peratures of crystallization. Because of the predicted rapid rates of ordering at high temperature, deviations from equilibrated distributions are not expected at those temperatures. However, in rapidly cooled volcanic rocks it seems likely that the rearrangement of cations at temperatures somewhat above the limiting temperature of ≈ 480°C for maximum order may not follow equilibrium conditions and that metastable cation distributions will be quenched. In view of the varying rates of cooling of volcanic rocks, it seems probable that the range of metastable distributions may actually be wider than that shown in Fig. 1. The effect of diluted foreign cations like Mn, Ca, Al, and so forth, on site occupancy numbers for Fe^{2+} at $M1$ and $M2$ and the rate constants are still unknown.

Our experimentally determined equilibrium temperatures for *intra*crystalline ordering at approximately 480°C in some metamorphic and igneous rocks can be compared with other data obtained from *inter*crystalline distributions and exsolution phenomena. The Fe^{2+},Mg distribution between coexisting orthopyroxene and clinopyroxene phases generally reflect crystallization temperatures for metamorphic and intrusive igneous rocks (*4*). McCallum (*5*) determined distribution coefficients for intercrystalline exchange in pyroxenes from the Stillwater complex, Montana. He found distribution coefficients between those of unexsolved orthopyroxene and clinopyroxene corresponding to magmatic temperatures (1100° to 1200°C), but values for exsolved coarse-size lamellae and the host crystals gave temperatures in the range 600° to 800°C. Apparently there is an adjustment of the Fe^{2+},Mg distribution between the exsolved phase and the host toward equilibrium at successively lower temperatures. It is reasonable to assume that, while cation migration occurs on the scale of microns in the case of exsolution phenomena, intercrystalline exchange involving distances of millimeters or centimeters is not possible during cooling of the rock. However, ordering of cations observed from Mössbauer studies of site occupancy involves distances of a few lattice constants and presumably takes place at much lower temperatures.

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Elastic Coefficients of Animal Bone

Abstract. *The elastic stiffness coefficients of dried bovine phalanx and femur and of fresh bovine phalanx were measured by an ultrasonic technique. An analysis of the crystallographic structure of the principal components of bone and its piezoelectric and pyroelectric behavior showed that bone is a texture that has the same elastic coefficient matrix as a hexagonal single crystal. The five elastic stiffness coefficients of fresh phalanx are:* C_{11}, *1.97;* C_{12}, *1.21;* C_{13}, *1.26;* C_{33}, *3.20; and* C_{44}, *0.54 (all in units of* 10^{11} *dynes per square centimeter). Value of axial and transverse Young's and shear moduli, compressibility, and the three Poisson's ratios were calculated.*

It has been proposed that the electromechanical effect (electrical potential generated by application of mechanical stress) observed in bone may have important physiological functions (*1*, *2*). Some processes in which this effect may be significant include bone remodeling, diffusional processes in bone nourishment, and hearing. To study these processes, one must understand the effect of mechancial stress on bone, that is, understand the elastic behavior of bone. In an attempt to find measurements of the elastic constants of bone in the literature, I discovered that all of the elastic data on bone had been measured by static techniques; that is, the bone was sufficiently stressed by tension, compression, or torsion so that measurably large displacements could be observed. This technique has two serious defects. First, the stress-strain relationship of bone is nonlinear (*3*). In order for the strain to be large enough to be measurable in a static test, it may be necessary to stress the bone into the nonlinear stress-strain region, thus yielding a meaningless result. Second, bone is a highly anisotropic material (*4*). It is not possible to characterize fully the elastic properties of such a material with only two or three technical elastic moduli, such as the axial Young's modulus or the axial shear modulus.

It was desired to determine elastic constants free of these two defects. Therefore, the structure of bone was analyzed in terms of a polycrystalline texture to determine the number and type of independent elastic constants. An ultrasonic technique was developed for the measurement of the constants, and statistical methods were used for the analysis of the results. From these results, the Young's modulus and the shear modulus as functions of direction relative to the bone axis were calculated. In this report I describe the method and the results of measurements on specimens of dried and fresh bovine bones.

The elastic properties of a material can be completely described by the components of the elastic stiffness matrix (C_{ij}). The elastic stiffnesses are the linear coefficients of proportionality between the stress matrix (σ_i) and the strain matrix (ε_j):

$$(\sigma_i) = (C_{ij})(\varepsilon_j) \quad (i, j = 1, 2, \ldots, 6) \quad (1)$$

When the i and j are equal to 1, 2, or 3, the symbols σ_i and ε_j refer to normal stresses and strains, respectively, in the crystallographic 1, 2, or 3 directions. The subscripts 4, 5, and 6 refer to shear stresses or strains (*5*). A consideration of the crystal structure of the major components of bone, hydroxyapatite (*6*) and collagen (*7*), and the piezoelectric (*8*) and pyroelectric (*9*) characteristics of bone suggested that it should behave elastically as a hexagonal material. In such a material (*5*), the elastic stiffness matrix takes the following form:

$$\begin{matrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \tfrac{1}{2}(C_{11}-C_{12}) \end{matrix}$$

Thus the elastic behavior of bone is characterized by five independent coefficients.

