PERP	2.65	2.62	.	3.41	3.48	3.52	3.55	3.57	3.58	.	.	.	GN16
HELL GATE,N.Y.													
GNEISS				.	.	.	.	3.61	.	.	.	.	GN18
HELL GATE,N.Y.													
GNEISS-GARNET		.	.	.	.	.	.	3.57	.	.	.	.	GN20
QUEBEC													
GNEISS		.	.	.	.	.	.	3.63	.	.	.	.	G 21
QUEBEC													
MARBLE	2.71	2.71	.	3.42	3.48	.	.	3.51	.	.	.	.	MA57
PROCTOR,VT.													
MARBLE	2.71	.	.	.	.	.	3.48	.	.	.	.	.	MA10
PROCTOR,VT.													
MARBLE	.	.	2.82)	3.10(	3.17	3.12+	3.21	3.21	3.25	.	.		MA08
DANBY,RUTLAND,VT.													
MARBLE PERP C	.	3.96	4.25=	4.40*	4.51	.	.	.	.	.	.	.	MA11
PAR C	.	3.87	4.23=	4.46*	4.49	.	.	.	.	.	.	.	MA11
YULE,COLO.													
QUARTZITE	2.647	.	.	.	.	.	4.03	4.05	.	.			QZ11
GEORGIA													
QUARTZITE	.	.	.	.	.	.	.	4.07	.	.	.	.	QZ14
PENNSYLVANIA													
QUARTZITE	.	3.40	.	.	3.70	3.73-	3.72-	.	.	.	.	.	QZ15
USSR 22													
AMPHIBOLITE	3.070	3.90	.	4.13	4.18	4.21	.	4.25	.	4.27	.	4.30	AM05
MADISON CO.,MONT.													
AMPHIBOLITE	3.14	.	.	.	.	.	.	4.22	.	.	.	.	AM06
MADISON CO.,MONT.													
ECLOGITE	3.444	4.26	.	4.39	4.43	4.48	.	4.53	.	4.55	.	4.58	EC03
HEALDSBURG,CAL.													
ECLOGITE	3.28	.	.	.	.	.	.		4.59	.	.	.	EC12
HEALDSBURG,CAL.													
ECLOGITE	3.360	3.83	.	4.15	4.22	4.27	.	4.33	.	4.35	.	4.38	EC06
OCCIDENTAL,CAL.													
ECLOGITE	3.44	.	.	.	.	.	.	.	4.32	4.35			EC11
OCCIDENTAL,CAL.													
ECLOGITE	3.28	.	.	.	.	.	.	.	4.59	.	.	.	EC13
CAL.													
ECLOGITE	3.577	4.07	.	4.36	4.41	4.47	.	4.52	.	4.55	.	4.60	EC04
NORWAY-1552													
ECLOGITE	3.578	3.70	.	4.38	4.46	4.52	.	4.58	.	4.61	.	4.66	EC05
NORWAY-1553													

SEDIMENTARY ROCKS

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
SANDSTONE	2.61	3.04	.	3.24	3.34	3.40	.	.	.	.	.	.	SS07
BROOKLINE,MASS.													
SANDSTONE	.	.	.	.	.	.	.	3.40	.	.	.	.	SS20
BROOKLINE,MASS.													
SANDSTONE	2.66	3.39	.	3.85	3.99	.	.	4.08	.	.	.	.	SS46
ALLENTOWN,PA.													
SANDSTONE	2.543	.	2.51	2.70	2.85	2.95	2.96	2.98	2.97	.	.		SS11
CAPLEN DOME,GALVESTON CO.TEX.													
SANDSTONE 1(POR=19.0)		1.58'	2.03=	2.17((									SS65
2				2.15))				(AXIAL PRESSURE)					SS66
BEREA,OHIO													
SANDSTONE		1.92'	2.26	2.35/				(DIFFERENTIAL PRESSURE)					SS52
BEREA													
SANDSTONE		1.83'	2.15	2.32/				(NET OVERBURDEN PRESSURE)					SS48
BEREA													
SANDSTONE	.	1.74'	1.95	2.08/	.	.	.	.	.	.	.	.	SS15
BEREA													
SANDSTONE (POR=3.3)				3.47**									SS58
ORISKANY,PENNSYLVANIA													
SANDSTONE 1(POR=17.4)		2.10/	2.13=	2.22((				(AXIAL PRESSURE)					SS63
2		2.26/	2.32=	2.40((									SS64
TORPEDO,OKLAHOMA													
SANDSTONE	.	1.99'	2.12	2.25/	.	.	.	.	.	.	.	.	SS18
TORPEDO													
SANDSTONE		2.04'	2.22	2.31/				(NET OVERBURDEN PRESSURE)					SS50
TORPEDO													
SANDSTONE (POR=15.3)				2.41((									SS55
TENSLEEP,WYOMING													
SANDSTONE	.	1.75'	1.94	2.06/	.	.	.	.	.	.	.	.	SS17
TENSLEEP													
SANDSTONE 1 (POR=7.4)				2.51((									SS56
2				2.64				(AXIAL PRESSURE)					SS57
FOX HILLS,WYOMING													
SANDSTONE (POR=23.5)				2.16))									SS59
JELM,WYOMING													
SANDSTONE (POR=29.7)				1.87))									SS60
TEAPOT,WYOMING													
SANDSTONE (POR=2.3)				2.71**									SS61
SUNDANCE,WYOMING													
SANDSTONE (POR=12.5)				2.34((									SS62
CHUGWATER,WYOMING													
SANDSTONE	.	2.16'	2.37	2.44/	.	.	.	.	.	.	.	.	SS14
BANDERA													
SANDSTONE		2.10'	2.24	2.32/				(NET OVERBURDEN PRESSURE)					SS49
BANDERA													
SANDSTONE		1.78'	1.83	1.87/				(NET OVERBURDEN PRESSURE)					SS51
AUSTIN													
SANDSTONE	.	2.05'	2.19	2.22/	.	.	.	.	.	.	.	.	SS16
SEMINOLE													
SANDSTONE	.	2.30'	2.57	2.66/	.	.	.	.	.	.	.	.	SS19
WEBER													

ROCK	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
SANDSTONE USSR 94	.	2.15	.	2.20	2.23	2.30	2.31	2.30	.	.	.	.	SS41
SANDSTONE USSR 204	2.18	1.89	.	.	2.04	.	.	2.21	.	.	.	.	SS08
SANDSTONE USSR 205	.	1.90	.	2.00	2.05	2.20	2.21	2.20	.	.	.	.	SS39
SANDSTONE USSR 208	2.14	1.92	.	.	2.09	.	.	.	.	.	.	.	SS09
SANDSTONE USSR 209	2.15	1.94	.	.	2.09	.	.	.	.	.	.	.	SS10
SANDSTONE USSR 213	.	3.07	.	.	3.18	3.35	3.43	3.43	.	.	.	.	SS40
GREYWACKE 6 PRIBRAM,CZECH.	2.749	3.90	.	3.94	3.97	4.02	4.06	4.08	.	.			GY03
GREYWACKE U2-7 PRIBRAM,CZECH.	2.688	3.61	.	3.63	3.65	3.68	3.69	3.71	.	.			GY04
LIMESTONE NAZARETH,PA.	2.69	3.15		3.27	3.29	3.32	3.33	3.34					LS03
LIMESTONE NAZARETH,PA.								3.34					LS26
LIMESTONE MANLIUS,RAVENA,N.Y.	2.688	.	.	.	.	.	2.95	.	3.01	3.02	2.93	2.77	LS23
LIMESTONE PAR	2.739		3.06	3.13	3.13	3.19	3.22	3.22	3.24				LS21
PERP	2.731		3.13	3.21	3.24	3.28	3.29	3.30	3.29				LS21
UPTON CO,TEX.													
LIMESTONE 1				3.05**									LS43
2				2.86**				(AXIAL PRESSURE)					LS44
CALICO													
LIMESTONE SOLENHOFEN,BAVARIA	2.656	2.88	2.95	2.99	3.01	3.02	3.03	3.05	3.04				LS01
LIMESTONE SOLENHOFEN,BAVARIA	2.602	.	.	.	.	.	2.95	.	3.00	3.05	2.95	2.90	LS22
LIMESTONE SOLENHOFEN,BAVARIA	.	2.62'	2.69	2.70/	.	.	.	.	.	.	.	.	LS27
LIMESTONE SOLENHOFEN,BAVARIA	2.605	2.75	.	2.91	2.98	.	.	3.08	.	.	.	.	LS41
LIMESTONE 1		2.77/2.90(		(2.95*									LS24
2				3.03(				(AXIAL PRESSURE)					LS28
SOLENHOFEN,BAVARIA													
LIMESTONE SOLENHOFEN,BAVARIA								3.08					LS25
LIMESTONE USSR	.	2.87	2.92=	2.98*	3.02	.	.	.	.	.	.	.	LS19
DOLOMITE BETHLEHEM,PA.	2.83	3.52	.	3.87	3.90	3.94	.	.	.	.	.	.	DO03
DOLOMITE BETHLEHEM,PA.	.	.	.	.	.	.	.	4.0	.	.	.	.	DO04
DOLOMITE USSR 1745	2.58	2.72	.	2.80*	.	.	.	.	.	.	.	.	DO01

MINERALS

ORTHO- AND RING SILICATES

MINERAL	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
OLIVINE GROUP													
MONTICELLITE CRESTMORE, CAL.	2.975	3.85	.	3.90	3.94	3.97	.	4.00	.	4.02	.	4.06	MO01
AL2SIO5 GROUP													
SILLIMANITE WILLIAMSTOWN, AUSTRALIA	3.187	4.93	.	5.04	5.06	5.08	.	5.11	.	5.13	.	5.15	SI01
OTHERS													
IDOCRASE CRESTMORE, CAL.	3.140	3.13	.	3.63	3.80	3.96	.	4.12	.	4.19	.	4.28	ID01

SINGLE CHAIN SILICATES

MINERAL	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
PYROXENE GROUP													
JADEITE BURMA	3.33	5.04	.	.	.	.	.	5.21+				5.35$	JD01
JADEITE JAPAN	3.203	4.65	.	4.71	4.72	4.75	.	4.78	.	4.79	.	4.82	JD02

NON-SILICATES

MINERAL	RHO	.01	0.1	0.5	1	2	3	4	5	6	8	10	IND
OXIDES													
MAGNESIA BERKELEY SYNTHETIC	3.580	5.96				5.98	5.98						MS01
ALUMINA G.E. LUCALOX	3.972	6.37		6.37	6.38	6.38	6.38	6.38					AA02
SULFIDES													
PYRITE NORANDA MINES, QUE.	4.85	3.81	.	3.87	3.92	3.96	3.98	4.00	.	.	.	.	PR01
CARBONATES													
MAGNESITE	2.848	4.05	.	4.08	4.11	4.14	.	4.19	.	4.23	.	4.29	MN01

Appendix 4

COMPRESSIONAL VELOCITY VERSUS TEMPERATURE (25°C to 600°C)

(SOURCES OF DATA LISTED IN APPENDIX 8)
(VELOCITY UNITS=KM./SEC. COLUMN HEADINGS ARE TEMPERATURE IN UNITS OF DEGREES CENTIGRADE. PRES=PRESSURE OF MEASUREMENTS IN UNITS OF KILOBARS.POR=POROSITY)

EXPLANATION OF SPECIAL SYMBOLS IN APPENDIXES 4-5

SYMBOL	EXPLANATION
25	TEMPERATURE=0-30 DEGREES CENTIGRADE
+	ADD 50 DEGREES TO COLUMN HEADING
-	SUBTRACT 50 DEGREES FROM COLUMN HEADING

ROCK	RHO	25	100	200	300	400	500	600	PRES	POR	INDEX
ANDESITE	2.618	5.310	5.273	5.251-	.	.	.	.	1.0	.	AD04
SALIDA,COLO.											
BASALT	2.586	5.80	5.79	5.80	5.79	.	.	.	4.0	.	BA06
CHAFFEE CO.,COLO.											
DIORITE	3.025	6.301	6.232	6.196-	.	.	.	.	1.0	.	DT01
SALEM,MASS.											
DUNITE	3.160	8.956	8.892	8.886	8.784	.	.	.	4.0	.	DU15
TWIN SISTERS MT.,WASH.											
DUNITE	3.198	7.86	7.83	.	7.40	.	.	.	4.0	.	DU16
BALSAM GAP,N.C.											
GRANITE		6.429	6.428	6.387	5.796				4.0		GR41
BARRIEFIELD,ONT.											
GRANITE	2.610	6.232	6.183	.	.	.	.	.	1.0	.	GR42
BEAR MT.,TEX.											
GRANITE	2.629	6.38	6.34	.	.	.	.	.	4.0	.	GR43
QUINCY,MASS.											
GRANITE	2.615	6.18	6.18	.	.	.	.	.	4.0	.	GR44
WESTERLY,R.I.											
GRANITE	2.634	6.29	6.26	6.20	6.04	.	.	.	4.0	.	GR45
WOODBURY,VT.											
GRANITE PINK	2.636	6.50	6.47	6.38	6.25	.	.	.	4.0	.	GR46
LLANO CO.,TEX.											
GRANITE GREY	2.609	6.25	6.18	6.14	6.00	.	.	.	4.0	.	GR47
LLANO CO.,TEX.											
JADEITE	3.33	9.01	8.97	8.90	8.78	8.74	8.67	.	9.0	.	JD01
BURMA											
LIMESTONE	2.656	6.123	6.023	5.910	5.866	.	.	.	4.0	.	LS01
SOLENHOFEN,BAVARIA											
LIMESTONE PERP	2.739	6.135	6.032	5.980	.	.	.	.	4.0	.	LS21
PAR	2.731	6.344	6.257	6.160	.	.	.	.	4.0	.	LS21
UPTON CO.,TEX.											
MARBLE	.	6.673	6.602	6.468	.	.	.	.	4.0	.	MA08
DANBY,VT.											
MARBLE PERP C	.	6.68	6.61	6.17	.	.	.	.	1.	.	MA11
PAR C	.	6.67	6.53	6.13	.	.	.	.	1.	.	MA11
YULE,COLO.											

