THE AMERICAN MINERALOGIST, VOL. 48, MARCH-APRIL, 1963

ERRORS IN THE MEASUREMENT OF 2V WITH THE UNIVERSAL STAGE

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ABSTRACT

Values of 2V obtained with the universal stage from thin sections of olivine and topaz crystals have been compared with highly accurate values obtained by direct measurement on spheres cut from the same crystals. It is found that many of the universal stage measurements contain errors due to refraction in the central assembly on the stage. These errors invariably increase when the angle of tilt of the stage and the refractive index of the segments are increased, and they are also greater when very small sub-stage diaphragm apertures are used. They are generally greater for orthoscopic than for conoscopic measurements, and the size of the errors in the former also appears to depend to a marked extent on the refractive index of the center plate of the stage, on the type of objective employed, and on the aperture of the objective diaphragm.

INTRODUCTION

When the optic axial angle of a mineral is measured with the universal stage the results are frequently quoted as being correct to the nearest degree or half degree—thus implying that there is a widespread belief in the accuracy of this type of measurement. Support for this belief would appear to be provided by the investigations of Hallimond (1950), who concluded that the error in locating an optic axis with the universal stage might be no more than a quarter of a degree, and of Fairbairn and Podolsky (1951), who found that the error in measuring an optic axial angle with the stage is sometimes no more than a few tenths of a degree. However, no systematic attempt has ever been made to show that this standard of accuracy can invariably be achieved, and, indeed, Johnston (1953) and Wyllie (1959) have shown that in some instances when measurements are made over both the acute and the obtuse bisectrix, there is a discrepancy between the two measurements. Wyllie accounted for these discrepancies in an apparently satisfactory manner by allowing for refraction in the central assembly on the stage, and, although Hess (1960, p. 15) subsequently obtained results which appear to contradict those of Johnston and Wyllie, some doubt must remain regarding the accuracy of all measurements of optic axial angle made with the universal stage.

As Johnston (1953) and Wyllie (1959) made conoscopic measurements on forsteritic olivines alone, while Fairbairn and Podolsky (1951) and Hess (1960) made orthoscopic measurements on a number of minerals, but not on olivine, it is conceivable that contradictory results have sometimes been obtained because measurements have been made on different minerals using different techniques. However, Schumann (1951), who used both conoscopic and orthoscopic methods to measure the optic axial angle of certain minerals, found that, although the conoscopic measurements on any given mineral tended to be more consistent than the orthoscopic measurements, the average of both sets of measurements tended to be similar.

In the present investigation an attempt has been made to clarify this confused situation by making repeated measurements of optic axial angle in thin sections with the universal stage. Both orthoscopic and conoscopic methods and a number of different objectives, pairs of segments and stage center plates have been used so that the effects produced by employing different techniques and equipment can be assessed. The magnitude of any errors in these measurements has been determined by comparing them with the direct measurements of optic axial angle made on spheres cut from the specimens used to provide the material for the thin sections (*cf.* Fairbairn and Podolsky, 1951).

SPECIMENS, STANDARDS AND PRELIMINARY DETERMINATIONS

The choice of minerals for study was governed by the following conditions; the refractive index had to be close to that of one of the pairs of segments employed (1.55–1.72) in order to avoid errors due solely to large refractive index differences; the optic axial angle had to be greater than 60°, so that something approaching the maximum error in measurement might be encountered (*cf.* Wyllie, 1959); a bisectrix had to be approximately normal to a readily identifiable crystallographic plane to facilitate the making of suitably orientated thin sections; the physical properties had to be such that a sphere could be made without undue difficulty (see Appendix), and the crystals from which both spheres and thin sections were made had to be transparent, optically homogeneous and free from defects. A crystal of olivine and another of topaz were found to be the only available specimens which satisfied all the above conditions.