The coefficients were calculated (*10*) from measurements of the velocities of shear and longitudinal ultrasonic waves

Table 1. Elastic stiffness coefficients and technical elastic moduli of bone. Units used: C_{11}, C_{12}, C_{13}, C_{33}, C_{44}, Young's moduli (axial and transverse), and shear moduli (axial and transverse) are expressed in 10^{11} dynes per square centimeter; compressibility in 10^{-11} square centimeter per dyne; Poisson's ratios are dimensionless.

Elastic parameter	Dried phalanx	Dried femur	Fresh phalanx
C_{11}	2.12 ± 0.07*	2.38 ± 0.14	1.97 ± 0.05
C_{12}	0.95 ± .03	1.02 ± .06	1.21 ± .04
C_{13}	1.02 ± .14	1.12 ± .21	1.26 ± .12
C_{33}	3.74 ± .16	3.34 ± .12	3.20 ± .11
C_{44}	0.75 ± .02	0.82 ± .02	0.54 ± .01
Young's modulus (axial)	3.05	2.60	2.20
Young's modulus (transverse)	1.59	1.79	1.13
Shear modulus (axial)	0.75	0.82	0.54
Shear modulus (transverse)	.65	.74	.45
Compressibility	.688	.633	.649
Poisson's ratio, μ_{12}†	.365	.321	.482
Poisson's ratio, μ_{13}	.334	.330	.397
Poisson's ratio, μ_{31}	.174	.228	.204

* The standard deviations of the values are given and are based on a statistical analysis in which it was assumed that the standard deviation in the measurement of a velocity was 3 percent and that the error in orientation of a sample was 5°. † Axes 1 and 2 are in the transverse plane; axis 3 is parallel to the bone axis.

propagated in specific directions in rectangular-parallelepiped shaped bone samples (*11*). The specimens used were dried samples of bovine femur and phalanx and fresh samples of phalanx. The dried materials were prepared by degreasing the bones in toluene, then drying them in a vacuum oven at 35°C. However, during the course of the experiments, the material was permitted to equilibrate with the moisture of the atmosphere. The fresh materials were immersed in a standard saline solution at all times except when measurements were being made. Opposite faces of the samples were flat and parallel within 12 μ and were polished. The ultrasonic velocities were determined by measuring the time of transit of ultrasonic pulses through the material. Samples were placed between two piezoelectric transducers, and the transmitting transducer was excited by a 1-μsec pulse from a 1.5 kv pulser. The transmitted signal was detected by the receiver transducer and was amplified by a two-stage, wideband amplifier. The time measurement was obtained by means of a 0- to 100-μsec delay potentiometer and an electronic time interval counter. The velocities were calculated from the transit times and the physical dimensions of the specimens.

The calculated elastic stiffness coefficients of the three types of material are presented in Table 1. The values in the table are based on the averages of 24, 24, and 36 measurements in different directions on five, six, and seven specimens of dried phalanx, dried femur, and fresh phalanx, respectively. All specimens of one type were cut from a single bone.

It is possible to calculate from the elastic stiffness coefficients all of the technical elastic moduli, such as the Young's modulus, shear modulus, Poisson's ratio, and the bulk compressibility (*12*). The first two moduli are functions of direction; their values in the axial and in the transverse bone direction are also given in Table 1. The three independent Poisson's ratios are given.

The technique used here is a relatively simple one. It may be applied to other studies of the elastic properties of bone in which variables such as type of bone, diet, and age of animal are considered.

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Fluid Drop-Like Transition of Erythrocytes under Shear

Abstract. *Red cells dispersed in a continuous medium of high viscosity possess the flow properties of fluid drops. The cells at rest are biconcave, while under shear they become progressively deformed into prolate ellipsoids, their long axis aligned parallel to the flow direction. The red cell membrane rotates around the hemoglobin like a tread of a tank. At high rates of shear this mechanism greatly reduces viscosity at all hematocrit values.*

The critical importance of red cell deformability to the flow properties of blood has recently been emphasized by several investigators (*1–4*). Their evidence has uniformly suggested that the deformability of the red cell is a major determinant of the shear thinning properties of blood at high rates of shear. The exact manner by which red cell deformability facilitates flow has not been established. Dintenfass (*1*) suggested that the membrane of the red cell under shear is subjected to liquefaction and gelation, thus allowing transmission of shear stress into the interior of the cell. Goldsmith (*2*) found the flow characteristics of red cells in tubes comparable to those of deformable liquid drops. In studies with packed cells in our laboratory (*5*) it was observed that the membrane actually rotates around the cell contents. All these concepts suggest that the red cell, when subjected to shear, assumes the flow properties of a fluid drop. Consequently, whole blood might thus be compared to an emulsion of hemoglobin droplets dispersed in plasma rather than a suspension of particles. This assumption has been tested in model experiments along the lines of emulsion rheology. As shown by Taylor (*6*), the viscosity of emulsions (η_s) is not only a function of the viscosity of the continuous medium (η_0) and the volume fraction (H) of the suspended phase but is strongly influenced by the ratio of the viscosities of suspended droplets (η_i) and continuous phase where

$$\eta_s = \eta_0(1 + 2.5H)\frac{(\eta_i/\eta_0 + 0.4)}{\eta_i/\eta_0 + 1} \quad (1)$$

This equation originally applied to dilute emulsions at high rates of shear (capillary viscometers). To test the assumption of red cell fluidity under shear, erythrocytes were immersed at various concentrations in highly viscous solutions and the viscosity of these "suspensions" was measured at both high and