ROCK	RHO	25	100	200	300	400	500	600	PRES	POR	INDEX
NORITE	3.057	6.877	6.851	6.831-	.	.	.	.	1.0	.	NG10
ESSEX CO.,N.Y.											
GABBRO	2.993	7.01	6.98	6.99	6.95	6.62	.	.	4.0	.	NG11
SAN MARCOS,CAL.											
GABBRO	2.885	6.81	6.73	6.64	6.52	.	.	.	4.0	.	NG12
DULUTH,MINN.											
GABBRO	2.933	6.86	6.85	6.82	6.76	.	.	.	4.0	.	NG13
QTZ MONZONITE	2.628	5.998	5.981	5.892-	.	.	.	.	1.0	.	QM03
WESTERLY,R.I.											
FUSED SILICA	2.20	5.97	6.02	6.08	6.13	6.18	6.22		0.0		QU05
FUSED SILICA		6.10	6.11	6.12	6.13	6.14	6.16	6.17	0.0		QU06
SANDSTONE	2.543	5.279	5.295	5.225	.	.	.	.	4.0	5.1	SS11
CAPLEN DOME,GALVESTON CO.,TEX.											
SANDSTONE	2.514	5.533	5.518	.	.	.	.	.	4.0	9.0	SS12
TRAVIS PEAK,MARION CO.,TEX.											
TRACHYTE	2.712	5.76	5.69	5.68	5.62	.	.	.	4.0	.	TA01

Appendix 5

SHEAR VELOCITY VERSUS TEMPERATURE (25°C to 600°C)

(SOURCES OF DATA LISTED IN APPENDIX 8)
(VELOCITY UNITS=KM./SEC. COLUMN HEADINGS ARE TEMPERATURE IN UNITS OF DEGREES CENTIGRADE. PRES=PRESSURE OF MEASUREMENTS IN UNITS OF KILOBARS.POR=POROSITY)

EXPLANATION OF SPECIAL SYMBOLS IN APPENDIXES 4-5

SYMBOL	EXPLANATION
25	TEMPERATURE=0-30 DEGREES CENTIGRADE
+	ADD 50 DEGREES TO COLUMN HEADING
-	SUBTRACT 50 DEGREES FROM COLUMN HEADING

ROCK	RHO	25	100	200	300	400	500	600	PRES	POR	INDEX
ALBITITE SYLMAR,PA.	2.62	3.496	3.469	3.443	3.414	3.377	3.370	.	3.0	.	AB04
ANDESITE SALIDA,COLO.	2.618	2.844	2.825	2.818-	.	.	.	.	1.0	.	AD04
AMPHIBOLITE MONTANA	3.14	4.224	4.200	4.175	4.151	.	.	.	5.0	.	AM06
ANORTHOSITE STILLWATER,MONT.	2.74	3.712	3.695	3.677	3.660	3.641	3.621	.	7.5	.	AN08
BASALT CHAFFEE CO.,COLO.	2.586	3.27	3.24	3.24	3.23	.	.	.	4.0	.	BA06
BRONZITITE STILLWATER,MONT.	3.27	4.58	4.54	4.51	4.47	4.43	4.39	.	8.0	.	BR05
DIABASE FREDERICK,MD.	2.96	3.85	3.81	.	.	.	.	.	3.0	.	DB14
DIORITE SALEM,MASS.	3.025	3.322	3.312	3.277-	.	.	.	.	1.0	.	DT01
DUNITE TWIN SISTERS MT.,WASH.	3.160	4.533	4.526	4.492	4.433	.	.	.	4.0	.	DU15
DUNITE BALSAM GAP,N.C.	3.198	4.15	4.11	3.79	.	.	.	.	4.0	.	DU16
DUNITE MT.DUN,NEW ZEALAND	3.249	4.406	4.332	4.263	4.194	4.123	.	.	8.5	.	DU17
DUNITE BALSAM GAP,N.C.	3.263	4.396	4.340	4.284	4.231	4.180	4.113	.	6.0	.	DU18
ECLOGITE OCCIDENTAL,CAL.	3.44	4.348	4.326	4.267	4.184	4.106	4.017	.	6.0	.	EC11
ECLOGITE HEALDSBURG,CAL.	3.28	4.585	4.558	4.532	4.505	4.479	4.452	4.425	5.0	.	EC12
GRANITE BARRIEFIELD,ONT.		3.231	3.243	3.196					4.0		GR41
GRANITE BEAR MT.,TEX.	2.610	3.474	3.327	.	.	.	.	.	1.0	.	GR42
GRANITE WOODBURY ,VT.	2.634	3.67	3.66	3.63	.	.	.	.	4.0	.	GR45
GRANITE PINK LLANO CO.,TEX.	2.636	3.36	3.36	3.35	.	.	.	.	4.0	.	GR46
GRANITE GREY LLANO CO.,TEX.	2.609	3.61	3.60	3.59	.	.	.	.	4.0	.	GR47

ROCK	RHO	25	100	200	300	400	500	600	PRES	POR	INDEX
GRANITE	2.65	3.59	3.57	3.56	3.54	3.53	3.51	3.46	3.5	.	GR48
BARRE,VT.											
GRANITE	2.62	3.596	3.577	3.549	3.508	.	.	.	5.0	.	GR49
CHELMSFORD,MASS.											
GRANITE	2.62	3.48	3.46	3.43	3.40	3.34	3.26	3.15	4.0	.	GR50
ROCKPORT,MASS.											
JADEITE	3.33	.	5.37	5.32		.	5.13		9.0	.	JD01
BURMA											
LIMESTONE	2.656	3.046	3.004	2.961	.	.	.	.	4.0	.	LS01
SOLENHOFEN,BAVARIA											
LIMESTONE PERP	2.739	3.222	3.181	3.176	.	.	.	.	4.0	.	LS21
PAR	2.731	3.296	3.274	3.244	.	.	.	.	4.0	.	LS21
UPTON CO.,TEX.											
MARBLE	.	3.209	3.146	3.106	.	.	.	.	4.0	.	MA08
DANBY,VT.											
MARBLE	2.71	3.483	3.438	3.387	3.334	.	.	.	.	.	MA10
PROCTOR,VT.											
MARBLE PERP C	.	4.51	4.29	4.11	.	.	.	.	1.	.	MA11
PAR C	.	4.49	4.27	4.14	.	.	.	.	1.	.	MA11
YULE,COLO.											
NORITE	3.057	3.632	3.558	3.529-	.	.	.	.	4.0	.	NG10
ESSEX CO.,N.Y.											
GABBRO	2.993	3.52	3.53	3.53	3.52	3.42	.	.	4.0	.	NG11
SAN MARCOS,CAL.											
GABBRO	2.885	3.53	3.48	3.46	3.44	.	.	.	4.0	.	NG12
DULUTH,MINN.											
GABBRO	2.933	3.71	3.71	3.71	3.68	.	.	.	4.0	.	NG13
GABBRO	2.90	3.758	3.717	3.672	3.616	3.552	3.477	.	5.0	.	NG14
MELLEN,WISC.											
QTZ DIORITE	2.81	3.59	3.57	3.54	.	.	.	.	3.0	.	QD06
SAN LUIS REY QUAD.,CAL.											
QTZ MONZONITE	2.628	3.229	3.226	3.181-	.	.	.	.	1.0	.	QM03
WESTERLY,R.I.											
FUSED SILICA	2.20	3.76	3.79+	3.81					0.0		QU05
QUARTZITE	2.647	4.095	4.037	4.027	4.015	3.998	3.974	3.937	4.0	.	QZ11
GEORGIA											
SANDSTONE	2.543	2.975	2.969	2.944	.	.	.	.	4.0	5.1	SS11
CAPLEN DOME,GALVESTON CO.,TEX.											
TRACHYTE	2.712	3.11	3.11	3.10	3.05	.	.	.	4.0	.	TA01

Appendix 6

PETROGRAPHIC MODAL ANALYSES OF CERTAIN ROCKS IN APPENDIXES

(QTZ=QUARTZ. PLAG=PLAGIOCLASE. K-SPAR=POTASSIUM FELDSPAR. AMPH=AMPHIBOLE. PYROX=PYROXENE. OLIV=OLIVINE.)

KEY FOR MINERALS IN THE ANALYSES OF APPENDIX 6

AB	ALBITE	EN	ENSTATITE	MU	MUSCOVITE
AC	ACTINOLITE	EP	EPIDOTE	OL	OLIGOCLASE
AE	AEGIRITE	FA	FAYALITE	OM	OMPHACITE
AL	ALMANDITE	GR	GROSSULARITE	OR	ORTHOCLASE
AN	ANORTHITE	HO	HORNBLENDE	ORTHO	ORTHORHOMBIC
AU	AUGITE	HY	HYPERSTHENE	PG	PIGEONITE
BI	BIOTITE	ID	IDOCRASE	PR	PYRITE
BR	BRONZITE	IL	ILMENITE	PY	PYROPE
CA	CALCITE	KY	KYANITE	QU	QUARTZ
CH	CHLORITE	MG	MAGNETITE	UR	URALITE
CO	CORDIERITE	MI	MICROCLINE	SE	SERPENTINE
CT	CHERT	MO	MONTICELLITE	SP	SPESSARTITE
DI	DIALLAGE	MONO	MONOCLINIC	ST	STAUROLITE
DO	DOLOMITE	MP	MICROPERTHITE	TR	TREMOLITE
DP	DIOPSIDE				
CARB	CARBONATES	FRAG	FRAGMENTS OF CLAY MATERIALS		

ROCK	QTZ	PLAG	K-SPAR	AMPH	PYROX	OLIV	GARNET	MICA	OTHER	REF
AB01		99 AN12		1 AC						2
AB02										
AB03										
AB04										
AD01		35	35 OR	5 HO	20 AU				5 MG	7
AD02		X AN05							X CH	23
AD04		X AN60			X AU				X MG	8
AM01	15	35 AN33		45 HO						6
AM04				75 MONO					6 SE	1
AM05				11 ORTHO					8 ORE	
AM06										
AM07	3	19 AN49		73 HO				1 BI	6	17
AM08	4	26 AN42		70 HO				1 BI	2	17
AM09	5	11 AN32		50 HO					34 EP	17
AM10	3	3 AN33		47 HO					47 EP	17
AN02		93 AN80			7 BR					1
AN06										
AN03		86 AN80			14 BR					1
AN04	1	94 AN60							5	2
AN08		99	AN85						1	2
BA03		50 AN40			35 AU				10 MG	11
BA04										
BA06		60 AN60			5				10 MG	9
									10 SE,10 CA	
BR01				4 HO	94 BR	2				1
BR03										
BR05										
BR06										

ROCK	QTZ	PLAG	K-SPAR	AMPH	PYROX	OLIV	GARNET	MICA	OTHER	REF
BR02		4 AN80		2 HO	92 BR				2	1
BR07										
CK03	26	4	52 MP		4		8	4 BI	1	15
CK04	29	15	47 MP		2		1	6 BI		15
CK05	30	15	36 MP		8		2	6 BI	1	15
CK06	27	41	12 MP		19			1 BI		15
CK07	5	40	3 MP	19 HO	31		1	2 BI		15
CK08	3	38	2 MP	13 HO	37			7 BI		15
CK09		2			29				69 EN	15
CK10		14		5 HO	61				6 EN	15
CK11		28		52 HO	19			1 BI		15
CK12	46	38 AN18	8 OR		6 HY			1 BI		1
CK13	49	15	35 MP					1 BI		15
CK14	53	14	34 MP							15
CK15	6	40	9 MP	5 HO	35			5 BI		15
CK16	3	37	16 MP		37			6 BI		15
CK17	4	42	4 MP	31 HO	17			3 BI		15
CK18	3	44	1 MP	32 HO	20			1 BI		15
CK19	2	50		37 HO	11			1 BI		15
DB01		50		10 HO	25 MONO				15 MG	13
DB02										
DB03										
DB04		25						38 BI	20 ST	6
									10 MG	
DB08		45 AN95	3		45 AU			2 BI	5	1
DB12										
DB09		66 AN54			32 AU				2	1
DB10		70 AN50			18 AU	1		2 BI	9	1
DB11		48 AN67			24 AU	1		1 BI		1
DB13					25 HY					
DB14										
DB19										
DB15		66 AN34			32 AU				2 MG	2
DB16		34 AN60			17 AU				46 UR	16
DB17		30 AN60			17 AU				50 UR	16
DB21		72 AN60			10 AU	10		3 BI	3	24
DB18					2 HY					
DO04	1								99 DO	4
DO06	1		1						98 CARB	25
DT01		X AN30		X	X AU				X	8
DU05						78 FA10			19 SE	1
DU11										
DU06						97 FA09			3 SE	1
DU12										
DU17										
DU07				1 HO		97 FA08			2 SE	1
DU16										
DU18										
DU19										
DU08						80 FA12			19 SE	1
DU09					7 EN	92 FA12			1 SE	1
DU13										
DU15										

