Compressional Wave Velocities in Single Crystals of Alkali Feldspar at Pressures to 10 Kilobars

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Introduction. The propagation of elastic waves in the earth's crust is governed by the elastic properties of the constituent minerals within crustal rocks. The ubiquity of the feldspars, together with their abundance in crustal rocks, indicates that seismic velocities in the crust are largely determined by the elastic properties of feldspar. Measurements of the velocity of compressional and shear waves in single crystals of potassium-sodium and plagioclase feldspars have been reported by *Alexandrov and Ryzhova* [1962], *Ryzhova* [1964], and *Ryzhova and Alexandrov* [1965]. The velocities were obtained at atmospheric pressure. *Simmons* [1964] reported compressional wave velocities for three directions in a single crystal of microcline under hydrostatic pressures of 0.03 to 10 kb. In the present paper compressional wave velocities are given for six directions in single crystals of albite and perthite to hydrostatic pressures of 10 kb.

Both single crystals were free of major imperfections. Refractive indices of the albite are as follows: $\alpha = 1.530$, $\beta = 1.534$, $\gamma = 1.541$. Composition of the albite obtained from universal-stage measurements of extinction angles varied from An_5 to An_8. The fine polysynthetic twinning of the microcline portion of the perthite made it impossible to obtain accurate refractive indices. Approximately 16% by volume of the perthite is composed of albite with a composition of An_4. Densities of both specimens are given in Table 1.

For orientation purposes the specimens have been considered monoclinic in symmetry. This simplification is justified by the repeated twinning present in both specimens [*Alexandrov and Ryzhova,* 1962]. Velocities for each feldspar were measured in directions which correspond to an orthogonal system of coordinates. The directions in the monoclinic system were converted to right-handed orthogonal coordinates (with axes X, Y, and Z) as follows: The Y axis of the orthogonal coordinate system coincides with the monoclinic crystallographic b axis. The Z axis is normal to the (001) cleavage planes. The X axis is perpendicular to the YZ plane and parallel to the crystallographic a axis.

The experimental technique is similar to that described by *Birch* [1960]. The velocities in Table 1 represent the first arrivals recorded on the oscilloscope screen. The absolute accuracy of the measurements is about 1% for pressures above 1 kb. At lower pressures the accuracy decreases because of a gradual onset of the first arrival.

Discussion. Measurements of compressional wave velocities in rocks show a rapid increase in velocity at pressures below 2 kb, then a slow increase with higher pressure. The large initial increase of velocity with pressure in rocks is attributed to closure of crack-like openings along grain boundaries [*Adams and Williamson,* 1923; *Birch,* 1961; *Walsh,* 1965]. Large initial changes in velocity with pressure are also characteristic of the single crystals of albite and perthite. A similar effect was reported by *Simmons* [1964], who found a rather rapid initial increase in velocity for a single crystal of microcline. In the cores cut from the single crystals of feldspar there are no openings along grain boundaries to produce the large increase in velocities at low pressures. However, the specimens do possess small cracklike openings along cleavage planes. A theoretical evaluation of the effect of cracks on the initial change in the elastic moduli of rocks has recently been presented by *Walsh* [1965]. Expressions for compressibility derived by Walsh show that cracks increase compressibility nearly as much as spherical pores of the same length. Cracks associated with cleavage planes may therefore

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TABLE 1. Compressional Wave Velocities as a Function of Pressure in Albite and Perthite

Sample		Density g/cm³	Orientation	Pressure, kb 0.03	0.1	0.2	0.4	0.6	0.8	1.0	2.0	4.0	6.0	8.0	10.0
Albite	1	2.63	100	4.58	5.87	5.05	5.23	5.30	5.33	5.36	5.44	5.53	5.59	5.63	5.66
	2	2.63	010	6.50	6.85	7.09	7.36	7.52	7.61	7.65	7.78	7.90	7.94	7.99	8.02
	3	2.62	001	4.80	5.45	6.10	6.84	7.02	7.13	7.19	7.35	7.44	7.49	7.55	7.58
	4	2.62	110	5.03	5.77	6.36	6.69	6.83	6.89	6.93	7.01	7.07	7.10	7.14	7.17
	5	2.62	101	3.78	4.18	4.65	4.96	5.10	5.18	5.24	5.35	5.44	5.51	5.56	5.63
	6	2.62	011	5.50	5.81	6.16	6.38	6.48	6.50	6.54	6.59	6.65	6.70	6.76	6.79
Perthite	1	2.58	100	3.94	4.25	4.48	4.75	4.90	4.97	5.02	5.16	5.27	5.31	5.35	5.39
	2	2.57	010	6.40	6.81	7.12	7.46	7.63	7.73	7.84	8.07	8.18	8.22	8.26	8.29
	3	2.58	001	3.80	4.35	5.07	5.93	6.37	6.62	6.90	7.20	7.37	7.42	7.44	7.45
	4	2.58	110	5.72	5.93	6.21	6.45	6.57	6.61	6.65	6.76	6.86	6.90	6.94	6.98
	5	2.58	$\bar{1}01$	4.19	4.60	5.10	5.65	6.09	6.28	6.53	6.79	7.01	7.07	7.09	7.12
	6	2.58	011	4.57	4.66	4.99	5.48	5.67	5.80	5.91	6.16	6.34	6.38	6.43	6.47

produce large effects on initial velocities in single crystals even though the porosity of a single crystal is small compared with that of a rock.