The optic axial angle of both minerals was measured directly on the spheres mounted between crossed polaroids on a one-circle goniometer. For olivine $2V_\alpha = 91.75° \pm 0.1°$; for topaz $2V_\gamma = 65.3° \pm 0.2°$. Due to the ambiguity of the universal stage measurements (Table 1) the sign of olivine had also to be determined on the sphere. Refractive indices were determined on cleavage fragments—(010) in the case of olivine, (001) for topaz, by means of the standard oil immersion technique. For olivine $\beta = 1.670 \pm 0.003$; for topaz $\beta = 1.612 \pm 0.003$. Similar fragments provided material for the preparation of suitably orientated thin sections. The homogeneity of the crystals was established in two ways—by making independent refractive index determinations on several cleavage fragments, and by making numerous determinations of optical orientation and 2V with the universal stage at different points in the thin sections.

TABLE 1. UNIVERSAL STAGE MEASUREMENTS SHOWING THE EFFECT OF CHANGING SEGMENTS, CENTER PLATES AND OBJECTIVES

Ref. Ind. of Segments n	Ref. Ind. of Center Plate	Objective	No. of Measure ments	Average 2V (ortho.)	Average 2V (cono.)	2V(sphere) −Average 2V(ortho.)	2V(sphere) −Average 2V(cono.)
Olivine			All values for $2V_\alpha$				
1.717 $n-\beta=0.047$	1.520	U.M.1	6	87.5°	90.8°	4.25°	0.95°
		U.M.2	6	86.9°	90.9°	4.85°	0.85°
		U.M.3	6	86.3°	91.0°	5.45°	0.75°
	1.720	U.M.1	4	90.4°	90.8°	1.35°	0.95°
		U.M.2	4	89.6°	90.7°	2.15°	1.05°
		U.M.3	4	89.3°	90.7°	2.45°	1.05°
1.649 $n-\beta=-0.021$	1.520	U.M.1	4	89.0°	90.9°	2.75°	0.85°
		U.M.2	4	88.5°	91.0°	3.25°	0.75°
		U.M.3	14	87.7°	91.0°	4.05°	0.75°
	1.653	U.M.1	4	90.6°	91.1°	1.15°	0.65°
		U.M.2	4	89.8°	91.2°	1.95°	0.55°
		U.M.3	4	89.3°	91.1°	2.45°	0.65°
	1.720	U.M.1	4	90.9°	91.0°	0.85°	0.75°
		U.M.2	4	90.5°	91.0°	1.25°	0.75°
		U.M.3	4	90.2°	90.9°	1.55°	0.85°
1.557 $n-\beta=-0.113$	1.520	U.M.1	4	91.0°	91.3°	0.75°	0.45°
		U.M.2	4	90.5°	91.3°	1.25°	0.45°
		U.M.3	4	90.2°	91.4°	1.55°	0.35°
	1.653	U.M.1	8	91.6°	91.6°	0.15°	0.15°
		U.M.2	8	91.6°	91.6°	0.15°	0.15°
		U.M.3	8	91.6°	91.6°	0.15°	0.15°
	1.720	U.M.1	4	91.8°	91.7°	−0.05°	0.05°
		U.M.2	4	92.1°	91.7°	−0.35°	0.05°
		U.M.3	4	92.3°	91.7°	−0.55°	0.05°
Topaz			All Values for $2V_\gamma$				
1.717 $n-\beta=0.105$	1.520	U.M.1	7	64.2°	64.7°	1.1°	0.6°
		U.M.2	7	63.4°	64.7°	1.9°	0.6°
		U.M.3	7	62.9°	64.7°	2.4°	0.6°
	1.720	U.M.1	5	64.6°	64.8°	0.7°	0.5°
		U.M.2	5	64.1°	64.7°	1.2°	0.6°
		U.M.3	5	64.0°	64.6°	1.3°	0.7°
1.649 $n-\beta=0.037$	1.520	U.M.1	5	64.6°	64.9°	0.7°	0.4°
		U.M.2	5	64.0°	65.2°	1.3°	0.1°
		U.M.3	20	63.6°	65.2°	1.7°	0.1°
	1.653	U.M.1	5	64.8°	65.1°	0.5°	0.2°
		U.M.2	5	64.2°	65.1°	1.1°	0.2°
		U.M.3	5	64.0°	65.1°	1.3°	0.2°
	1.720	U.M.1	10	64.8°	65.0°	0.5°	0.3°
		U.M.2	10	64.5°	65.0°	0.8°	0.3°
		U.M.3	10	64.4°	65.0°	0.9°	0.3°
1.557 $n-\beta=-0.055$	1.520	U.M.1	5	65.3°	65.3°	0.0°	0.0°
		M.U.2	5	64.8°	65.3°	0.5°	0.0°
		U.M.3	14	64.5°	65.3°	0.8°	0.0°
	1.653	U.M.1	5	65.3°	65.3°	0.0°	0.0°
		U.M.2	5	65.4°	65.3°	−0.1°	0.0°
		U.M.3	5	65.4°	65.3°	−0.1°	0.0°
	1.720	U.M.1	5	65.3°	65.3°	0.0°	0.0°
		U.M.2	5	65.4°	65.3°	−0.1°	0.0°
		U.M.3	5	65.5°	65.3°	−0.2°	0.0°