ROCK	QTZ	PLAG	K-SPAR	AMPH	PYROX	OLIV	GARNET	MICA	OTHER	REF
DU10						90 FA55			10	1
DU14										
EC02	X			X HO			X		X RU	23
EC06				63 HO			20	4 MU	13	3
EC11										
EC07				20 HO	20 HY		12 (AL48PY45GR6AD1)	10 BI	35 EP	1
EC08					70 OM		25 (AL30PY7)		5	1
EC09					55 OM		26 (AL52PY26GR18AD4)			1
EC10					72 OM		24 (AL57PY12GR19AD10SP2)		4	1
EC03										
EC12										
GD01	27	40 AN30	23 OR					7 BI	2 CH	1
GD02	34	28 AN15	30 MP					3 MU	4 MG	12
GN09	20	15 AN34					5	15 BI	17 KY 25 CO	6
GN10	40	36 AN24						10 BI		6
GN11	21		65					12 BI	2	20
GN12	9	75						16 BI		20
GN14	20	40 AN33	20 OR					16 BI	4	1
GN17	23	53 AN30						21 BI	5	12
GN19										
GN23	32	23 AN20	39 MI					5 BI	1 MU	17
GN24	22	26 AN23	41 MI					10 BI	1 MU	17
GN25	21	56 AN31	3 MI	12 HO				7 BI	1	17
GN26	20	46 AN33		17 HO				17 BI	1	17
GN27	9	50 AN35		22 HO				18 BI	1	17
GN28	39	32 AN32						21 BI	4 MU	17
GN29	73(+AB+OR)		13 MI					12 BI	2	24
GN30										
GR06	30	25	40					5 BI		19
GR07										
GR08	28		68					8 BI	6	20
GR22	25	15	50 MI					11		7
GR23	33		57 OR					5	4 PR	7
GR24	32	5	58 MI					6		7
GR25	28	31 AN20	35 MI					3 BI	1 MU	1
GR37										
GR44										
GR56										
GR26	26	13 AN05	50 MP	10					1	1
GR43										
GR53										
GR78										
GR82										
GR27	28		64 MP	6					2	1
GR38										
GR50										
GR52										
GR79										
GR84										
GR28	26	38 AN05	32 OR					4 MU		1
GR39										

ROCK	QTZ	PLAG	K-SPAR	AMPH	PYROX	OLIV	GARNET	MICA	OTHER	REF
GR29	31	31 AN20	31 MI					4 MU	2 CH	1
GR49										
GR55										
GR30	28	14 AN20	54 OR						1 CH	1
GR31	26	37 AN05	25 OR					9 BI	3 MU	1
GR40										
GR48										
GR57										
GR32	26	27 AN20	41					3 BI	3	1
GR33	20		70 OR					2 BI	5 CH	1
GR41										
GR58										
GR34	30	19	47 OR						4	1
GR36	27	51 AN05	17 OR						5	1
GR59										
GR42	X	X	X MI					X		8
GR45	40	17 AN20	28 MI					10 BI	5 MU	18
GR46	25	30 AN30	45 MI							18
GR47	20	20 AN20	55 MI					5 BI		18
GR80	19	40 AN05	33					6 BI	1 MG	24
GR81	12	16 AN05	65 MP	4					3	24
GR87	X		X					X BI	X MU	28
GR88	28.9									29
GR89	15.6									29
GY03	2		42						23 EP	16
									30 FRAGMENT	
HB01		1		2	42 AU	38 FA35		2 BI	9 SE	1
ID01					4 DI				60 ID	4
ID02									36 CA	
LA01		100 AN57-60								26
LA02		100 AN53								27
LA03		100 AN56								27
LS22									96 CA	22
									4 MN	
LS23	1								99 CA	22
LS45									96 CA	30
MA08									99 CA	5
MA09										
MA57	1								99 CA	24
MA58										
MI01		21 AN10	79 OR							26
MO01									83 MO	4
MO02									17 CA	
NG01	10	37 AN50		5	28 HY			16 BI	4	10
NG04										
NG03		X			X HY				X	23
NG05		72 AN60			14 DI	11		1 BI	2	1
NG14										
NG19										
NG06		53 AN60		1	46 PG-AU-HY					1
NG09										
NG07		51 AN65			32 AU			1 BI	1	1
NG18					15 HY					1
NG21										
NG08		55 AN60		35 HO					10 MG	9
NG11										

ROCK	QTZ	PLAG	K-SPAR	AMPH	PYROX	OLIV	GARNET	MICA	OTHER	REF
NG10		X AN60		X HO	X HY	X		X		8
NG12		70 AN80			5 AU	20			5 MG	9
NG13		40 AN55		35 HO	15			8 BI	2 MG	9
NG16		60			30				10 MG	13
OL01		98 AN12		2 AC						1
OL02		100 AN15-16								26
OL03		100 AN24								27
OL04		100 AN29								27
PE01		14			25	56			5	10
PE04										
PE02		15			20	60			2	20
PE03		10 AN60			21	61			6	10
PX01		9 AN60			85	5			1	10
PX02		1			80	17			2	10
PX03		16			76	5			3	10
PX04		8			61	25			3	10
PX05		20 AN60			75	5				10
PX06				1	93 DP	5 FA15			2 SE	1
QD01	28	50 AN45		7 HO				15 BI	1	1
QD04										
QD02	19	50 AN50		13 HO				17 BI		1
QD06										
QD03	13	48 AN20	6	21 HO					12	1
QD05										
QM01	34	33 AN30	27 OR					4 BI	2	1
QM02										
QM03	X	X AN90	XX					XX		8
QM04	X							X BI	X MU	28
QZ11	99+									3
QZ12	96	1	1 MI						2 CA	17
QZ13	69	20 AN27						10 BI	1	17
SC12	27								36 CH	12
SC16										
SC13	57	10 AN29	5 MP					19 MU	6 EP	12
SC15										
SC14	59	9 AN11	4 MP					20 MU	4 EP	12
SC18	29	35 AN22					5	30 BI	1 MG	17
SC19	8	23 AN25					2	14 BI	27 KY	17
								23 MU	3 MG	
SC20	35	15 AN26					1	13 BI	19 KY	17
								15 MU	2 MG	
SC21	44	13 AN25					2	23 BI	3 ST	17
								13 MU	1 MG	
SE06						10			50 SE	13
									30 CA	
SE14						15			70 SE	4
									15 DO	
SE26					25	75				14
SS03	96									7
SS04	92									7
SS15	84	1	2						7 CT	21
SS65									2 CA	
SS66										
SS18	90								1 CT	21
SS63									4	
SS64										

ROCK	QTZ	PLAG	K-SPAR	AMPH	PYROX	OLIV	GARNET	MICA	OTHER	REF
SS42	94	2	2							21
SS17										
SS55										
SS46	80		5	MP				7	7 MG	24
SS47			1	MI						
SS56	45	12	1					7	23 CA	21
SS57									10 CT	
SS58	97									21
SS59	82	6	3						4 CT	21
SS60	77	1	3					2	4 CT	21
SS61	43	2	2	MI					50 CA	21
									3 CT	
SS62	75	2						2	15 CA	21
SY02			84	OR	13	AU	2	1	BI	1
SY03										
TA01		18	AN60	60 OR	14				3 MG	9
									5 ANALCIME	

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10	AFANASYEV,G.D.,ET AL,AKAD.NAUK SSSR DOKLADY,V.155,NO.5,1058-1061,1964
11	VOLAROVICH,M.P.,Z.I.STAKHOVSKAYA,BULL.ACAD.SCI.USSR,NO.5,329-335,1958
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Appendix 7

CHEMICAL ANALYSES OF CERTAIN ROCKS IN APPENDIXES 1 THROUGH 5

ROCK	SIO2	AL2O3	FE2O3	FE O	MG O	CA O	NA2O	K2O	H2O	TIO2	MN O	REF
AN03	47.5	32.3	0.7	0.4	0.4	16.0	1.9	0.4	0.2		0.2	1
AN04	53.7	27.2	0.3	1.4	0.5	11.3	3.8	0.7	0.8	0.1		1
BR01	54.7	1.8	0.5	9.2	30.2	2.2	.	.	0.5	0.1	0.2	1
BR03												
BR05												
BR02	55.4	1.6	.	9.4	32.5	0.5	.	.	.	0.1	0.2	1
BR07	55.30	2.20	0.45	10.05	29.80	1.80	0.30		0.10	0.10	0.15	8
DB07	52.5	15.1	0.8	10.7	5.2	6.9	5.5	1.4	1.8	1.0	.	1
DB08	52.3	15.2	1.9	8.6	6.5	11.0	2.1	0.7	0.6	1.1	0.2	1
DB12												
DB09	52.7	14.1	2.0	9.8	6.4	9.4	2.6	0.9	.	.	0.4	1
DB10	49.9	16.3	.	13.5	6.2	6.6	1.8	2.3	0.8	1.5	.	1
DB11	51.3	15.1	1.1	9.3	8.0	11.4	2.0	0.3	0.4	0.8	0.2	1
DB13												
DB14												
DB19												
DB15	52.94	15.52	3.20	8.76	5.80	9.42	2.68	0.81	0.04	0.60	0.10	2
DB18	48.24	18.12	1.25	6.70	9.41	11.84	2.56	0.26	0.66	0.82	0.08	8
DB21												
DU05	40.9	0.1	.	8.3	50.1	.	.	.	0.2	.	0.2	1
DU11												
DU06	39.5	0.9	0.7	7.6	48.8	.	.	.	0.9	.	0.1	1
DU12												
DU07	38.4	0.6	1.6	6.6	51.5	0.1	.	.	.	.	0.1	1
DU16												
DU18												
DU19												
DU09	40.6	0.1	.	8.0	50.6	0.1	0.1	.	0.1	0.1	0.1	1
DU13												
DU10	36.7	1.6	.	38.0	22.2	0.5	0.3	.	.	.	1.1	1
DU14												
DU17	37.40	1.54	1.89	6.36	49.92	.	.	.	1.42	.	0.13	6
EC09	48.7	11.7	1.4	6.8	16.7	13.9	0.4	0.2	0.1	.	.	1
EC10	48.6	14.0	3.5	9.4	6.6	11.9	3.9	0.2	0.6	1.1	0.3	1
EC03												
EC12												
GN15	72.5	13.3	1.9	0.6	0.4	1.8	3.6	3.9	1.5	0.3		1
GR25	72.2	14.4	0.9	1.0	0.4	1.4	3.3	5.5	0.4	0.3	.	1
GR37												
GR44												
GR26	74.9	11.6	2.3	1.3	0.1	0.4	4.3	4.6	0.3	0.2	.	1
GR43												
GR78												
GR27	77.6	11.9	0.6	0.9	.	0.3	3.8	5.0	0.2	0.3	.	1
GR38												
GR50												
GR79												
GR28	73.4	14.4	0.1	0.7	0.3	1.1	4.0	5.1	0.4	0.3	.	1
GR39												
GR31	69.6	15.4	2.7	.	.	1.8	5.4	4.3	1.0	.	.	1
GR40												
GR48												

ROCK	SIO2	AL2O3	FE2O3	FE O	MG O	CA O	NA2O	K2O	H2O	TIO2	MN O	REF
GT01	39.1	19.6	3.7	1.7	0.2	34.9	.	.	0.1	0.2	0.4	1
GT02	36.3	20.2	0.1	32.0	4.8	2.0	.	.	.	2.5	1.7	1
GT03	35.4	21.0	.	19.1	0.1	0.4	.	.	.	.	23.8	1
GT04	36.3	21.0	.	37.1	3.6	1.5	.	.	.	.	0.4	1
HB01	41.2	1.2	4.0	8.2	34.4	1.4	0.2	0.3	5.2	0.3	.	1
ID01	37.41	17.89	3.16	6.47	4.80	33.78	0.35	.	0.62	.	1.52	3
ID02												
JD02	58.5	23.5	0.5	.	0.8	1.3	13.6	0.3	0.2	.	.	1
JD04												
JD03	59.3	24.8	0.3	0.2	0.3	0.8	14.1	0.2	.	.	.	1
MG01	1.2	1.6	65.7	12.0	0.5	0.2	0.1	.	0.7	16.3	0.5	1
NE01	43.42	31.29	0.29	1.72	0.05	0.72	14.93	6.50	.	0.05	0.02	7
NE02	43.14	31.03	0.10	1.56	0.15	1.17	15.22	6.50	.	0.06	0.02	7
NG07	52.80	13.04	0.31	8.74	9.98	11.94	1.61	0.48	0.31	0.84	0.19	1
NG18												
NG14	47.62	22.48	.	8.74	7.38	9.66	2.84	0.32	0.56	0.42	0.15	1
NG05												
NG19												
OB01	73.6	13.6	0.6	1.3	0.3	1.4	4.2	4.3	.	0.3	.	4
OB02												
OV01	41.2			8.0	49.7	0.1					0.1	1
SE26	37.75	1.79	4.15	3.64	36.61	1.99	0.43		12.43	0.04	0.09	5
SY02	55.8	14.7	2.6	9.0	1.0	4.6	4.6	4.8	0.8	0.7	.	1
SY03												

