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# MUSCOVITES WITH ISOTROPIC AND ANISOTROPIC ELASTICITY IN THE BASAL PLANE[1]

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ABSTRACT

Studies on the elastic behavior of muscovite revealed that some specimens were found to be elastically isotropic in the basal plane while some others exhibited pronounced anisotropy. X-ray topographic examination of these crystals revealed a corrugated structure of the basal plane of muscovite in 'anisotropic' samples. If measurements are carried out on corrugation-free samples, no noticeable anistropy of the elastic behavior in the basal plane is observed.

## INTRODUCTION

The minerals belonging to the mica group are ionic solids and have long been important in the electronic industry by virtue of their unique electrical and thermal properties. An enormous amount of research work has been and is still being carried out on the various aspects of crystal growth of mica as well as the above mentioned physical properties. In fact, in two recent literature surveys (Roy, 1952; Vedam and Vand, 1966) it was found that over 600 papers have been published on these topics alone, without taking into consideration the various papers dealing with its commercial exploitation, economic aspects, etc.

The most abundant form of mica, muscovite, possesses one other extremely useful characteristic, namely its mechanical behavior. In particular, mention may be made of its extremely high flexibility, almost perfect elastic behavior till fracture, and fairly high strength in its basal plane. A literature search reveals that only one paper (Alexandrov and Ryzhova, 1961) has so far been devoted directly to the determination of mechanical properties of biotite, phlogopite and muscovite micas, and even in this case the investigators considered all these micas to belong to the hexagonal symmetry as regards their elastic behavior. They confirmed this by measuring the velocities of elastic waves traveling along the [100], [010] and [110] directions of the crystals. In phlogopite and biotite the velocities along the above mentioned three directions coincided within the limits of experimental error. However, in the case of muscovite a deviation from this condition appeared. These authors did not ex-

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amine the causes of this deviation, nor were the experimental specimens well characterized.

Our own preliminary measurements revealed considerable anisotropy of the elastic behavior in the basal plane of muscovite in some samples, while others exhibited isotropic behavior, even though all the specimens exhibited identical optical characteristics. This article reports the results of the study on the origin of this anomalous elastic behavior.

## Experimental

Since the elastic properties of muscovite can be seriously influenced by the irregularities like polytypism and twinning or any macroscopic defects (bubbles, cracks or exfoliation, twinning, etc.), all samples used were carefully examined by the optical microscope. Polytypism and twinning can be revealed by anomalies of optical interference figures as described by Bloss, Gibbs, and Cummings (1959). A large number of selected muscovite samples from different localities were also examined by the X-ray precession camera for the space group determination and possible twinning.

The layer structure of muscovite crystals does not allow refinement of physical dimensions of the specimens by grinding or chemical polishing because of exfoliation near the edges owing to penetrating abrasive particles or liquids between the sheets. Hence the final required physical dimensions of rectangular shape must be achieved by cutting only. Again, any type of mechanical cutting invariably results in ruptures and cracks of sheets. To prevent this cracking, muscovite sheets were inserted between highly polished metal blocks and compressed with a force sufficient to prevent splitting. Then the sheets were cut as close as possible to the edges of the blocks, with a 0.15 mm thick 40 teeth/cm jigsaw.

The thickness of samples had to be adjusted for each sample individually due to differences in the cleavage-easiness of sheets. The average thickness of primary cleaved sheets was 0.3 mm. The numerous cleavage steps of about 0.05 mm height were removed by a subsequent repeated cleaving until a perfect cleavage was obtained. The average thickness of muscovite sheets freed from splitting steps was about 0.15 mm.

The various details of the experimental set up for the determination of the Young's modulus by bending experiments (pure flexure) and the mathematical expression involved in evaluating the Young's modulus from the experimental data are well known (Voigt 1910, Love 1934, Cady 1964) and hence are not decribed here. All the measurements were carried out with an Instron precision universal testing machine, with a specially built bending jig described below.

