The measurement of large optic axial angles with the universal stage

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Summary. A comparison has been made of the relative speed, accuracy, and precision of several methods of measuring large optic axial angles with the universal stage. It is concluded that a method based on the direct location of a single optic axis and the application of the Biot–Fresnel law will frequently be the most satisfactory when only the standard, low refractive index centre plate for the stage is available. If a centre plate of high refractive index is employed, however, good results can normally be obtained by using the more rapid method based on the direct location of both optic axes.

THERE are three main methods of measuring 2V with the universal stage: by using isogyres to locate both optic axes directly (the so-called 'direct' method); by locating one optic axis directly and deriving the position of the second axis indirectly; or by deducing the position of both optic axes by some indirect method. In the past, most observers have probably felt that the 'direct' method yielded the most accurate results, as the process of locating both optic axes conveys the impression that the precision of the operation is high. Although it has been shown (Fairbairn and Podolsky, 1951; Munro, 1963) that this impression is correct when only small angles of tilt of the stage are required (i.e. when 2V is small), it has also been established (Wyllie, 1959; Munro, 1963) that when large angles of tilt are necessary, refraction in the central assembly of the stage may introduce considerable errors into the measurement.

Measurement of a large optic axial angle is also made difficult by another factor, namely, that if the crystals of a mineral are randomly oriented in a thin section, it will be possible to locate both optic axes directly only in the comparatively few crystals that are oriented with a bisectrix approximately perpendicular to the plane of the thin section. As a consequence, the direct measurement of 2V in such a specimen normally involves a laborious and time-consuming search for suitably oriented grains. In view of these difficulties, and in view of the recent advances that have been made in the development of indirect methods of measuring 2V (e.g. Joel and Muir, 1958; Joel, 1964; Tocher, 1964*c*), it seems desirable to investigate the possibility that some of these indirect methods might yield more accurate results than the direct method when 2V is large, with no more expenditure of time and effort.

The investigation summarized in the accompanying table was carried out on olivine crystals in thin sections of an olivine-gabbro from the Caledonian basic complex at Huntly, Aberdeenshire. These crystals appear to have uniform optical properties throughout the rock, and display no evidence of zoning. Only the 'orthoscopic'[1] method was employed, for although the 'conoscopic' method (in which a Bertrand lens is used to produce interference figures in the focal plane of the ocular) sometimes enables 2V to be measured with higher accuracy (Munro, 1963), it can only be used when the crystals are reasonably large and are optically uniform. The 'orthoscopic' method, on the other hand, can be employed on small, zoned crystals, or (as is often necessary in a thin section) on crystals that consist of a mosaic of slightly disoriented fragments, and is thus capable of more general application.

In general, only sufficient measurements were made with each technique to provide some indication of the relative speed, accuracy, and precision of the different methods, but in the case of the 'doubling' technique, use was also made of the data obtained in the course of a petrofabric analysis of the gabbro (sample 120 olivines).

Discussion

The similarity in the average values for $2V_\alpha$ yielded by all of the methods (88–89°) suggests that it is legitimate to make comparisons between the different groups of measurements and to assume that the true value for $2V_\alpha$ lies in the range $88\frac{1}{2}° \pm \frac{1}{2}$ %.

Direct measurements. The range of variation (1–4°) of the measurements made about a particular bisectrix is smaller than in any of the other groups of measurements, suggesting that observational errors are smaller when this method is employed. However, the measurements made using the standard centre plate supplied by Leitz (*n* 1·520) show the discrepancies between the values for 2V obtained by measurements

[1] The illuminating beam passing through the thin section does not consist of parallel rays when a normal microscope and universal stage are employed (Munro, 1963), and hence truly orthoscopic illumination can never be achieved with this equipment.

over different bisectrices that have been noted in earlier investigations (Johnston, 1953; Wyllie, 1959), which have been shown to be due to refraction in the central assembly of the stage. The total error in a single measurement due to this factor and to observational errors may be large (up to 4°).[1]

TABLE I. 'Orthoscopic' measurements on olivine crystals in olivine–gabbro, Sinsharnie quarry, Huntly, Aberdeenshire. Segments, *n* 1·717; centre plate, *n* 1·520 (except where specified); U.M. 3 objective; Leitz CM microscope and four-axis universal stage. Objective diaphragm closed to minimum aperture, sub-stage diaphragm fully open.