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Appendix 8

REFERENCES FOR DATA IN APPENDIXES 1 THROUGH 5

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AB07	WOEBER,A.F.,ET AL,GEOPHYSICS,V.28,658-663,1963
AD01	AUBERGER,M. AND J.S.RINEHART,J.GEOPHYS.RES.,V.66,191-199,1961
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GR28	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
GR29	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
GR30	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
GR31	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
GR32	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
GR33	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
GR34	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
GR35	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
GR36	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
GR37	SIMMONS,G.,J.GEOPHYS.RES.,V.69,1123-1130,1964
GR38	SIMMONS,G.,J.GEOPHYS.RES.,V.69,1123-1130,1964
GR39	SIMMONS,G.,J.GEOPHYS.RES.,V.69,1123-1130,1964
GR40	SIMMONS,G.,J.GEOPHYS.RES.,V.69,1123-1130,1964
GR41	HUGHES,D.S. AND J.H.CROSS,GEOPHYSICS,V.16,577-593,1951
GR42	HUGHES,D.S. AND H.J.JONES,BULL.GEOL.SOC.AM.,V.61,843-856,1950
GR43	HUGHES,D.S.AND C.MAURETTE,GEOPHYSICS,V.21,277-284,1956
GR44	HUGHES,D.S.AND C.MAURETTE,GEOPHYSICS,V.21,277-284,1956
GR45	HUGHES,D.S.AND C.MAURETTE,GEOPHYSICS,V.21,277-284,1956
GR46	HUGHES,D.S.AND C.MAURETTE,GEOPHYSICS,V.21,277-284,1956
GR47	HUGHES,D.S.AND C.MAURETTE,GEOPHYSICS,V.21,277-284,1956
GR48	BIRCH,F.,BULL.GEOL.SOC.AM.,V.54,263-286,1943
GR49	BIRCH,F.,BULL.GEOL.SOC.AM.,V.54,263-286,1943
GR50	BIRCH,F.,BULL.GEOL.SOC.AM.,V.54,263-286,1943
GR51	BIRCH,F.,GEOL.SOC.AM.SPEC.PAPER,NO.62,101-117,1955
GR52	BIRCH,F.,GEOL.SOC.AM.SPEC.PAPER,NO.62,101-117,1955
GR53	BIRCH,F.,GEOL.SOC.AM.SPEC.PAPER,NO.62,101-117,1955
GR54	BIRCH,F.,GEOL.SOC.AM.SPEC.PAPER,NO.62,101-117,1955

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GR55	BIRCH,F.,GEOL.SOC.AM.SPEC.PAPER,NO.62,101-117,1955
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GR57	BIRCH,F.,GEOL.SOC.AM.SPEC.PAPER,NO.62,101-117,1955
GR58	BIRCH,F.,GEOL.SOC.AM.SPEC.PAPER,NO.62,101-117,1955
GR59	BIRCH,F.,GEOL.SOC.AM.SPEC.PAPER,NO.62,101-117,1955
GR60	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
GR61	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
GR62	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
GR63	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
GR64	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
GR65	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
GR66	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
GR67	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
GR68	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
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GR70	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
GR71	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
GR72	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
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GR74	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
GR75	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
GR76	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
GR77	VOLAROVICH,M.P.,ET AL,DOKLADY ACAD.SCI.USSR,V.135,1237-1239,1961
GR78	BIRCH,F.AND D.BANCROFT,J.GEOL.,V.46,59-87,1938
GR79	BIRCH,F.AND D.BANCROFT,J.GEOL.,V.46,59-87,1938
GR80	BIRCH,F.AND D.BANCROFT,J.GEOL.,V.46,59-87,1938
GR81	IDE,J.M.,PROC.NATL.ACAD.SCI.,V.22,482-496,1936
GR82	IDE,J.M.,PROC.NATL.ACAD.SCI.,V.22,482-496,1936
GR83	IDE,J.M.,PROC.NATL.ACAD.SCI.,V.22,482-496,1936
GR84	IDE,J.M.,PROC.NATL.ACAD.SCI.,V.22,482-496,1936
GR85	IDE,J.,PROC.NATL.ACAD.SCI.U.S.,V.22,482-496,1936
GR86	KRISHNAMURTHI,M.AND S.BALAKRISHNA,PROC.IND.ACAD.SCI.V.38A,498-501,1953
GR87	WOEBER,A.F.,ET AL,GEOPHYSICS,V.28,658-663,1963
GR88	SHIMOZURU,D.,JAP.J.GEOPHYS.,V.2,NO.3,85PP.,1960
GR89	SHIMOZURU,D.,JAP.J.GEOPHYS.,V.2,NO.3,85PP.,1960
GT01	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
GT02	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
GT03	VERMA,R.K.,J.GEOPHYS.RES.,V.65,757-766,1960
GT04	VERMA,R.K.,J.GEOPHYS.RES.,V.65,757-766,1960
GY01	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
GY02	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
GY03	PROS,Z.,ET AL,STUDIA GEOPHYS. ET GEOD.,CZECH.,V.6,NO.4,347-368,1962
GY04	PROS,Z.,ET AL,STUDIA GEOPHYS. ET GEOD.,CZECH.,V.6,NO.4,347-368,1962
HA01	WYLLIE,M.R.J.,ET AL,GEOPHYSICS,V.21,41-70,1956
HB01	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
HE01	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
HE02	WOEBER,A.F.,ET AL,GEOPHYSICS,V.28,658-663,1963
HO01	ALEXANDROV,K.S.AND T.V.RYZHOVA,BULL.ACAD.SCI.USSR,NO.9,871-875,1961
HO02	ALEXANDROV,K.S.AND T.V.RYZHOVA,BULL.ACAD.SCI.USSR,NO.9,871-875,1961
HO03	WOEBER,A.F.,ET AL,GEOPHYSICS,V.28,658-663,1963
ID01	SIMMONS,G.,J.GEOPHYS.RES.,V.69,1123-1130,1964
ID02	SIMMONS,G.,J.GEOPHYS.RES.,V.69,1117-1121,1964
JD01	HUGHES,D.S. AND T. NISHIIAKE,IN GEOPHYSICAL PAPERS DEDICATED TO PROFESSOR KENZO SASSA,KYOTO,JAPAN,KYOTO UNIVERSITY GEOPHYS. INST.,379-385,1963
JD02	SIMMONS,G.,J.GEOPHYS.RES.,V.69,1123-1130,1964

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JD04	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
KA01	SUBBARAO,K. AND B. RAMACHANDRA RAO,NATURE,V.180,NO.4573,978,1957
KA02	WOEBER,A.F.,ET AL,GEOPHYSICS,V.28,658-663,1963
LA01	ALEXANDROV,K.S.AND T.V.RYZHOVA,BULL.ACAD.SCI.USSR,NO.2,129-131,1962
LA02	RYZHOVA,T.V.,BULL.ACAD.SCI.USSR,NO.7,633-635,1964
LA03	RYZHOVA,T.V.,BULL.ACAD.SCI.USSR,NO.7,633-635,1964
LM01	WOEBER,A.F.,ET AL,GEOPHYSICS,V.28,658-663,1963
LS01	HUGHES,D.S. AND J.H.CROSS,GEOPHYSICS,V.16,577-593,1951
LS02	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
LS03	BIRCH,F. AND D.BANCROFT,J.GEOL.,V.46,[illegible],1940
LS04	AUBERGER,M. AND J.S.RINEHART,J.GEOPHYS.RES.,V.66,191-199,1961
LS05	BALAKRISHNA,S.,PROC.IND.ACAD.SCI.,V.41A,12-15,1955
LS06	BALAKRISHNA,S.,PROC.IND.ACAD.SCI.,V.36A,375-380,1952
LS07	BALAKRISHNA,S.,PROC.IND.ACAD.SCI.,V.41A,12-15,1955
LS08	BALAKRISHNA,S.,PROC.IND.ACAD.SCI.,V.50A,NO.6,363-365,1959
LS09	BALAKRISHNA,S.,PROC.IND.ACAD.SCI.,V.36A,375-380,1952
LS10	PRASADA RAO,G.H.S.V.,PROC.IND.ACAD.SCI.,V.25A,238-246,1947
LS11	PRASADA RAO,G.H.S.V.,PROC.IND.ACAD.SCI.,V.25A,238-246,1947
LS12	BALAKRISHNA,S.,PROC.IND.ACAD.SCI.,V.49A,NO.6,318-321,1959
LS13	BALAKRISHNA,S.,PROC.IND.ACAD.SCI.,V.49A,NO.6,318-321,1959
LS14	BALAKRISHNA,S.,PROC.IND.ACAD.SCI.,V.49A,NO.6,318-321,1959
LS15	BALAKRISHNA,S.,PROC.IND.ACAD.SCI.,V.50A,NO.6,363-365,1959
LS16	BALAKRISHNA,S.,PROC.IND.ACAD.SCI.,V.50A,NO.6,363-365,1959
LS17	RAMANA,Y.V.,J.SCI.INDUS.RES.,INDIA.,V.19B,NO.11,446-447,1960
LS18	SZEMEREDY,P.,TUDOMANY EGYETEM ANNALES,SEC.GEOL.BUDAPEST,V.1,89-95,1957
LS19	FANG,WEI-CHING,BULL.ACAD.SCI.USSR,NO.10,1004-1008,1961
LS20	VOLAROVICH,M.P.,ET AL,BULL.ACAD.SCI.USSR,NO.8,1198-1205,1963
LS21	HUGHES,D.S. AND J.H.CROSS,GEOPHYSICS,V.16,577-593,1951
LS22	AHRENS,T.J.AND S. KATZ,J.GEOPHYS.RES.,V.68,529-538,1963
LS23	AHRENS,T.J.AND S. KATZ,J.GEOPHYS.RES.,V.68,529-538,1963
LS24	WYLLIE,M.R.J.,ET AL,GEOPHYSICS,V.27,569-589,1962
LS25	BIRCH,F.,GEOL.SOC.AM.SPEC.PAPER,NO.62,101-117,1955
LS26	BIRCH,F.,GEOL.SOC.AM.SPEC.PAPER,NO.62,101-117,1955
LS27	VOLAROVICH,M.P.,ET AL,BULL.ACAD.SCI.USSR,NO.5,486-492,1959
LS28	WYLLIE,M.R.J.,ET AL,GEOPHYSICS,V.27,569-589,1962
LS29	PESELNICK,L. AND W.F.OUTERBRIDGE,J.GEOPHYS.RES.,V.66,581-588,1961
LS30	PESELNICK,L. AND W.F.OUTERBRIDGE,J.GEOPHYS.RES.,V.66,581-588,1961
LS31	KING,M.S. AND I.FATT,GEOPHYSICS,V.27,590-598,1962
LS32	KING,M.S. AND I.FATT,GEOPHYSICS,V.27,590-598,1962
LS33	PESELNICK,L.,J.GEOPHYS.RES.,V.67,4441-4448,1962
LS34	PESELNICK,L.,J.GEOPHYS.RES.,V.67,4441-4448,1962
LS35	PESELNICK,L.,J.GEOPHYS.RES.,V.67,4441-4448,1962
LS36	PESELNICK,L.,J.GEOPHYS.RES.,V.67,4441-4448,1962
LS37	PESELNICK,L.,J.GEOPHYS.RES.,V.67,4441-4448,1962
LS38	PESELNICK,L.,J.GEOPHYS.RES.,V.67,4441-4448,1962
LS39	PESELNICK,L.,J.GEOPHYS.RES.,V.67,4441-4448,1962
LS40	BALAKRISHNA,S.,PROC.IND.ACAD.SCI.,V.41A,12-15,1955
LS41	BIRCH,F.AND D.BANCROFT,J.GEOL.,V.46,59-87,1938
LS42	KRISHNAMURTHI,M.AND S.BALAKRISHNA,PROC.IND.ACAD.SCI.V.38A,498-501,1953
LS43	GREGORY,A.R.,PROC.ROCK MECH.SYMP.,5TH,439-471,PERGAMON PRESS,N.Y.,1963
LS44	GREGORY,A.R.,PROC.ROCK MECH.SYMP.,5TH,439-471,PERGAMON PRESS,N.Y.,1963
LS45	GREGSON,V.G.,ET AL,AFCRL63-662,STANFORD RES.INST.,FINAL REPT.,1963
LT01	WOEBER,A.F.,ET AL,GEOPHYSICS,V.28,658-663,1963
MA01	BALAKRISHNA,S.,CURRENT SCI.,V.28,NO.7,285,1959
MA02	BALAKRISHNA,S.,PROC.IND.ACAD.SCI.,V.36A,375-380,1952

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MA03	BALAKRISHNA,S.,PROC.IND.ACAD.SCI.,V.36A,375-380,1952
MA04	BALAKRISHNA,S.,GEOL.SOC. INDIA JOUR.,V.1,136-143,1959
MA05	BALAKRISHNA,S.,PROC.IND.ACAD.SCI.,V.50A,NO.6,363-365,1959
MA06	PRASADA RAO,G.H.S.V.,PROC.IND.ACAD.SCI.,V.25A,238-246,1947
MA07	PRASADA RAO,G.H.S.V.,PROC.IND.ACAD.SCI.,V.25A,238-246,1947
MA08	HUGHES,D.S. AND J.H.CROSS,GEOPHYSICS,V.16,577-593,1951
MA09	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
MA10	BIRCH,F.,BULL.GEOL.SOC.AM.,V.54,263-286,1943
MA11	TOOLEY,R.D.,J.GEOPHYS.RES.,V.67,3604,1962
MA12	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA13	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA14	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA15	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA16	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA17	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA18	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA19	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA20	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA21	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
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MA26	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA27	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
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MA33	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA34	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA35	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA36	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA37	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA38	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA39	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
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MA41	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA42	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA43	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
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MA45	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA46	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA47	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
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MA50	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA51	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA52	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA53	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA54	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA55	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA56	KUBOTERA,A.,J.PHYS.EARTH,V.2,33-38,1954
MA57	BIRCH,F.AND D.BANCROFT,J.GEOL.,V.46,59-87,1938
MA58	IDE,J.M.,PROC.NATL.ACAD.SCI.,V.22,482-496,1936