The feldspars have perfect cleavage parallel to (001) and a good cleavage parallel to the (010) plane. In addition, the perthite studied has parting parallel to (110) and ($\bar{1}10$). The albite has parting approximately parallel to the ($\bar{2}01$) and (101) planes. The cleavages are better developed than the partings and thus have a greater influence on low-pressure velocities. The effect of cleavage cracks on the initial velocities in single feldspar crystals is related to the orientation and quality of the cleavages. For each direction of measured velocity the distribution of cleavage planes is anisotropic; i.e., the cleavage fissures have definite angular relationships to the directions of measured compressional wave velocities. Cleavage cracks normal to the propagation direction of compressional waves affect velocities differently from cleavages which are parallel to the transmission direction (Figure 1). The largest initial increase in velocity is characteristic of propagation normal to the (001) cleavage planes. The transmitted energy cannot bypass the (001) cleavage fractures and thus has relatively low velocities at low pressures. Propagation normal to the (010) cleavage planes results in a less rapid increase in velocity with pressure because the (010) cleavage is of lower quality than the (001) cleavage. Energy propagating parallel to the (001) and (010) cleavage planes largely bypasses the cracks and hence shows the smallest initial increase of velocity with pressure. The relationships between the initial velocity changes in the (110), (011), and (101) directions and the cleavages are obscured by the complex partings of the single crystals. At pressures above 1 to 2 kb all cleavage cracks and partings have presumably closed, and the velocities are related to the elasticity of the solid crystals.

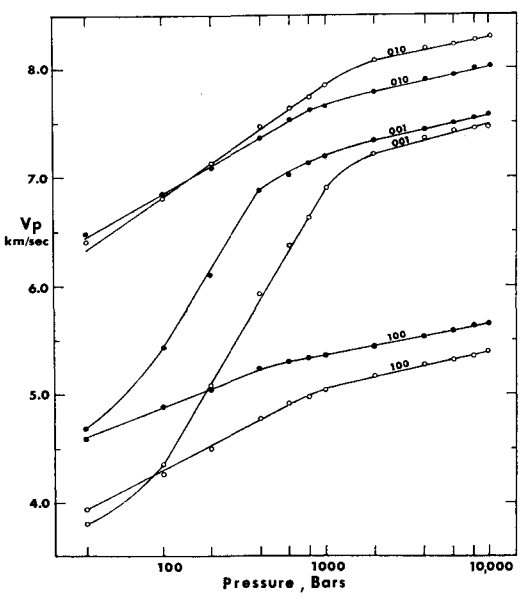

Fig. 1. Velocity versus the logarithm of pressure for propagation directions normal and parallel to the cleavages of albite and perthite. Dots indicate albite; circles, perthite.

Velocity anisotropy in a single crystal reflects

TABLE 2. Cell Dimensions of Various Alkali Feldspars

Feldspar	*a*, A	*b*, A	*c*, A	Reference
High-albite	8.149	12.880	7.106	*Ferguson et al.* [1958]
Low-albite	8.139	12.789	7.156	*Ferguson et al.* [1958]
Orthoclase	8.5616	12.9962	7.1934	*Cole et al.* [1949]
Intermediate-microcline	8.5784	12.9600	7.2112	*Bailey and Taylor* [1955]
Maximum-microcline	8.57	12.98	7.22	*MacKenzie* [1954]

the anisotropy in the crystal structure and in particular the directional rigidity of the crystal lattice. The correlation of elastic wave velocities in silicates with crystal structure has been studied by *Alexandrov and Ryzhova* [1961*a*, *b*, 1962]. They found, for example, high compressional wave velocities for propagation parallel to the silicon-oxygen tetrahedral chains in pyroxenes and amphiboles. Similarly, velocities along silicon-oxygen tetrahedral layers in mica are much higher than velocities in a propagation direction normal to the layers. Thus the chains and layers of the inosilicates and phyllosilicates are presumably the most rigid elements of the crystal structures.

The data in Table 1 indicate that compressional wave velocities vary considerably with propagation direction in single feldspar crystals. The correlation of elastic wave velocities with the feldspar structure is complicated by the lack of clearly expressed structural features, such as continuous chains or layers characteristic of the pyroxenes, amphiboles, and micas. However, a comparison of velocities at high pressure for propagation directions parallel to the feldspar *a* and *b* axes and in the (001) direction (Figure 1) shows that compressional wave velocities parallel to the *a* axis are the lowest in value. Since velocities are apparently lowest in directions along which the crystal lattice is the easiest to deform, the least rigid direction in feldspar approximates the *a* axis. The elastic anisotropy of the feldspar framework is also illustrated by a comparison of cell edges for various alkali feldspars (Table 2). The *a* cell edges of potassium and sodium feldspars are markedly different, whereas the *b* and *c* cell edges are almost identical. Thus the substitution of smaller sodium cations for potassium in the interstices of the $(Si, Al)O_4$ framework is accompanied by a large contraction in *a* and little change in the *b* and *c* cell edges. The directional rigidity of the feldspar lattice as indicated by velocity measurements is therefore in agreement with the elastic adjustment of the feldspar framework to cations different of sizes.

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