The anisotropy of elastic properties of muscovite in the basal plane is expected to be very low, potentially in the range of experimental errors. The experimental error of the Instron instrument, if all the mechanical and electrical units involved in the measurement are considered, was estimated to be $\pm 1.5$–$2.0$ percent. The experimental error in bending experiments can be significant due to the inaccuracy in the alignment of the bending device itself in view of the specific properties of muscovite. Hence, to keep the experimental error as low as possible requires devoting special attention to the three-point bending device construction. Due to the high flexibility of muscovite the supporters for the knife edges had to be built higher than usual. To eliminate the friction at the knife edges caused by sliding of muscovite during the measurement, a highly polished steel cylindrical rod suitably supported was initially chosen instead of the knife edge. However, even this was found to introduce some friction as evidenced by the hysteresis in the stress-strain curves. Hence these cylindrical rods were supported with frictionless ball bearings and the stress-strain curves

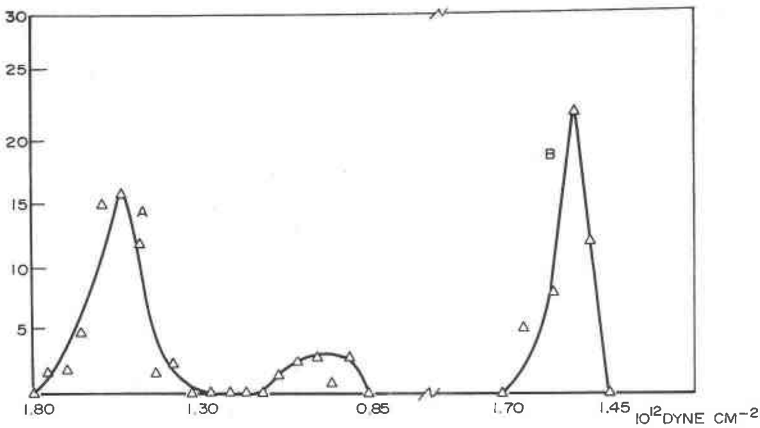


FIG. 1. Distribution curves of the Young's modulus of muscovite in the basal plane (the ordinate represents the frequency of observation and the abscissi represents the values of Young's modulus).

A. Values of Young's modulus greater than $1.30 \times 10^{12}$ dyne/cm$^2$ are obtained from "corrugation free" specimens and those less than this value are from samples with corrugations.

B. Data on selected corrugation-free specimens.

measured on such frictionless revolving supporters were smooth, retractable, and linear, even when very high stresses were applied.

Dimensions of samples were based on availability of large enough specimens, so that a number of samples at each of the different orientations in the basal plane can be fabricated from the same original specimen. As described above the thickness of the sample was within 0.15–2.0 mm limit. After some preliminary experiments the width of samples was chosen to be 20 mm. The optimum length of 30 mm of the sample was also chosen experimentally.

The experimental error of stress-strain curve measurements was estimated on the basis of the reproducibility of measurements of selected flat samples of muscovite to be ± 3 percent.

## RESULTS AND DISCUSSION

The values of the Young's moduli of muscovite were determined along [100], ⟨110⟩, ⟨310⟩, and [010] directions in the basal plane. It was noticed that the results obtained on a number of specimens exhibited considerable scatter about the mean value. If a distribution curve was plotted from all the values obtained regardless of the orientation, two separate maxima were clearly visible (see Fig. 1-A). The ratio of 1:5 of these maxima was too large to be regarded as a manifestation of the crystal anisotropy but, rather, should be attributed to some defects randomly occurring in some muscovite crystals. This distribution curve was plotted from a relatively small number of measurements and there were no indications as to what extent the unknown factors might have influenced the elastic behavior of muscovite samples; therefore, the samples for further investigation were selected according to the experimental error limits rather than with regard to maxima of the distribution curve.

Since all these samples did not reveal any optically observable differences amongst them, they were examined by Berg-Barrett X-ray diffraction topography (Caslavsky and Vedam, 1970). The topographs obtained revealed remarkably sharp contrasting stripes or striations in most of the specimens. All specimens which exhibited values of the Young's modulus lower than $1.30 \times 10^{12}$ dyne/cm$^2$ exhibited these striations. The striations usually ran throughout the entire crystal in one direction or abruptly changed their direction. In any case they were always confined to one or two directions. In the latter cases the following combinations of directions were observed: [100] with [110] or [$1\bar{1}0$], and [110] with [$1\bar{1}0$].

A detailed analysis of these striations observed in the Berg-Barrett topographs and their origin have already been described elsewhere (Caslavsky and Vedam, 1970). It was concluded there that this unusual contrast arises from the corrugation of the basal planes of the muscovite mica.