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MG01	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
MG02	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
MG03	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
MG04	WOEBER,A.F.,ET AL,GEOPHYSICS,V.28,658-663,1963
MG05	HIRASAWA,K.,BUTSURI-TANKO,V.15,72-84,(IN JAPANESE),1962
MI01	ALEXANDROV,K.S.AND T.V.RYZHOVA,BULL.ACAD.SCI.USSR,NO.2,129-131,1962
MI02	SIMMONS,G.,J.GEOPHYS.RES.,V.69,1117-1121,1964
MI03	WOEBER,A.F.,ET AL,GEOPHYSICS,V.28,658-663,1963
MN01	SIMMONS,G.,J.GEOPHYS.RES.,V.69,1123-1130,1964
MN02	SIMMONS,G.,J.GEOPHYS.RES.,V.69,1117-1121,1964
MO01	SIMMONS,G.,J.GEOPHYS.RES.,V.69,1123-1130,1964
MO02	SIMMONS,G.,J.GEOPHYS.RES.,V.69,1117-1121,1964
MS01	ANDERSON,O.L.AND E.SCHREIBER,J.GEOPHYS.RES.,TO BE PUBLISHED,OCT.,1965
MS02	ANDERSON,O.L.AND P.GLYNN,J.PHYS.CHEM.SOLIDS,TO BE PUBLISHED
MS03	SOGA,N.,SUMMARY TECH.REPT.,AFOSR 33(615)-1700,LAMONT GEOL.OBS.,1965
MU01	ALEXANDROV,K.S.AND T.V.RYZHOVA,BULL.ACAD.SCI.USSR,NO.12,1165-1168,1961
NE01	RYZHOVA,T.V.AND K.S.ALEXANDROV,BULL.ACAD.SCI.USSR,PT.2,1125-1127,1962
NE02	RYZHOVA,T.V.AND K.S.ALEXANDROV,BULL.ACAD.SCI.USSR,PT.2,1125-1127,1962
NG01	AFANASYEV,G.D.,ET AL,AKAD.NAUK SSSR DOKLADY,V.155,NO.5,1058-10611964
NG02	HAYAKAWA,M.,IN GEOPHYSICAL PAPERS DEDICATED TO PROFESSOR KENZO SASSA, KYOTO,JAPAN,KYOTO UNIVERSITY GEOPHYS. INST.,25-32,1963
NG03	PRASADA RAO,G.H.S.V.,PROC.IND.ACAD.SCI.,V.25A,238-246,1947
NG04	VOLAROVICH,M.P.,ET AL,AKAD.NAUK SSSR DOKLADY,V.157,NO.6,1349-1351,1964
NG05	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
NG06	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
NG07	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
NG08	SIMMONS,G.,J.GEOPHYS.RES.,V.69,1123-1130,1964
NG09	SIMMONS,G.,J.GEOPHYS.RES.,V.69,1123-1130,1964
NG10	HUGHES,D.S. AND H.J.JONES,BULL.GEOL.SOC.AM.,V.61,843-856,1950
NG11	HUGHES,D.S.AND C.MAURETTE,GEOPHYSICS,V.22,23-31,1957
NG12	HUGHES,D.S.AND C.MAURETTE,GEOPHYSICS,V.22,23-31,1957
NG13	HUGHES,D.S.AND C.MAURETTE,GEOPHYSICS,V.22,23-31,1957
NG14	BIRCH,F.,BULL.GEOL.SOC.AM.,V.54,263-286,1943
NG15	VOLAROVICH,M.P.,ET AL,DOKLADY ACAD.SCI.USSR,V.135,1237-1239,1961
NG16	VOLAROVICH,M.P.,ET AL,DOKLADY ACAD.SCI.USSR,V.135,1237-1239,1961
NG17	BIRCH,F.AND D.BANCROFT,J.GEOL.,V.46,59-87,1938
NG18	BIRCH,F.AND D.BANCROFT,J.GEOL.,V.46,59-87,1938
NG19	BIRCH,F.AND D.BANCROFT,J.GEOL.,V.46,59-87,1938
NG20	IDE,J.M.,PROC.NATL.ACAD.SCI.,V.22,482-496,1936
NG21	IDE,J.M.,PROC.NATL.ACAD.SCI.,V.22,482-496,1936
OB01	BIRCH,F.,J.GEOPHYS.RES.,V.65,1083-1102,1960
OB02	BIRCH,F.AND D.BANCROFT,J.GEOL.,V.46,59-87,1938
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TP02	PRASADA RAO,G.H.S.V.,PROC.IND.ACAD.SCI.,V.25A,238-246,1947
TP03	PRASADA RAO,G.H.S.V.,PROC.IND.ACAD.SCI.,V.25A,238-246,1947
TP04	KRISHNAMURTHI,M.AND S.BALAKRISHNA,PROC.IND.ACAD.SCI.V.38A,498-501,1953
TR01	WOEBER,A.F.,ET AL,GEOPHYSICS,V.28,658-663,1963
TU01	WOEBER,A.F.,ET AL,GEOPHYSICS,V.28,658-663,1963
VB01	WOEBER,A.F.,ET AL,GEOPHYSICS,V.28,658-663,1963
WO01	SIMMONS,G.,J.GEOPHYS.RES.,V.69,1117-1121,1964
ZR01	BHIMASENACHAR,J.AND G.VENKATARATNAM,J.ACOUST.SOC.AM.,V.27,922-925,1955

Appendix 9

PROPERTIES OF POLYCRYSTALLINE AGGREGATES OF CERTAIN MINERALS (CALCULATED FROM ELASTIC CONSTANTS OF SINGLE CRYSTALS)

(MODULI UNITS-KILOBARS.)
(CRYSTAL CLASS UNDER INDEX.SYMBOLS,CU-CUBIC,HX-HEXAGONAL,TR-TRIGONAL,
TE-TETRAGONAL,OR-ORTHORHOMBIC)

CODE FOR FIELD IN CROSS INDEX

XX******	XX REFERS TO CRYSTAL CLASS.EXAMPLE,CU-CUBIC,TE-TETRAGONAL
XX***	XX REFERS TO THE CATION OR ELEMENT BY NUMBER IN LIST BELOW
****XX**	XX REFERS TO THE PRINCIPAL ANION BY NUMBER IN LIST BELOW
******XX	XX REFERS TO THE NUMBER OF THE LISTING FOR A PARTICULAR SOLID
TR453702	TR-TRIGONAL,45-SILICON,37-OXYGEN,02-SECOND LISTING FOR QUARTZ

CODE LISTING OF ELEMENTS AND ANIONS BY NUMBER

01	AG,SILVER	41	PT,PLATINUM
02	AL,ALUMINUM	42	RB,RUBIDIUM
03	AU,GOLD	43	S,SULPHUR
04	AS,ARSENIC	44	SE,SELENIUM
05	B,BORON	45	SI,SILICON
06	BA,BARIUM	46	SN,TIN
07	BE,BERYLLIUM	47	SB,ANTIMONY
08	BI,BISMUTH	48	TA,TANTALUM
09	BR,BROMINE	49	TE,TELLURIUM
10	C,CARBON	50	TL,THALLIUM
11	CA,CALCIUM	51	TH,THORIUM
12	BLANK	52	TI,TITANIUM
13	CL,CHLORINE	53	W,TUNGSTEN
14	CD,CADMIUM	54	V,VANADIUM
15	CS,CESIUM	55	ZN,ZINC
16	CO,COBALT	56	ZR,ZIRCONIUM
17	CR,CHROMIUM	57	Y,YTTRIUM
18	CU,COPPER	58	U,URANIUM
19	FE,IRON	59	SR,STRONTIUM
20	F,FLUORINE	60	NO3,NITRATE
21	GA,GALLIUM	61	CO3,CARBONATE
22	GE,GERMANIUM	62	SO4,SULPHATE
23	GD,GADOLINIUM	63	B5O8,PENTABORATE
24	H,HYDROGEN	64	(NH4)C4H4O6 4H2O, AMMONIUM TARTRATE
25	HG,MERCURY	65	NA C4 H4O6 4H2O, SODIUM TARTRATE
26	I,IODINE	66	SIO4,ORTHOSILICATE
27	IN,INDIUM	67	(CHO2)2, FORMATE HYDRATE
28	K,POTASSIUM	68	PO4, PHOSPHATE
29	LI,LITHIUM	69	NA C6H12O6,SODIUM DEXTROSE
30	MG,MAGNESIUM	70	TIO3,TITINATE
31	MN,MANGANESE	71	NH4,AMMONIUM
32	MO,MOLYBDENUM	72	AL2SI6O18,ALUMINOSILICATE
33	NA,SODIUM	73,NH3,AMMONIA	
34	NI,NICKEL	74	BRO3, BROMATE
35	NB,NIOBIUM		
36	5,NITROGEN		
37	O,OXYGEN		
38	PD,PALLADIUM		
	7,PH S7HORUS		
40	PB,LEAD		

CODE FOR SPECIAL MINERALS OF COMPLICATED COMPOSITION

8000	TOURMALINE	
8001	TOPAZ	
8002	GARNET	3RO.AL2O3.3SIO2 (R=MN,FE,MG,CA)
8003	SPINEL	MGO.XAL2O3

MG2SIO4--FORSTERITE
OR306601
R.K.VERMA,J.GEOPHYS.RES.,65(1960),P.762 OR306601
DENSITY= 3.324 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

3240.	590.	790.	-0.	0.	0.	0.34	-0.07	-0.09	-0.	0.	0.
	1980.	780.	-0.	0.	0.		0.59	-0.16	-0.	0.	0.
		2490.	-0.	0.	0.			0.48	0.	-0.	-0.
			667.	0.	0.				1.50	-0.	-0.
				810.	-0.					1.23	0.
					793.						1.26

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	1337.	824.	2051.	2435.	0.2445
REUSS	1289.	793.	1975.	2347.	0.2446
ARITH.MEAN	1313.	809.	2013.	2391.	0.2446

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	8.559	4.978	6.341	5.522
REUSS	8.402	4.885	6.227	5.419
ARITH.MEAN	8.480	4.932	6.284	5.471

VMEAN= 5.484 KM/SEC
PERCENT ERROR= 0.2479
DEBYE TEMP.= 754.451

ZIRCON
TE566601
H.B.HUNTINGTON,'SOLID STATE PHYSICS' VOL7(1958)P.274,ACADEMIC PRESS TE566601
DENSITY= 4.680 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

735.	90.	-54.	-0.	0.	0.	1.39	-0.16	0.14	-0.	0.	0.
	735.	-54.	-0.	0.	0.		1.39	0.14	-0.	0.	0.
		460.	-0.	0.	0.			2.21	-0.	0.	0.
			138.	0.	0.				7.25	-0.	-0.
				138.	-0.					7.25	0.
					160.						6.25

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	210.	217.	485.	500.	0.1252
REUSS	191.	184.	417.	435.	0.1352
ARITH.MEAN	200.	200.	451.	468.	0.1302

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	3.268	2.153	2.120	2.357
REUSS	3.050	1.981	2.018	2.172
ARITH.MEAN	3.159	2.067	2.069	2.265

VMEAN= 2.254 KM/SEC
PERCENT ERROR= 0.5063
DEBYE TEMP.= 304.460

GARNET 1
CU800201
R.K.VERMA,J.GEOPHYS.RES.,65,(1960),P.762 CU800201
DENSITY= 4.247 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

3073.	1097.	1097.	-0.	0.	0.	0.40	-0.11	-0.11	-0.	0.	0.
	3073.	1097.	-0.	0.	0.		0.40	-0.11	-0.	0.	0.
		3073.	-0.	0.	0.			0.40	0.	-0.	-0.
			952.	0.	0.				1.05	-0.	-0.
				952.	-0.					1.05	0.
					952.						1.05

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	1756.	966.	2450.	3044.	0.2675
REUSS	1756.	966.	2449.	3044.	0.2675
ARITH.MEAN	1756.	966.	2449.	3044.	0.2675

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	8.466	4.770	6.429	5.305
REUSS	8.465	4.769	6.429	5.305
ARITH.MEAN	8.465	4.769	6.429	5.305

VMEAN= 5.399 KM/SEC
PERCENT ERROR= 1.7341
DEBYE TEMP.= 740.572

GARNET 2
CU800202
R.K.VERMA,J.GEOPHYS.RES.,65,(1960),P.762 CU800202
DENSITY= 4.183 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

3048.	1123.	1123.	-0.	0.	0.	0.41	-0.11	-0.11	-0.	0.	0.
	3048.	1123.	-0.	0.	0.		0.41	-0.11	-0.	0.	0.
		3048.	-0.	0.	0.			0.41	0.	-0.	-0.
			944.	0.	0.				1.06	-0.	-0.
				944.	-0.					1.06	0.
					944.						1.06

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	1765.	951.	2419.	3033.	0.2715
REUSS	1765.	951.	2419.	3033.	0.2715
ARITH.MEAN	1765.	951.	2419.	3033.	0.2715

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	8.515	4.769	6.495	5.307
REUSS	8.515	4.768	6.495	5.307
ARITH.MEAN	8.515	4.769	6.495	5.307

VMEAN= 5.400 KM/SEC
PERCENT ERROR= 1.7307
DEBYE TEMP.= 746.533

TOPAZ
OR800101
W.VOIGT,ANN.PHYSIK D. CHEMIE,34 (1888) P.981 OR800101
DENSITY= 3.500 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

2870.	1280.	850.	-0.	0.	0.	0.43	-0.13	-0.08	-0.	0.	0.
	3560.	900.	-0.	0.	0.		0.35	-0.07	-0.	0.	0.
		3000.	-0.	0.	0.			0.38	0.	-0.	-0.
			1100.	0.	0.				0.91	-0.	-0.
				1350.	-0.					0.74	0.
					1330.						0.75

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	1721.	1183.	2887.	3298.	0.2211
REUSS	1695.	1158.	2829.	3239.	0.2219
ARITH.MEAN	1708.	1170.	2858.	3268.	0.2215

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	9.706	5.812	7.012	6.430
REUSS	9.619	5.751	6.959	6.363
ARITH.MEAN	9.663	5.782	6.985	6.396