	Method		No. of Measure-ments	Range of Values of $2V_\alpha$	Average $2V_\alpha$	
Both optic axes located directly	Measurement over α		12	84 –87½°	86°	88½°
	,, ,, γ		8	89 –93°	91°	
	,, ,, α	Centre plate *n* 1·720	12	87 –90°	88°	89°
	,, ,, γ	Centre plate *n* 1·720	6	89½–91°	90°	
One optic axis located directly	Second axis located by 'doubling' over α		50	81 –97°	88°	
	Second axis located by 'doubling' over γ		22	83 –94°	88½°	
	Second axis located by using the Biot–Fresnel law (Joel and Muir, 1958)		20	86 –92°	88½°	
Both optic axes located indirectly using conical extinction curves (Joel and Tocher, 1964) and a progressive approximation method (Tocher, 1964c)			10	85½–94°	89°	

It is apparent, therefore, that when the refractive index of the main component of the central assembly of the stage differs appreciably from that of the segments, several measurements must be made over each bisectrix in order to obtain mean values for $2V_\alpha$ (or $2V_\gamma$) over α and for $2V_\alpha$ (or $2V_\gamma$) over γ, which can then be averaged to provide a reasonably accurate final value for $2V_\alpha$ (or $2V_\gamma$). This is an operation that will often involve a lengthy and time-consuming search for suitably oriented grains—thus, in the course of the petrofabric analysis

[1] These errors are larger than those recorded in a previous investigation (Munro, 1963, Table 2). This is partly because bisectrices were often initially inclined to the microscope axis in the olivines studied here, necessitating the use of higher angles of tilt than those previously employed, but, in addition, errors arose because the olivine crystals in the thin sections of the Sinsharnie gabbro generally consist of a mosaic of small fragments, each with the indicatrix in a slightly different orientation.

of the Sinsharnie gabbro it was found that only 12 of the 120 randomly oriented crystals examined were in suitable orientations for the direct measurement of $2V_\alpha$ over α, and only 4 for the direct measurement of $2V_\alpha$ over γ.

The errors due to refraction in the central assembly of the stage can be reduced if a centre plate with approximately the same refractive index as the segments is employed (Munro, 1963), and it can be seen from the table above that the discrepancy between the direct measurements made over different bisectrices is almost eliminated by using a centre plate of n 1·720. With this plate, therefore, virtually the only source of error is the lack of precision in locating the optic axes, and a reasonably accurate value for 2V can be obtained from a much smaller number of measurements.

A similar improvement in accuracy could also be obtained by using segments with approximately the same refractive index as the standard centre plate (n 1·520). However, unless the refractive indices of the mineral under study are considerably less than that of this plate, 2H will now be appreciably larger than 2V, and an even smaller proportion of the crystals will be suitably oriented for the direct measurement of 2V.

Single axis measurements. The 'doubling' method—which involves the doubling of the measured angle between an optic axis and a bisectrix—has been widely used in the past as a means of determining 2V. Like all methods which are dependent on locating the position of a single optic axis, this method can normally be applied to the majority of the crystals in a thin section when they are in random orientation (e.g. this method could be applied to 72 out of the sample of 120 olivines from the Sinsharnie gabbro). In addition, the accuracy with which a single optic axis can be located is often high, because this operation in many instances requires only small angles of tilt of the stage. However, as the results of this investigation show, and as previous investigators have also noted (Turner, 1942; Hallimond, 1950; Joel and Muir, 1958), there is often a considerable error in locating a principal optical plane 'orthoscopically' with the universal stage. Any errors due to this deficiency will be magnified by the 'doubling' procedure, and, as a result, values for 2V may sometimes be in error by as much as 7–8°. In consequence, a much larger number of measurements will have to be made with this technique before the degree of accuracy is similar to that obtainable by the other methods.

The second method based on locating the position of a single optic axis (Joel and Muir, 1958) utilizes the Biot–Fresnel law and involves the determination of the vibration directions associated with a number of chosen wave-normals. Only small angles of tilt of the stage need be used, and, as the table shows, this method is capable of yielding results in which the error is no greater than 2–3°. Indeed, if crystals in a favourable orientation are available—i.e. crystals in which wave-normals making appreciable angles with the optic axial plane can be employed, then the errors will generally be smaller than this figure. Although each measurement is a fairly lengthy operation (*c.* one hour) there is normally no need to search for suitably oriented crystals, and a reasonably accurate value for 2V can be obtained from comparatively few measurements.