UNIVERSAL STAGE MEASUREMENTS

Microscopic equipment. Two Leitz CM microscopes and several U.M. 1 (×5; n.a. 0.10), U.M.2 (×10; n.a. 0.22) and U.M.3 (×20; n.a. 0.33) objectives were used. Although Leitz recommends that U.M.3 objectives should be used with a special condenser of large numerical aperture capable of producing an illuminating beam which will completely fill the objective, satisfactory results—particularly interference figures, were obtained with all the objectives used in this investigation when the standard condenser for the CM microscope (n.a. ca. 0.22) was employed. This is in accord with the observations made by other investigators (Schumann, 1937, 1941, 1951; Hallimond, 1953) which indicate that satisfactory interference figures can be obtained with the universal stage when a number of different substage assemblies are used.

Several Leitz U.T.4 (four axis) universal stages and several pairs of segments of refractive index 1.557, 1.649 and 1.717 were employed. Measurements were made using the standard center plates for the stages (refractive index 1.520) and specially manufactured plates of higher refractive index (1.653 and 1.720).

Procedure with the universal stage. The optic axial angles of the minerals were measured in sodium light at a number of different points in each of the thin sections. At every point both optic axes were located (*i.e.* brought into apparent coincidence with the microscope axis) ten times orthoscopically and ten times conoscopically—five orthoscopic and five conoscopic observations being made in each of two "45° positions" which were 90° apart. The average of each group of ten orthoscopic or ten conoscopic readings was then used to provide orthoscopic and conoscopic values of 2H, and from these corresponding values of 2V were derived by calculation. In most instances this calculation only involved the application of the standard correction for the difference between the refractive index of the mineral and that of the segments, but occasionally, a correction had to be introduced to allow for the inclination of the optic axial plane when the angle between this plane and the plane of the thin section departed appreciably from 90°.

All the orthoscopic measurements listed in Table 1 were made with both the substage diaphragm (the diaphragm below the polarizer) and the objective diaphragm fully stopped down, as this arrangement is generally recommended for accurate orthoscopic observations (*cf.* Emmons, 1943; Berek, 1924). It also ensured that all these determinations were made under standard conditions of illumination. Although it was found that interference figures could be obtained by simply inserting the Bertrand lens without adjusting the diaphragms, all the conoscopic measurements listed in Table 1 were made with the substage diaphragm open to approximately one quarter of the maximum aperture possible, as clearer interference figures were thereby obtained. No attempt was made to determine the aperture of this diaphragm with precision when these measurements were made, but the effects produced by varying the apertures of both the sub-stage and objective diaphragms were made the subject of a special investigation (Tables 2 and 3).

Discussion

General relations

From an inspection of Tables 1–3 it is possible to arrive at certain conclusions concerning the relations between the different universal stage measurements and the measurements made on the spheres. These relations are:

1. *Conoscopic measurements.* (a) 2V measured conoscopically with the stage may sometimes equal 2V measured directly in the sphere of the mineral concerned, but it is generally smaller than, and never exceeds the latter. The discrepancy between the two measurements increases with the refractive index of the segments and with the size of the angle being measured (Table 1).