VMEAN= 6.440 KM/SEC
PERCENT ERROR= 0.6823
DEBYE TEMP.= 892.284

TOURMALINE
TR800001
W.VOIGT,ANN.PHYSIK D. CHEMIE,41(1890) P.712 TR800001
DENSITY= 3.100 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

2756.	704.	90.	-79.	0.	0.	0.39	-0.10	-0.01	0.06	-0.	-0.
	2756.	90.	79.	0.	0.		0.39	-0.02	-0.06	0.	0.
		1638.	-79.	0.	0.			0.62	0.07	-0.	-0.
			680.	0.	0.				1.49	-0.	-0.
				680.	0.					1.47	0.
					1005.						1.00

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	991.	891.	2056.	2179.	0.1480
REUSS	884.	834.	1903.	1995.	0.1412
ARITH.MEAN	937.	862.	1979.	2087.	0.1446

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	8.382	5.360	5.653	5.888
REUSS	8.022	5.185	5.339	5.689
ARITH.MEAN	8.202	5.272	5.496	5.789

VMEAN= 5.836 KM/SEC
PERCENT ERROR= 0.8165
DEBYE TEMP.= 789.097

TOURMALINE
TR800002
W.P.MASON,'PIEZOELECTRIC CRYSTALS ...'(1950),VAN NOSTRAND TR800002
DENSITY= 3.100 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

2720.	400.	350.	-68.	0.	0.	0.38	-0.05	-0.07	0.04	-0.	-0.
	2720.	350.	68.	0.	0.		0.39	-0.07	-0.05	0.	0.
		1650.	-68.	0.	0.			0.64	0.07	-0.	-0.
			650.	0.	0.				1.56	-0.	-0.
				650.	0.					1.54	0.
					1160.						0.86

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	1032.	891.	2076.	2221.	0.1679
REUSS	975.	821.	1923.	2070.	0.1713
ARITH.MEAN	1004.	856.	2000.	2145.	0.1696

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	8.463	5.362	5.770	5.897
REUSS	8.170	5.145	5.608	5.662
ARITH.MEAN	8.316	5.254	5.689	5.780

VMEAN= 5.804 KM/SEC
PERCENT ERROR= 0.4171
DEBYE TEMP.= 787.844

SI O2--ALPHA QUARTZ
TR453701
R.BECHMANN, PHYS.REV.,110(1958),P.1060 TR453701
DENSITY= 2.650 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

867.	70.	119.	179.	0.	0.	1.26	-0.19	-0.05	-0.43	-0.	-0.
	867.	119.	-179.	0.	0.		1.31	-0.21	0.53	0.	0.
		1072.	179.	0.	0.			1.02	-0.37	-0.	-0.
			579.	0.	0.				2.14	0.	0.
				579.	0.					1.73	0.
					399.						2.51

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	380.	478.	1010.	1017.	0.0703
REUSS	370.	425.	922.	937.	0.0843
ARITH.MEAN	375.	452.	966.	977.	0.0773

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	6.196	4.246	3.788	4.624
REUSS	5.946	4.006	3.736	4.373
ARITH.MEAN	6.071	4.126	3.762	4.498

VMEAN= 4.446 KM/SEC
PERCENT ERROR= 1.1880
DEBYE TEMP.= 575.933

SI O2--ALPHA QUARTZ
TR453702
W.P.MASON,BELL SYST.TECH.J. 22(1943),P.178 TR453702
DENSITY= 2.650 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

861.	51.	105.	183.	0.	0.	1.27	-0.16	-0.03	-0.44	-0.	-0.
	861.	105.	-183.	0.	0.		1.31	-0.20	0.52	0.	0.
		1070.	183.	0.	0.			1.02	-0.37	-0.	-0.
			587.	0.	0.				2.12	0.	0.
				587.	0.					1.70	0.
					405.						2.47

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	368.	485.	1010.	1014.	0.0561
REUSS	357.	430.	921.	931.	0.0703
ARITH.MEAN	363.	457.	966.	973.	0.0632

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	6.186	4.276	3.727	4.651
REUSS	5.928	4.030	3.672	4.394
ARITH.MEAN	6.057	4.153	3.700	4.522

VMEAN= 4.468 KM/SEC
PERCENT ERROR= 1.2142
DEBYE TEMP.= 578.962

SI O2--ALPHA QUARTZ
TR453703
I.KOGA AND M.ARUGA,PHYS.REV.,109,(1958),P.1467 TR453703
DENSITY= 2.649 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

868.	70.	119.	-181.	0.	0.	1.26	-0.19	-0.05	0.44	-0.	-0.
	868.	119.	181.	0.	0.		1.31	-0.22	-0.53	0.	0.
		1059.	-181.	0.	0.			1.04	0.38	-0.	-0.
			583.	0.	0.				2.13	-0.	-0.
				583.	0.					1.72	0.
					399.						2.51

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	379.	479.	1011.	1017.	0.0693
REUSS	369.	425.	921.	936.	0.0839
ARITH.MEAN	374.	452.	966.	976.	0.0766

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	6.197	4.251	3.782	4.629
REUSS	5.942	4.005	3.732	4.371
ARITH.MEAN	6.070	4.128	3.757	4.500

VMEAN= 4.627 KM/SEC
PERCENT ERROR= 2.7549
DEBYE TEMP.= 576.057

SIO2 --BETA QUARTZ
HX453701
F.W.KAMMER ET AL.,J.APPL.PHYS.,19(1948)P.265 HX453701
DENSITY= 2.533 GMS/CU CM
TEMPERATURE= 873 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

1165.	160.	335.	-0.	0.	0.	0.94	-0.05	-0.27	-0.	0.	0.
	1165.	335.	-0.	0.	0.		0.94	-0.27	-0.	0.	0.
		1105.	-0.	0.	0.			1.07	0.	-0.	-0.
			360.	0.	0.				2.78	-0.	-0.
				360.	-0.					2.78	0.
					501.						2.00

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	566.	418.	1006.	1123.	0.2066
REUSS	565.	407.	985.	1108.	0.2094
ARITH.MEAN	565.	412.	995.	1115.	0.2080

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	6.659	4.061	4.727	4.485
REUSS	6.612	4.009	4.722	4.429
ARITH.MEAN	6.635	4.035	4.724	4.457

VMEAN= 4.491 KM/SEC
PERCENT ERROR= 0.7521
DEBYE TEMP.= 562.102

SIO2--BETA QUARTZ
HX453703
F.W.KAMMER,T.E.PARDUE AND H.F.FRISSEL,J.APPL.PHYS.,19(1948),P.265 HX453703
DENSITY= 2.493 GMS/CU CM
TEMPERATURE=1073 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

1351.	330.	480.	-0.	0.	0.	0.87	-0.11	-0.29	-0.	0.	0.
	1351.	480.	-0.	0.	0.		0.87	-0.29	-0.	0.	0.
		1245.	-0.	0.	0.			1.03	0.	-0.	-0.
			386.	0.	0.				2.59	-0.	-0.
				386.	-0.					2.59	0.
					516.						1.94

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	725.	435.	1087.	1305.	0.2523
REUSS	725.	426.	1068.	1293.	0.2545
ARITH.MEAN	725.	430.	1078.	1299.	0.2534

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	7.234	4.176	5.393	4.635
REUSS	7.200	4.132	5.392	4.589
ARITH.MEAN	7.217	4.154	5.393	4.612

VMEAN= 4.646 KM/SEC
PERCENT ERROR= 0.7359
DEBYE TEMP.= 578.576

MG O--MAGNESIA--PERICLASE
CU303701
S.BHAGAVANTAM,PROC.IND.ACAD.SCI.,A41 (1955),P.72 CU303701
DENSITY= 3.593 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

2860.	870.	870.	0.	0.	0.	.40	-.09	-.09	0.00	0.00	0.00
	2860.	870.	0.	0.	0.		.40	-.09	0.00	0.00	0.00
		2860.	0.	0.	0.			.40	0.00	0.00	0.00
			1480.	0.	0.				.67	0.00	0.00
				1480.	0.					.67	0.00
					1480.						.67

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	1533.	1285.	3015.	3247.	.1770
REUSS	1533.	1238.	2927.	3184.	.1818
ARITH.MEAN	1533.	1262.	2971.	3216.	.1794

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	9.506	5.982	6.532	6.583
REUSS	9.413	5.870	6.532	6.467
ARITH.MEAN	9.460	5.926	6.532	6.525

VMEAN= 6.610 KM/SEC
PERCENT ERROR= 1.2886
DEBYE TEMP.= 922

MG O--MAGNESIA--PERICLASE
CU303702
C.SUSSE,J.RECHERCHES,12,(1961)P.21 CU303702
DENSITY= 3.598 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

2998.	991.	991.	0.	0.	0.	.39	-.09	-.09	0.00	0.00	0.00
	2998.	991.	0.	0.	0.		.39	-.09	0.00	0.00	0.00
		2998.	0.	0.	0.			.39	0.00	0.00	0.00
			1575.	0.	0.				.63	0.00	0.00
				1575.	0.					.63	0.00
					1575.						.63

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	1659.	1346.	3179.	3455.	.1867
REUSS	1660.	1282.	3060.	3370.	.1927
ARITH.MEAN	1660.	1314.	3119.	3412.	.1897

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	9.798	6.116	6.791	6.737
REUSS	9.677	5.970	6.791	6.584
ARITH.MEAN	9.738	6.043	6.791	6.661

VMEAN= 6.741 KM/SEC
PERCENT ERROR= 1.1884
DEBYE TEMP.= 942

MG O--MAGNESIA--PERICLASE
CU303706
D.H.CHUNG AND W.G.LAWRENCE,,ARMY RES.OFF.RPT.7,DA-31-124,(1963)ALFRED U CU303706
DENSITY= 3.581 GMS/CU CM
TEMPERATURE= 298 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

2892.	880.	880.	0.	0.	0.	.40	-.09	-.09	0.00	0.00	0.00
	2892.	880.	0.	0.	0.		.40	-.09	0.00	0.00	0.00
		2892.	0.	0.	0.			.40	0.00	0.00	0.00
			1546.	0.	0.				.64	0.00	0.00
				1546.	0.					.64	0.00
					1546.						.64

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	1550.	1329.	3102.	3323.	.1721
REUSS	1550.	1272.	2997.	3247.	.1777
ARITH.MEAN	1550.	1301.	3050.	3285.	.1749

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	9.633	6.093	6.579	6.702
REUSS	9.522	5.961	6.579	6.564
ARITH.MEAN	9.577	6.027	6.579	6.633

VMEAN= 6.715 KM/SEC
PERCENT ERROR= 1.2219
DEBYE TEMP.= 936

MG O--MAGNESIA--PERICLASE
CU303707
Y.T.CHOU AND R.W.WHITMORE,J.APPL.PHYS.32(1961)P.1920 CU303707
DENSITY= 3.583 GMS/CU CM
TEMPERATURE= 300 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

2893.	877.	877.	0.	0.	0.	.40	-.09	-.09	0.00	0.00	0.00
	2893.	877.	0.	0.	0.		.40	-.09	0.00	0.00	0.00
		2893.	0.	0.	0.			.40	0.00	0.00	0.00
			1548.	0.	0.				.64	0.00	0.00
				1548.	0.					.64	0.00
					1548.						.64

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	1548.	1331.	3105.	3324.	.1714
REUSS	1548.	1274.	3001.	3248.	.1770
ARITH.MEAN	1548.	1303.	3053.	3286.	.1742

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	9.632	6.096	6.574	6.705
REUSS	9.521	5.964	6.574	6.567
ARITH.MEAN	9.576	6.030	6.574	6.636

VMEAN= 6.718 KM/SEC
PERCENT ERROR= 1.2229
DEBYE TEMP.= 937

AL2 O3--ALUMINA--CORUNDUM
TR023701
J.B.WACHTMAN,JR. ET AL,J.RES.N.B.S., 64A (1960) P.213 TR023701
DENSITY= 3.986 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

4968.	1636.	1109.	235.	0.	0.	0.23	-0.07	-0.03	-0.04	-0.	-0.
	4968.	1109.	-235.	0.	0.		0.24	-0.04	0.06	0.	0.
		4981.	235.	0.	0.			0.22	-0.04	-0.	-0.
			1474.	0.	0.				0.70	0.	0.
				1474.	0.					0.68	0.
					1666.						0.60

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	2514.	1660.	4082.	4728.	0.2318
REUSS	2504.	1617.	3992.	4660.	0.2343
ARITH.MEAN	2509.	1639.	4037.	4694.	0.2330

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	10.890	6.453	7.941	7.146
REUSS	10.812	6.369	7.925	7.057
ARITH.MEAN	10.851	6.411	7.933	7.102

VMEAN= 7.167 KM/SEC
PERCENT ERROR= 0.9117
DEBYE TEMP.=1035.511

AL2O3--ALUMINA--CORUNDUM
TR023702
B.T.BERNSTEIN,J.APPL.PHYS.,TO BE PUBLISHED TR023702
DENSITY= 3.986 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

4902.	1654.	1130.	232.	0.	0.	0.24	-0.07	-0.04	-0.04	-0.	-0.
	4902.	1130.	-232.	0.	0.		0.24	-0.04	0.06	0.	0.
		4902.	232.	0.	0.			0.22	-0.04	-0.	-0.
			1454.	0.	0.				0.71	0.	0.
				1454.	0.					0.69	0.
					1624.						0.62

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	2504.	1626.	4010.	4672.	0.2354
REUSS	2494.	1585.	3923.	4607.	0.2378
ARITH.MEAN	2499.	1605.	3967.	4639.	0.2366

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	10.825	6.386	7.925	7.075
REUSS	10.750	6.305	7.909	6.989
ARITH.MEAN	10.787	6.346	7.917	7.032