Wholly indirect method. The results of recent research (e.g. Joel, 1964; Joel and Muir, 1964; Tocher, 1964 *a*, *b*, *c*) indicate that 2V can be determined wholly indirectly with the universal stage by a number of different methods, although, as yet, there is no record of the use of any of these methods as practical determinative techniques. These methods, which are generally based on extinction measurements, require more manipulation of the universal stage and stereographic net than the other methods discussed above, but have the advantages that they may be used on any crystal, irrespective of its orientation, and are unlikely to be subject to refraction errors, as they can be employed with only small angles of tilt of the stage. Of the various methods available, that adopted here involved two processes: firstly the precise location of the principal vibration directions by means of conical extinction curves (Joel and Tocher, 1964) and, secondly, the progressive approximation to the optic axes, using certain simple geometrical relations between the vibration directions associated with a particular wave-normal and the axes, principal planes, and circular sections of the indicatrix (Tocher, 1964*c*). The results obtained suggest that only a small number of measurements are necessary in order to obtain a reasonably accurate value for 2V by this method. Indeed, if one of the measurements included in the table (2V = 94°, in which small errors in locating and plotting extinction positions have probably been magnified) is discarded, then the range of variation of the remaining nine indirect measurements is no more than $4\frac{1}{2}$°—i.e. it is comparable to the range of variation displayed by some of the direct measurements.

Conclusions

All of the methods employed appear to be capable of yielding results of similar accuracy, but the labour involved and the precision obtained in a single measurement of a large optic axial angle varies greatly. In general, 'direct' measurements appear to be the most precise (i.e. are subject to smaller observational errors) and although comparatively few crystals in a thin section may be in a suitable orientation, this method will probably be the most rapid when refraction errors in the central assembly are unimportant (i.e. when the segments and the centre plate of the stage have approximately the same refractive index). This implies that, with the standard universal stage centre plate, the direct method will be the most satisfactory only when the low refractive index segments are used. The mineral under study must then be of low refractive index, as 2H will otherwise be considerably greater than 2V, and very few measurements will be possible in a normal thin section.

If a centre plate of high refractive index is available, however, the 'direct' method can be used with high refractive index segments for most rock-forming minerals, and it may often be advantageous to use such a combination of segments and centre plate, even when the mineral is of low refractive index, since direct measurements will then be possible in a higher proportion of the crystals.

If no centre plate of high refractive index is available then, in most instances, the most satisfactory method of measuring a large optic axial angle appears to be that of Joel and Muir (1958), since observational errors with this method are often low, and some compensation for the length of time necessary for a measurement is provided by there being little need to search for suitably oriented crystals.

It seems probable that the accuracy and precision of the measurements made by a wholly indirect method will often be as high as in measurements made by any of the other techniques used in this investigation. However, as these indirect methods are laborious and time consuming, they will normally only be employed in special circumstances—e.g. when the optic axial angle of every crystal of the mineral under study must be measured, or when only a limited number of crystals, all unfavourably oriented for the other methods, is available.

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References

FAIRBAIRN (H. W.) and PODOLSKY (T.), 1951. Amer. Min., vol. 36, p. 823.
HALLIMOND (A. F.), 1950. Mining Mag., vol. 83, pp. 12 and 77.
JOEL (N.), 1964. Min. Mag., vol. 33, p. 769.
—— and MUIR (I. D.), 1958. *Ibid.*, vol. 31, p. 878.

JOEL (N.) and MUIR (I. D.), 1964. Amer. Min., vol. 49, p. 286.
—— and TOCHER (F. E.), 1964. Min. Mag., vol. 33, p. 853.
JOHNSTON (R.), 1953. Geol. Mag., vol. 90, p. 161.
MUNRO (M.), 1963. Amer. Min., vol. 48, p. 308.
TOCHER (F. E.), 1964*a*. Min. Mag., vol. 33, p. 780.
—— 1964*b*. *Ibid.*, p. 1038.
—— 1964*c*. Amer. Min., vol. 49, p. 1622.
TURNER (F. J.), 1942. Amer. Journ. Sci., vol. 240, p. 571.
WYLLIE (P. J.), 1959. Amer. Min., vol. 44, p. 49.

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