(b) The discrepancy between the direct and the universal stage measurements tends to be greater when the substage diaphragm is fully stopped down, but this discrepancy decreases progressively as the aperture of the diaphragm is increased until a setting is reached beyond which increase in aperture produces no corresponding change in the magnitude of the discrepancy (Table 2).

No other factors appear to produce any consistent variation in the values of 2V measured conoscopically.

2. *Orthoscopic measurements.* (a) When the standard center plate (n −1.520) is used, 2V measured orthoscopically with the stage is generally smaller than 2V measured conoscopically, and hence is normally less than 2V measured directly in the sphere of the mineral concerned. These discrepancies increase with the refractive index of the segments and with the size of the angle being measured. However, the values of 2V obtained by orthoscopic measurements become larger when the refractive index of the center plate is increased, and if the refractive index of the latter is appreciably greater than that of the segments, 2V measured orthoscopically may equal or exceed, not only 2V measured conoscopically, but also 2V measured directly (Table 1).

(b) As the aperture of the substage diaphragm is increased the discrepancies between the direct and the orthoscopic measurements, and between the conoscopic and the orthoscopic measurements decrease.

TABLE 2. UNIVERSAL STAGE MEASUREMENTS SHOWING THE EFFECT OF VARYING THE APERTURE OF THE SUB-STAGE DIAPHRAGM

Objective diaphragm closed to the minimum aperture. Center plate n−1.520

Sub-stage Diaphragm Setting	Objective	Olivine. Segments n−1.717				Topaz. Segments n−1.557			
		$2V_\alpha$(ortho.)	$2V_\alpha$(cono.)	$2V_\alpha$(sphere) $-2V_\alpha$(ortho.)	$2V_\alpha$(sphere) $-2V_\alpha$(cono.)	$2V_\gamma$(ortho.)	$2V_\gamma$(cono.)	$2V_\gamma$(sphere) $-2V_\gamma$(ortho.)	$2V_\gamma$(sphere) $2V_\gamma$(cono.)
Closed to smallest aperture	U.M.1	87.3°	88.8°	4.45°	2.95°	65.2°	65.2°	0.1°	0.1°
	U.M.2	86.8°	88.6°	4.95°	3.15°	64.8°	65.3°	0.5°	0.0°
	U.M.3	86.1°	89.2°	5.65°	2.55°	64.7°	65.3°	0.6°	0.0°
Slightly open	U.M.1	89.9°	90.2°	1.85°	1.55°	65.3°	65.2°	0.0°	0.1°
	U.M.2	89.0°	90.3°	2.75°	1.45°	65.2°	65.3°	0.1°	0.0°
	U.M.3	87.8°	90.3°	3.95°	1.45°	64.9°	65.3°	0.4°	0.0°
One quarter open	U.M.1	90.7°	90.8°	1.05°	0.95°	65.3°	65.2°	0.0°	0.1°
	U.M.2	90.5°	90.9°	1.25°	0.85°	65.3°	65.2°	0.0°	0.1°
	U.M.3	90.3°	90.8°	1.45°	0.95°	65.2°	65.3°	0.1°	0.0°
Half open	U.M.1	91.1°	90.9°	0.65°	0.85°	65.3°	65.3°	0.0°	0.0°
	U.M.2	90.8°	90.9°	0.95°	0.85°	65.2°	65.3°	0.1°	0.0°
	U.M.3	91.0°	91.0°	0.75°	0.75°	65.2°	65.3°	0.1°	0.0°
Fully open	U.M.1	91.0°	90.9°	0.75°	0.85°	65.3°	65.3°	0.0°	0.0°
	U.M.2	90.9°	90.9°	0.85°	0.85°	65.2°	65.3°	0.1°	0.0°
	U.M.3	91.1°	91.0°	0.65°	0.75°	65.3°	65.2°	0.0°	0.1°