A comparison of the Young's modulus data with the corrugation topology revealed a strong correlation. The correlation of Young's moduli with the corrugation topology is schematically represented in Figure 2. In every case the axis of bending is parallel with the width of the sample and the values of the Young's modulus given are for this direction.

It is seen that the corrugation lowers the Young's modulus value. Minimum values were obtained on samples where the corrugation was parallel to the axis of bending. This fact was confirmed by a measurement of two samples cut from the same muscovite sheet corrugated in only one direction. The sample for which the deformation axis was perpendicular to the corrugation and a second sample for which the deformation axis was parallel with the corrugation gave the Young's modulus values $1.36 \times 10^{12}$ dyne/cm$^2$ and $0.86 \times 10^{12}$ dyne/cm$^2$, respectively. Owing to the change in the direction of corrugation in the muscovite sheets, attempts to prepare more identical sample-pairs from one muscovite sheet were unsuccessful. However, several samples cut from various sheets of muscovite with corrugation parallel and perpendicular to the deformation axis were measured to determine the relation between the density or the number of corrugations and the Young's modulus values. No noticeable correlation could be observed but the determined Young's moduli of corrugated samples were systematically lower when compared with the average values of non-corrugated samples. Hence it is obvious that any

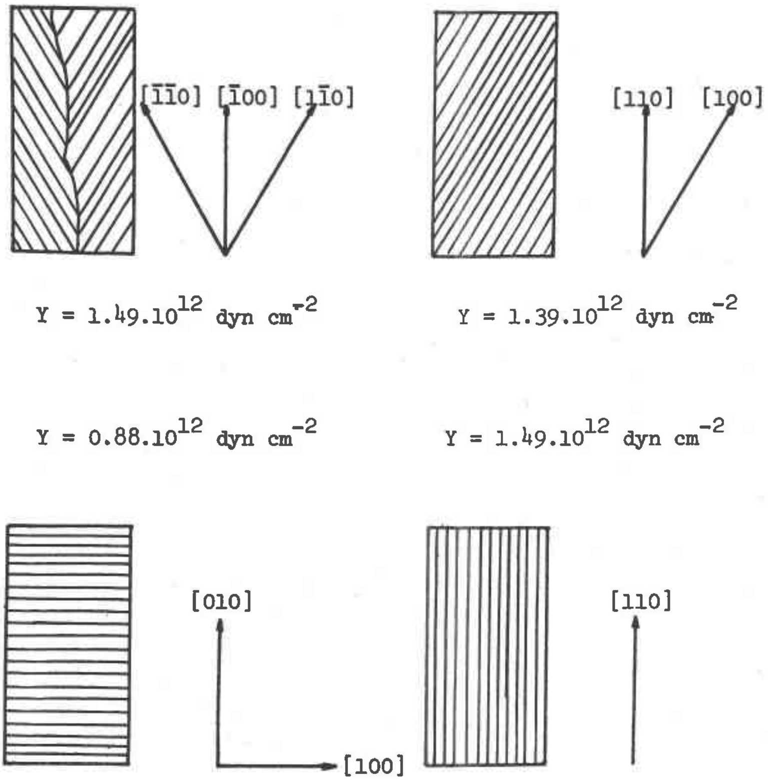


FIG. 2. Schematic representation of relation between direction of corrugation and value of Young's modulus. The axis of bending is parallel with the width of sample, and the values of the Young's modulus given are for this direction.

conclusions regarding the true mechanical properties of the intrinsic material be made on the results obtrined on unambiguously corrugation-free crystals.

Hence one would expect the muscovite sheets free of corrugation to have values statistically distributed within the experimental error limits. Therefore, fifty samples selected from the corrugation-free muscovite sheets were cut for further studies. The distribution curve (Fig. 1-B) plotted from these values regardless of crystallographic orientation showed only one maximum with an average value of $1.59\times10^{12}$ dyne/cm$^2$. For comparison with the values of the elastic constants reported by Alexandrov and Ryzhova (1961) their values of the elastic constant $c_{ij}$ were converted to $s_{ij}$ from which the Young's modulus along [100] direction of muscovite was calculated. The value so obtained, $1.65\times10^{12}$

dyne/cm$^2$, is in good agreement with the value obtained by the authors' measurements.

The present studies also revealed that if measurements are carried out on corrugation-free speciemns, ıo noticeable anisotropy of the Young's modulus in the basal plane exceeding the experimental error limits is observable.

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