VMEAN= 7.096 KM/SEC
PERCENT ERROR= 0.9098
DEBYE TEMP.=1025.319

SAPPHIRE--AL2 O3
TR023703
W.A.MAYER AND E.A.HEIDMAN,ACOUST.SOC.AM.AMER.JOUR.32(1960)P.1699 TR023703
DENSITY= 3.986 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

4960.	1350.	1170.	-230.	0.	0.	0.23	-0.05	-0.04	0.04	-0.	-0.
	4960.	1170.	230.	0.	0.		0.23	-0.04	-0.05	0.	0.
		5020.	-230.	0.	0.			0.22	0.04	-0.	-0.
			1410.	0.	0.				0.73	-0.	-0.
				1410.	0.					0.71	0.
					1805.						0.55

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	2480.	1675.	4102.	4713.	0.2275
REUSS	2475.	1625.	4000.	4642.	0.2307
ARITH.MEAN	2478.	1650.	4051.	4678.	0.2291

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	10.873	6.482	7.887	7.174
REUSS	10.790	6.384	7.880	7.071
ARITH.MEAN	10.832	6.433	7.883	7.122

VMEAN= 7.435 KM/SEC
PERCENT ERROR= 4.2033
DEBYE TEMP.=1038.516

FE2O3--HEMATITE
TR193701
W.VOIGT,ANN.PHYSIK.,22(1907),P.129 TR193701
DENSITY= 5.120 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

2470.	560.	160.	-130.	0.	0.	0.43	-0.10	-0.02	0.08	-0.	-0.
	2470.	160.	130.	0.	0.		0.43	-0.03	-0.08	0.	0.
		2320.	-130.	0.	0.			0.44	0.07	-0.	-0.
			870.	0.	0.				1.18	-0.	-0.
				870.	0.					1.15	0.
					935.						1.07

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	1002.	960.	2184.	2283.	0.1386
REUSS	990.	937.	2136.	2238.	0.1403
ARITH.MEAN	996.	948.	2160.	2261.	0.1394

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	6.676	4.330	4.424	4.750
REUSS	6.611	4.277	4.396	4.692
ARITH.MEAN	6.644	4.304	4.410	4.721

VMEAN= 4.820 KM/SEC
PERCENT ERROR= 2.0688
DEBYE TEMP.= 644.292

TIO2--RUTILE
TE523701
F.BIRCH,J.GEOPHYS. RES.,65,(1960),P.3855 TE523701
DENSITY= 4.264 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

2730.	1760.	1490.	-0.	0.	0.	0.66	-0.38	-0.09	-0.	0.	0.
	2730.	1490.	-0.	0.	0.		0.66	-0.09	-0.	0.	0.
		4840.	-0.	0.	0.			0.26	0.	-0.	-0.
			1250.	0.	0.				0.80	-0.	-0.
				1250.	-0.					0.80	0.
					1940.						0.52

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	2198.	1259.	3171.	3876.	0.2756
REUSS	2106.	1012.	2617.	3456.	0.2929
ARITH.MEAN	2152.	1135.	2894.	3666.	0.2843

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	9.533	5.433	7.179	6.037
REUSS	9.002	4.872	7.027	5.436
ARITH.MEAN	9.267	5.152	7.103	5.736

VMEAN= 5.585 KM/SEC
PERCENT ERROR= 2.7168
DEBYE TEMP.= -0.

TI O2
TE523702
S.K.JOSHI AND S.S.MITRA,PROC.PHYS.SOC.LONDON,76,NO.12(1960),P.295 TE523702
DENSITY= 4.260 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

2800.	1800.	1400.	-0.	0.	0.	0.63	-0.37	-0.08	-0.	0.	0.
	2800.	1400.	-0.	0.	0.		0.63	-0.08	-0.	0.	0.
		4600.	-0.	0.	0.			0.27	0.	-0.	-0.
			1200.	0.	0.				0.83	-0.	-0.
				1200.	-0.					0.83	0.
					1600.						0.62

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	2156.	1173.	2979.	3720.	0.2826
REUSS	2102.	992.	2571.	3425.	0.2962
ARITH.MEAN	2129.	1083.	2775.	3572.	0.2894

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	9.344	5.248	7.113	5.839
REUSS	8.965	4.824	7.025	5.385
ARITH.MEAN	9.155	5.036	7.069	5.612

VMEAN= 5.503 KM/SEC
PERCENT ERROR= 1.9730
DEBYE TEMP.= 530.717

SPINEL--MG AL2 O4
CU800301
R.K.VERMA,J.GEOPHYS.RES.,65,(1960),P.762 CU800301
DENSITY= 3.630 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

3005.	1537.	1537.	-0.	0.	0.	0.51	-0.17	-0.17	-0.	0.	0.
	3005.	1537.	-0.	0.	0.		0.51	-0.17	-0.	0.	0.
		3005.	-0.	0.	0.			0.51	0.	-0.	-0.
			1586.	0.	0.				0.63	-0.	-0.
				1586.	-0.					0.63	0.
					1586.						0.63

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	2026.	1245.	3101.	3687.	0.2589
REUSS	2026.	1083.	2758.	3470.	0.2732
ARITH.MEAN	2026.	1164.	2929.	3579.	0.2660

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	10.077	5.856	7.471	6.497
REUSS	9.777	5.462	7.471	6.079
ARITH.MEAN	9.927	5.659	7.471	6.288

VMEAN= 6.321 KM/SEC
PERCENT ERROR= 0.5229
DEBYE TEMP.= 889.255

CR2FEO4--CHROMITE
CU171901
M.S.DORAISWAMI,PROC.IND.ACAD.SCI.,A25,(1947)P.413 CU171901
DENSITY= 4.450 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

3225.	1437.	1437.	-0.	0.	0.	0.43	-0.13	-0.13	-0.	0.	0.
	3225.	1437.	-0.	0.	0.		0.43	-0.13	-0.	0.	0.
		3225.	-0.	0.	0.			0.43	0.	-0.	-0.
			1167.	0.	0.				0.86	-0.	-0.
				1167.	-0.					0.86	0.
					1167.						0.86

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	2033.	1058.	2704.	3443.	0.2799
REUSS	2033.	1040.	2665.	3420.	0.2815
ARITH.MEAN	2033.	1049.	2685.	3432.	0.2807

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	8.796	4.875	6.759	5.430
REUSS	8.765	4.834	6.759	5.386
ARITH.MEAN	8.781	4.854	6.759	5.408

VMEAN= 5.492 KM/SEC
PERCENT ERROR= 1.5255
DEBYE TEMP.= 704.089

FE3O4--MAGNETITE
CU193701
M.S.DORAISWAMI,PROC.INDIAN ACAD.SCI.,A25(1947)P.413 CU193701
DENSITY= 5.200 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

2730.	1060.	1060.	-0.	0.	0.	0.47	-0.13	-0.13	-0.	0.	0.
	2730.	1060.	-0.	0.	0.		0.47	-0.13	-0.	0.	0.
		2730.	-0.	0.	0.			0.47	0.	-0.	-0.
			970.	0.	0.				1.03	-0.	-0.
				970.	-0.					1.03	0.
					970.						1.03

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	1617.	916.	2311.	2838.	0.2622
REUSS	1617.	911.	2301.	2831.	0.2628
ARITH.MEAN	1617.	914.	2306.	2835.	0.2625

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	7.387	4.197	5.575	4.665
REUSS	7.378	4.185	5.575	4.653
ARITH.MEAN	7.383	4.191	5.575	4.659

VMEAN= 4.737 KM/SEC
PERCENT ERROR= 1.6392
DEBYE TEMP.= 631.711

FE3O4--MAGNETITE
CU193702
A.E.CLARK AND R.E.STRAKNA,J.APPL.PHYS.32(1961)P.1172 CU193702
DENSITY= 5.200 GMS/CU CM
TEMPERATURE= 296 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

2730.	1060.	1060.	-0.	0.	0.	0.47	-0.13	-0.13	-0.	0.	0.
	2730.	1060.	-0.	0.	0.		0.47	-0.13	-0.	0.	0.
		2730.	-0.	0.	0.			0.47	0.	-0.	-0.
			970.	0.	0.				1.03	-0.	-0.
				970.	-0.					1.03	0.
					970.						1.03

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	1617.	916.	2311.	2838.	0.2622
REUSS	1617.	911.	2301.	2831.	0.2628
ARITH.MEAN	1617.	914.	2306.	2835.	0.2625

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	7.387	4.197	5.575	4.665
REUSS	7.378	4.185	5.575	4.653
ARITH.MEAN	7.383	4.191	5.575	4.659

VMEAN= 4.737 KM/SEC
PERCENT ERROR= 1.6392
DEBYE TEMP.= 631.711

PYRITE
CU194301
G.SIMMONS AND F.BIRCH,J.APPL.PHYS.,34(1963)P.2737 CU194301
DENSITY= 4.929 GMS/CU CM
TEMPERATURE= 298 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

3818.	310.	310.	-0.	0.	0.	0.27	-0.02	-0.02	-0.	0.	0.
	3818.	310.	-0.	0.	0.		0.27	-0.02	-0.	0.	0.
		3818.	-0.	0.	0.			0.27	0.	-0.	-0.
			1094.	0.	0.				0.91	-0.	-0.
				1094.	-0.					0.91	0.
					1094.						0.91

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	1479.	1358.	3119.	3290.	0.1555
REUSS	1479.	1288.	2995.	3196.	0.1626
ARITH.MEAN	1479.	1323.	3057.	3243.	0.1591

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	8.169	5.248	5.478	5.763
REUSS	8.052	5.111	5.478	5.620
ARITH.MEAN	8.111	5.180	5.478	5.691

VMEAN= 5.767 KM/SEC
PERCENT ERROR= 1.3211
DEBYE TEMP.= 711.616

ZN S--SPHALERITE
CU554302
N.G.EINSPRUCH AND R.J. MANNING,J.OF THE ACOUST.SOC.OF AMER.35(1963)215 CU554302
DENSITY= 4.079 GMS/CU CM
TEMPERATURE= 302 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

976.	590.	590.	-0.	0.	0.	1.88	-0.71	-0.71	-0.	0.	0.
	976.	590.	-0.	0.	0.		1.88	-0.71	-0.	0.	0.
		976.	-0.	0.	0.			1.88	0.	-0.	-0.
			451.	0.	0.				2.22	-0.	-0.
				451.	-0.					2.22	0.
					451.						2.22

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	719.	348.	898.	1182.	0.3057
REUSS	719.	294.	776.	1110.	0.3201
ARITH.MEAN	719.	321.	837.	1146.	0.3129

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	5.384	2.920	4.197	3.258
REUSS	5.217	2.684	4.197	3.005
ARITH.MEAN	5.300	2.802	4.197	3.131

VMEAN= 3.146 KM/SEC
PERCENT ERROR= 0.4548
DEBYE TEMP.= 344.203

ZN S--SPHALERITE
CU554303
D.BERLINCOURT,H.JAFFE AND L.R.SHIOZAWA,PHYS.REV.129(1963.P.1013 CU554303
DENSITY= 4.088 GMS/CU CM
TEMPERATURE= 298 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

1046.	653.	653.	-0.	0.	0.	1.84	-0.71	-0.71	-0.	0.	0.
	1046.	653.	-0.	0.	0.		1.84	-0.71	-0.	0.	0.
		1046.	-0.	0.	0.			1.84	0.	-0.	-0.
			461.	0.	0.				2.17	-0.	-0.
				461.	-0.					2.17	0.
					461.						2.17

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	784.	355.	926.	1258.	0.3167
REUSS	784.	300.	797.	1184.	0.3305
ARITH.MEAN	784.	327.	862.	1221.	0.3236

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	5.546	2.947	4.379	3.293
REUSS	5.380	2.707	4.379	3.035
ARITH.MEAN	5.463	2.827	4.379	3.164

VMEAN= 3.180 KM/SEC
PERCENT ERROR= 0.4844
DEBYE TEMP.= 348.081

BA SO4--BARITE
OR066201
H.B.HUNTINGTON,'SOLID STATE PHYS.',VOL7(1958)P.274 ACADEMIC PRESS OR066201
DENSITY= 4.499 GMS/CU CM
TEMPERATURE= 288 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

880.	477.	269.	-0.	0.	0.	1.73	-0.99	-0.17	-0.	0.	0.
	781.	289.	-0.	0.	0.		2.00	-0.30	-0.	0.	0.
		1040.	-0.	0.	0.			1.09	0.	-0.	-0.
			117.	0.	0.				8.55	-0.	-0.
				279.	-0.					3.58	0.
					255.						3.92

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	530.	241.	628.	852.	0.3154
REUSS	529.	205.	544.	802.	0.3286
ARITH.MEAN	530.	223.	586.	827.	0.3220

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	4.351	2.316	3.432	2.587
REUSS	4.222	2.133	3.429	2.392
ARITH.MEAN	4.287	2.224	3.431	2.489

VMEAN= 2.481 KM/SEC
PERCENT ERROR= 0.3241
DEBYE TEMP.= 304.718

BA SO4--BARITE
OR066202
T.SESHAGIRI RAO,PROC.INDIAN ACAD.SCI.,A33(1951),P.251 OR066202
DENSITY= 4.432 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

862.	523.	341.	-0.	0.	0.	1.84	-0.99	-0.27	-0.	0.	0.
	917.	356.	-0.	0.	0.		1.74	-0.27	-0.	0.	0.
		1084.	-0.	0.	0.			1.10	0.	-0.	-0.
			120.	0.	0.				8.33	-0.	-0.
				287.	-0.					3.48	0.
					274.						3.65

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	589.	246.	647.	917.	0.3282
REUSS	588.	211.	566.	870.	0.3397
ARITH.MEAN	589.	228.	607.	893.	0.3340