TABLE 3. UNIVERSAL STAGE MEASUREMENTS SHOWING THE EFFECT OF VARYING THE APERTURE OF THE OBJECTIVE DIAPHRAGM

Olivine. Segments n−1.717; Center plate n−1.520

Setting of the Objective Diaphragm	Objectives	$2V_\alpha$(ortho.)	$2V_\alpha$(cono.)	$2V_\alpha$(sphere) $-2V_\alpha$(ortho.)	$2V_\alpha$(sphere) $-2V_\alpha$(cono.)
Closed to Smallest Aperture	U.M.1	87.3°	90.8°	4.45°	0.95°
	U.M.2	86.8°	90.8°	4.95°	0.95°
	U.M.3	86.1°	90.9°	5.65°	0.85°
Partly open	U.M.1	86.5°	90.7°	5.25°	1.05°
	U.M.2	85.5°	91.0°	6.25°	0.75°
	U.M.3	84.9°	91.1°	6.85°	0.65°
Fully open	U.M.1	85.9°	91.0°	5.85°	0.75°
	U.M.2	85.4°	91.0°	6.35°	0.75°
	U.M.3	84.9°	90.9°	6.85°	0.85°

Eventually, at a critical aperture—which generally becomes progressively greater as U.M.1, U.M.2 and U.M.3 objectives are substituted for each other in that order, orthoscopic and conoscopic measurements yield similar values of 2V, and further increase in aperture is not accompanied by any corresponding change in those values (Table 2).

(c) The discrepancy between the direct and the orthoscopic measurements generally increases when U.M.1, U.M.2 and U.M.3 objectives are substituted for each other in that order, except when the substage diaphragm aperture is large (Tables 1–3).

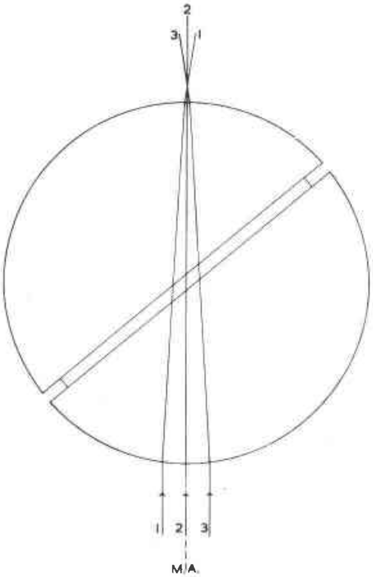
(d) In general, the discrepancy between the direct and the orthoscopic measurements increases with the aperture of the objective diaphragm. The changes are more marked at small diaphragm apertures than at large, particularly when U.M.3 and U.M.2 objectives are used, suggesting that each objective may have a critical setting beyond which increase in aperture is not accompanied by any corresponding increase in the magnitude of the discrepancy.

As the spheres of olivine and topaz were found to be virtually perfect geometrically and optically, and as the replacement of one piece of equipment (microscope, universal stage etc.) by another of similar type was never accompanied by an appreciable change in the values of 2V measured with the stage, it can be inferred that the discrepancies between the direct and the universal stage measurements are due to observational errors and/or fundamental defects in the design of the universal stage. However, although it is obvious that the cumulative effect of observational errors in the measurements on the spheres (±0.1° for olivine; ±0.2° for topaz), incorrect refractive index determinations (±0.2°) and observational errors in the universal stage measurements (generally less than ±0.2°) might conceivably be appreciable, the large size (4–5°) of certain of the discrepancies, and the generally consistent pattern of variation which they display cannot be accounted for by invoking these factors. In consequence, although it cannot be claimed that the values for the discrepancies listed in the accompanying tables are entirely free from observational errors (hence certain minor inconsistencies visible in the tables, particularly when the discrepancies are small), it is suggested that they probably provide a reasonably accurate indication of the errors in the universal stage measurements due to some defect in the design of the instrument. An attempt will now be made to show that this defect is almost certainly the inhomogeneity of the central assembly on the stage, and that these errors arise as a result of refraction within this assembly.

The Effects of Refraction in the Central Assembly on the Stage

In the past, it seems to have been generally accepted that measurements made with the universal stage need only to be corrected for any difference between the refractive index of the mineral under study and that of the segments. If this assumption is correct, then the passage of a beam of light through the center of the stage would be as shown in Fig. 1—the slight lateral displacement of the rays due to refraction at the surfaces of the thin section being neglected as the latter can be regarded as being of negligible thickness. However, as Wyllie (1959) has pointed out, when the stage is tilted the refraction at the surfaces of the other parallel layers which form the central assembly on the stage—glass center plate, microscope slide and cover slip, cement layers and films of mounting oil, cannot normally be ignored. It is apparent, in fact, that the behavior of the beam of light in passing through the tilted stage will be approximately as shown in Fig. 2. Although all measurements made with the stage will be affected by refraction in this assembly, as there are considerable differences between the patterns of variation displayed by the conoscopic and the orthoscopic measurements, it would seem appropriate to conduct further discussion of these measurements under separate headings.

Conoscopic measurements When an optic axis is located conoscopically with a microscope, rays which travel in the direction of the axis in the thin section are brought to a focus in the center of the field of view of the ocular to define the center of an isogyre. These rays normally travel parallel to the microscope axis prior to entering the objective, but when the universal stage is in use, this will not strictly be the case owing to the refraction which occurs at the surfaces of the upper segment. However, as the latter has a large radius of curvature, the departure of the path of



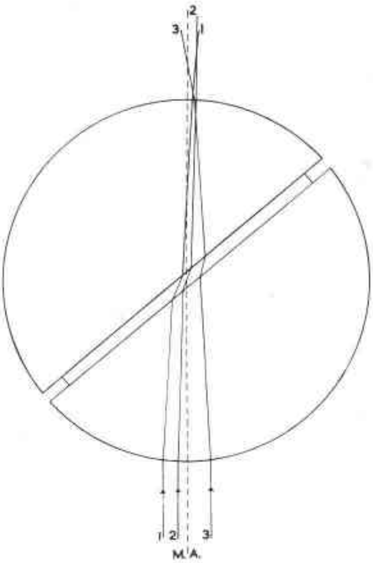


FIG. 1. (left) Passage of a beam of light through the universal stage under ideal conditions with no appreciable refraction in the central assembly. M.A.—microscope axis.

FIG. 2. (right) Simplified representation of the passage of a beam of light through the universal stage taking refraction in the central assembly into account. Refractive index of all components of the central assembly taken as being 1.54, refractive index of the segments 1.72. M.A.—microscope axis.

these rays from parallelism to the microscope axis will be small, and they will probably follow a path approximating to that of ray (2) in Fig. 2. As it is normally assumed that the path of these rays corresponds more closely to that of ray (2) in Fig. 1 (and, indeed all measurements in Tables 1–3 were interpreted on this basis) it is obvious that there will be an error in determining the attitude of the optic axis with respect to the plane of the section, even after the normal refractive index correction (see above) has been applied. In general, the measured angle of inclination will be too small as the refractive indices of most of the component parts of the central assembly are normally less than that of the segments (as shown in Fig. 2). This error would be expected to increase if the angle of tilt of the stage is increased, or if the refractive index of the segments is increased, as the effects of the refraction in the central assembly are normally increased in both instances (see 1(a)).

If the refractive index of any of the main (thicker) components in the central assembly—in particular, the center plate of the stage, is greater than that of the segments, it is conceivable that the effects of refraction at the surfaces of this component might nullify, or even outweigh, the effects of refraction at the surfaces of the other components of low refractive index. The error in a measurement would be expected to decrease accordingly, but examination of Table 1 shows that only the measurements made on olivine with segments n—1.557 display the expected relations when the center plate is changed, and, in general, such changes appear to have little consistent effect on the conoscopic measurements. However, as the values for the discrepancies in the conoscopic measurements are always small, and are thus probably sensitive to observational errors, it is possible that small effects produced by changing the center plates are masked by these errors, except when a large angle is measured and there is a considerable difference between the refractive index of the segments and that of the center plate.