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	4.548	2.354	3.646	2.635
REUSS	4.430	2.183	3.643	2.450
ARITH.MEAN	4.489	2.269	3.645	2.543

VMEAN= 2.544 KM/SEC
PERCENT ERROR= 0.0318
DEBYE TEMP.= 309.722

SRSO4--CELESTITE
OR596201
T.SESHAGIRI RAO,PROC.INDIAN ACAD.SCI.,A33(1951),P.251 OR596201
DENSITY= 3.955 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

1044.	773.	605.	-0.	0.	0.	2.20	-1.39	-0.37	-0.	0.	0.
	1061.	619.	-0.	0.	0.		2.19	-0.40	-0.	0.	0.
		1286.	-0.	0.	0.			1.14	0.	-0.	-0.
			135.	0.	0.				7.41	-0.	-0.
				279.	-0.					3.58	0.
					27.						37.04

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	821.	181.	506.	1062.	0.4228
REUSS	820.	86.	249.	934.	0.4494
ARITH.MEAN	820.	133.	377.	998.	0.4361

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	5.182	2.140	4.555	2.421
REUSS	4.860	1.473	4.552	1.678
ARITH.MEAN	5.021	1.806	4.553	2.050

VMEAN= 2.019 KM/SEC
PERCENT ERROR= 1.4978
DEBYE TEMP.= 260.581

CALCITE
TR116101
J.BHIMASENACHAR,PROC.INDIAN ACAD.SCI.,A22(1945),P.199 TR116101
DENSITY= 2.705 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

1374.	440.	450.	203.	0.	0.	1.01	-0.37	-0.18	-0.71	-0.	-0.
	1374.	450.	-203.	0.	0.		1.43	-1.02	1.67	0.	0.
		801.	203.	0.	0.			2.41	-1.93	-0.	-0.
			342.	0.	0.				5.48	0.	0.
				342.	0.					2.92	0.
					467.						2.14

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	692.	377.	958.	1195.	0.2853
REUSS	584.	262.	683.	933.	0.3048
ARITH.MEAN	638.	320.	821.	1064.	0.2950

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	6.647	3.735	5.058	4.156
REUSS	5.871	3.111	4.644	3.477
ARITH.MEAN	6.259	3.423	4.851	3.816

VMEAN= 3.838 KM/SEC
PERCENT ERROR= 0.5765
DEBYE TEMP.= 492.059

CALCITE
TR116102
L.PESELNICK AND R.A.ROBIE,J.APPL.PHYS.,33(1962),P.2889 TR116102
DENSITY= 2.712 GMS/CU CM
TEMPERATURE= 298 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

1371.	482.	568.	200.	0.	0.	1.08	-0.28	-0.43	-0.53	-0.	-0.
	1371.	568.	-200.	0.	0.		1.77	-1.55	2.06	0.	0.
		811.	200.	0.	0.			3.24	-2.49	-0.	-0.
			350.	0.	0.				5.76	0.	0.
				350.	0.					2.86	0.
					445.						2.25

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	754.	358.	927.	1232.	0.3158
REUSS	639.	227.	609.	942.	0.3412
ARITH.MEAN	697.	293.	768.	1087.	0.3285

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	6.739	3.633	5.273	4.055
REUSS	5.894	2.894	4.855	3.250
ARITH.MEAN	6.316	3.264	5.064	3.652

VMEAN= 3.680 KM/SEC
PERCENT ERROR= 0.7430
DEBYE TEMP.= 471.371

CALCITE
TR116103
L.PESELNICK AND R.A.ROBIE,J.APPL.PHYS.,34(1963)P.2495 TR116103
DENSITY= 2.712 GMS/CU CM
TEMPERATURE= 298 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

1445.	571.	534.	-205.	0.	0.	1.07	-0.49	-0.15	0.88	-0.	-0.
	1445.	534.	205.	0.	0.		1.67	-1.29	-2.16	0.	0.
		831.	-205.	0.	0.			2.73	2.43	-0.	-0.
			327.	0.	0.				6.49	-0.	-0.
				327.	0.					3.06	0.
					437.						2.29

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	778.	357.	929.	1254.	0.3165
REUSS	627.	230.	616.	934.	0.3362
ARITH.MEAN	702.	294.	772.	1094.	0.3263

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	6.798	3.628	5.354	4.052
REUSS	5.867	2.914	4.806	3.270
ARITH.MEAN	6.333	3.271	5.080	3.661

VMEAN= 3.684 KM/SEC
PERCENT ERROR= 0.6109
DEBYE TEMP.= 472.458

ARAGONITE
OR116101
W.VOIGT,ANN.PHYSIK,24(1907)P.290 OR116101
DENSITY= 2.930 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

1630.	380.	17.	-0.	0.	0.	0.68	-0.30	0.04	0.	-0.	-0.
	890.	160.	-0.	0.	0.		1.29	-0.23	-0.	0.	0.
		860.	-0.	0.	0.			1.21	0.	-0.	-0.
			430.	0.	0.				2.33	-0.	-0.
				260.	-0.					3.85	0.
					427.						2.34

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	499.	412.	969.	1048.	0.1774
REUSS	455.	373.	878.	952.	0.1781
ARITH.MEAN	477.	392.	924.	1000.	0.1777

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	5.980	3.748	4.128	4.127
REUSS	5.699	3.567	3.940	3.928
ARITH.MEAN	5.840	3.657	4.034	4.027

VMEAN= 4.012 KM/SEC
PERCENT ERROR= 0.3945
DEBYE TEMP.= 533.224

NA CL--HALITE
CU331301
K.SPANGENBERG,AND S.HAUSSUHL,ZEIT KRIST.,109,(1957)P.422 CU331301
DENSITY= 2.164 GMS/CU CM
TEMPERATURE= 295 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

493.	131.	131.	0.	0.	0.	2.28	-.47	-.47	0.00	0.00	0.00
	493.	131.	0.	0.	0.		2.28	-.47	0.00	0.00	0.00
		493.	0.	0.	0.			2.28	0.00	0.00	0.00
			128.	0.	0.				7.81	0.00	0.00
				128.	0.					7.81	0.00
					128.						7.81

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	251.	149.	373.	450.	.2554
REUSS	251.	144.	364.	444.	.2583
ARITH.MEAN	251.	147.	369.	447.	.2568

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	4.562	2.625	3.409	2.915
REUSS	4.534	2.588	3.409	2.875
ARITH.MEAN	4.548	2.606	3.409	2.895

VMEAN= 2.942 KM/SEC
PERCENT ERROR= 1.5835
DEBYE TEMP.= 304

NA CL--HALITE
CU331303
D.LAZARUS, PHYS.REV.,76,(1949)P.545 CU331303
DENSITY= 2.162 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

491.	123.	123.	0.	0.	0.	2.26	-.45	-.45	0.00	0.00	0.00
	491.	123.	0.	0.	0.		2.26	-.45	0.00	0.00	0.00
		491.	0.	0.	0.			2.26	0.00	0.00	0.00
			128.	0.	0.				7.81	0.00	0.00
				128.	0.					7.81	0.00
					128.						7.81

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	245.	150.	374.	446.	.2490
REUSS	245.	145.	365.	439.	.2523
ARITH.MEAN	245.	148.	369.	443.	.2506

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	4.542	2.637	3.370	2.926
REUSS	4.510	2.596	3.370	2.882
ARITH.MEAN	4.526	2.616	3.370	2.904

VMEAN= 2.950 KM/SEC
PERCENT ERROR= 1.5604
DEBYE TEMP.= 306

NA CL--HALITE
CU331304
E.P.PAPADAKIS,J.APPL.PHYS.34(1963)P.1875 CU331304
DENSITY= 2.162 GMS/CU CM
TEMPERATURE= 300 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

490.	128.	128.	0.	0.	0.	2.28	-.47	-.47	0.00	0.00	0.00
	490.	128.	0.	0.	0.		2.28	-.47	0.00	0.00	0.00
		490.	0.	0.	0.			2.28	0.00	0.00	0.00
			130.	0.	0.				7.69	0.00	0.00
				130.	0.					7.69	0.00
					130.						7.69

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	248.	150.	375.	449.	.2510
REUSS	248.	146.	367.	444.	.2537
ARITH.MEAN	248.	148.	371.	446.	.2524

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	4.557	2.637	3.391	2.927
REUSS	4.531	2.602	3.391	2.890
ARITH.MEAN	4.544	2.620	3.391	2.908

VMEAN= 2.956 KM/SEC
PERCENT ERROR= 1.5982
DEBYE TEMP.= 306

K CL--SYLVITE
CU281301
K.SPANGENBERG,AND S.HAUSSUHL,ZEIT KRIST.,109,(1957)P.422 CU281301
DENSITY= 1.988 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

398.	62.	62.	-0.	0.	0.	2.62	-0.35	-0.35	-0.	0.	0.
	398.	62.	-0.	0.	0.		2.62	-0.35	-0.	0.	0.
		398.	-0.	0.	0.			2.62	0.	-0.	-0.
			63.	0.	0.				15.87	-0.	-0.
				63.	-0.					15.87	0.
					63.						15.87

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	174.	105.	262.	314.	0.2701
REUSS	174.	84.	217.	286.	0.2921
ARITH.MEAN	174.	94.	240.	300.	0.2811

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	3.974	2.298	2.958	2.551
REUSS	3.793	2.055	2.958	2.293
ARITH.MEAN	3.883	2.177	2.958	2.422

VMEAN= 2.420 KM/SEC
PERCENT ERROR= 0.0905
DEBYE TEMP.= 229.067

K CL--SYLVITE
CU281303
K.SPANGENBERG,AND S.HAUSSUHL,ZEIT KRIST.,109,(1957)P.422 CU281303
DENSITY= 1.980GMS/CU CM
TEMPERATURE=295 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

408.	69.	69.	0.	0.	0.	2.57	-.37	-.37	0.00	0.00	0.00
	408.	69.	0.	0.	0.		2.57	-.37	0.00	0.00	0.00
		408.	0.	0.	0.			2.57	0.00	0.00	0.00
			64.	0.	0.				15.62	0.00	0.00
				64.	0.					15.62	0.00
					64.						15.62

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	181.	106.	266.	323.	.2762
REUSS	182.	85.	221.	295.	.2974
ARITH.MEAN	181.	95.	243.	309.	.2868

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	4.042	2.315	3.031	2.572
REUSS	3.863	2.074	3.031	2.316
ARITH.MEAN	3.952	2.195	3.031	2.444

VMEAN= 2.443 KM/SEC
PERCENT ERROR= .0369
DEBYE TEMP.= 160.065

CA F2--FLUORITE
CU112001
L.BERGMANN,'DER ULTRASCHALL...'(1954), S.HIRZEL,VERLAG CU112001
DENSITY= 3.180 GMS/CU CM
TEMPERATURE= 293 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

1628.	433.	433.	-0.	0.	0.	0.69	-0.15	-0.15	-0.	0.	0.
	1628.	433.	-0.	0.	0.		0.69	-0.15	-0.	0.	0.
		1628.	-0.	0.	0.			0.69	0.	-0.	-0.
			334.	0.	0.				2.99	-0.	-0.
				334.	-0.					2.99	0.
					334.						2.99

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	831.	439.	1121.	1417.	0.2827
REUSS	831.	406.	1046.	1372.	0.2902
ARITH.MEAN	831.	422.	1084.	1395.	0.2865

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	6.675	3.717	5.113	4.138
REUSS	6.568	3.571	5.113	3.983
ARITH.MEAN	6.622	3.644	5.113	4.061

VMEAN= 4.111 KM/SEC
PERCENT ERROR= 1.2313
DEBYE TEMP.= 506.231

CA F2--FLOURITE
CU112002
D.R.HUFFMAN AND M.H.NORWOOD,PHYS.REV.,117,(1960)P.709 CU112002
DENSITY= 3.179 GMS/CU CM
TEMPERATURE= 300 DEGREES KELVIN

ELASTIC CONSTANTS (KBARS.) ELASTIC MODULI(1/KBAR*1000)

1640.	530.	530.	-0.	0.	0.	0.72	-0.18	-0.18	-0.	0.	0.
	1640.	530.	-0.	0.	0.		0.72	-0.18	-0.	0.	0.
		1640.	-0.	0.	0.			0.72	0.	-0.	-0.
			337.	0.	0.				2.97	-0.	-0.
				337.	-0.					2.97	0.
					337.						2.97

	BULK MOD	SHEAR MOD	YOUNG MOD	LONG MOD	POISSON RATIO
VOIGT	900.	424.	1100.	1466.	0.3014
REUSS	900.	400.	1045.	1433.	0.3065
ARITH.MEAN	900.	412.	1072.	1449.	0.3040

VELOCITY	LONG	SHEAR	BULK	AVERAGE
VOIGT	6.789	3.653	5.320	4.077
REUSS	6.714	3.546	5.320	3.964
ARITH.MEAN	6.751	3.599	5.320	4.021

VMEAN= 4.078 KM/SEC
PERCENT ERROR= 1.4128
DEBYE TEMP.= 501.166

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13. ABSTRACT

This state-of-the-art report summarizes experiments and data on sound velocities in rocks and minerals and projects useful lines of research. The report discusses in detail the three common measuring techniques now employed: (1) resonance methods, (2) pulse-transmission methods (time-of-flight), and (3) ultrasonic-interferometric methods.

Promising techniques, both direct and indirect, are described, the most important of these is the resonance of small spheres. Methods of estimating elastic constants at high pressure and high temperature are indicated.

The data extant on the sound velocities in rocks and minerals are considerable and are tabulated in several appendixes. The lack of systematic coverage and quality of these data is discussed.

A method of estimating unmeasured properties in a class of rocks, using data already reported for that class, is reviewed. Techniques of estimating isotropic sound velocities from single-crystal elastic-constant data are reviewed.

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