To account for the relations summarized under 1(b) another effect produced by refraction in the tilted central assembly must be taken into account—the lateral displacement of the entire illuminating beam as it traverses this assembly (Fig. 2). This can be observed directly when the Bertrand lens is inserted as a migration of the image of the light source (actually the image of the aperture in the substage diaphragm) from the center of the field of view, which accompanies, and increases with, the tilting of the stage. As a result, if conoscopic measurements are made with the substage diaphragm stopped down, only a small area near the periphery of the field of view will be brightly illuminated when an optic axis is located. Under these conditions of highly asymmetric illumination, errors, which can be eliminated by opening the diaphragm beyond a certain minimum aperture, would be expected to occur in the measurements.

It should perhaps be emphasized that this minimum aperture never appears to be greater than a quarter of the maximum aperture possible, and that all the conoscopic measurements in Table 1 were made with the diaphragm at apertures at least as great as this.

Orthoscopic measurements Although much of the preceding discussion has general significance when the relations of the orthoscopic measurements are considered, certain additional features have to be taken into account in order that these relations may be more fully understood.

Firstly, if reference is made to Figs. 1 and 2, it is obvious that the beam which passes through the thin section and emerges from the upper segment consists of converging rays, even when the incident beam consists of parallel rays and there is no refraction in the central assembly. As a result, observations made with a normal microscope and stage can never be truly orthoscopic, and when an optic axis is located "orthoscopically" with this equipment, it is found that extinction is never complete throughout the field of view. In fact, it is apparent that an axis is located by bringing the center of a broad, poorly focussed isogyre into coincidence with the intersection of the crosswires.

Secondly, it is found that when the substage diaphragm is fully stopped down only a small area of the thin section is brightly illuminated and that this area normally migrates towards the margin of the field of view when the stage is tilted—obviously as a result of the lateral displacement of the light beam in the central assembly. In consequence, when an optic axis is located "orthoscopically" in the manner described above, the center of the brightly lit area will not coincide with the intersection of the crosswires, or with the center of the "orthoscopic isogyre."

Having located an optic axis "orthoscopically," an indication of why there are differences between many of the associated orthoscopic and conoscopic measurements can be obtained by simply inserting the Bertrand lens. It is then found that the isogyre which is visible (*i.e.* the "conoscopic" isogyre), is situated so that its center coincides with the center of the image of the light source. Owing to the apparent displacement of the latter which normally accompanies the tilting of the stage, its center, and that of the isogyre, will not coincide with the center of the crosswires. It appears, therefore, that an optic axis is located "orthoscopically" when the isogyre produced by the main portion of the illuminating beam in the focal plane of the ocular is centered with respect to that beam, but not with respect to the microscope.

If the refractive index of the center plate is less than, or does not greatly exceed that of the segments, as is normally the case, the apparent displacement of the light source with inclination of the stage is towards the downtilted side. As the isogyre simultaneously moves towards the uptilted side it is evident that under these conditions the latter will pass through the center of the image of the light source at an angle of tilt smaller than that required to bring it into coincidence with the intersection of the crosswires. 2V measured orthoscopically will thus be smaller than 2V measured conoscopically. Any factors which increase the apparent displacement of the light source—increase in angle of tilt, increase in the refractive index of the segments, will obviously lead to an increase in the discrepancy between these two positions and hence to an increase in the discrepancy between the orthoscopic and conoscopic measurements of 2V.

If the refractive index of the center plate is appreciably greater than that of the segments, however, the apparent displacement of the light source is towards the uptilted side of the stage, and the isogyre will then pass through the center of the image of the light source at an angle of tilt greater than that required to bring it into coincidence with the intersection of the crosswires. 2V measured orthoscopically will now be larger than 2V measured conoscopically. Thus it is possible to account for all the relations summarized under 2(a) above.

In order to explain the effects produced by changing the diaphragm apertures or the type of objective employed (see 2(b, c, d)), it is necessary to take an additional factor into account—namely, that when an optic axis is located "orthoscopically," the image of the light source produced by the objective is often partly obscured by the margin of the objective diaphragm. The isogyre observed with the Bertrand lens is then found to be centrally related, not to the image of the entire light source, but to the portion of this image which is visible.

An increase in the aperture of the substage diaphragm will be observed as an increase in the diameter of the image of the light source, and, when the latter is partly obscured by the objective diaphragm, this increase in diameter will have the effect of displacing the center of the visible portion of the light source towards the center of the field of view. The accuracy of the measurements will be correspondingly increased up to a limiting point when the aperture of the substage diaphragm is such that the image of the light source completely fills the aperture of the objective diaphragm. This critical aperture varies with the objective because the image of the light source produced at a particular substage diaphragm aperture is found to show a progressive increase in diameter when U.M.3, U.M.2 and U.M.1 objectives are substituted for each other in that order (see 2(b)). This also explains the general relations between measurements made with the different objectives (see 2(c)) as it is apparent that when measurements are repeated using the objectives in the order given above, then the effect is the same as that produced when only a U.M.3 objective is used and the aperture of the substage diaphragm is progressively increased.

When the image of the light source is partly obscured by the margin of the objective diaphragm, it is obvious that an increase in the aperture of this diaphragm will result in a larger portion of this image being made visible. The center of the effective light source is accordingly displaced towards the periphery of the field of view—i.e. towards the downtilted side of the stage when the center plate has a comparatively low refractive index. Eventually a limiting position is reached when the aperture of the diaphragm is such that the image of the entire light source is visible. In view of the relations described above it is obvious that this limiting position will be reached at progressively larger apertures when U.M.3, U.M.2 and U.M.1 objectives are used in that order—as appears to be the case in Table 3 (see 2(d)).

All the features of the orthoscopic observations conform to a consistent pattern therefore, and, indeed, it is possible to locate the "orthoscopic extinction position" by inserting the Bertrand lens and adjusting the stage until the center of an isogyre is made to coincide with the center of the visible portion of the image of the light source. Unless the apparent displacement of the light source is small, the orthoscopic measurements will tend to be much less accurate than the conoscopic, and this difference in accuracy will increase with the apparent displacement of the light source. However, although this is a clearly defined relationship (Table 2), it would seem advisable to stress that it has been somewhat exaggerated in the present investigation by using different substage diaphragm apertures for most of the associated orthoscopic and conoscopic measurements.

Although it has been established that there is this general relationship between the phenomena which can be observed when an optic axis is located both "orthoscopically" and conoscopically, it has not been found possible to explain why this is the case, although a number of different factors have been considered. The eccentricity of the segment surfaces with respect to the various rotation axes of the stage does not seem to be important as measurement shows that this is invariably small ($<1.5\%$ of the radius of the segments). It is possible that the accuracy of the orthoscopic measurements might be increased if truly orthoscopic illumination were achieved in the thin section by situating the light source at the lower focus of the optical system consisting of the center plate of the stage, the lower segment and the condenser. However, as inclination of the stage will obviously result in this focus being laterally displaced, it would seem that when the stage is used in the normal manner constant orthoscopic illumination cannot be obtained with a normal substage assembly.

It is noteworthy that the beam emerging from the upper segment when the stage is tilted is normally inclined to the microscope axis (Fig. 2), and as the "orthoscopic extinction position" seems to be determined by phenomena associated with the entire illuminating beam, this may, in part, explain why an isogyre centered on the crosswires when viewed in the plane of the section no longer maintains that relation when viewed in the focal plane of the ocular. However, a general solution to this problem might be found more readily if reference were to be made to observations in an optical system where two lens systems (equivalent to the substage assembly and the assembly in the microscope tube) are maintained in coaxial positions while a third lens system set between these (equivalent to the segments and the central assembly on the stage) is tilted to various angles.

CONCLUSIONS

Although a satisfactory explanation cannot be provided for all the features of the universal stage measurements made in this investigation, these measurements enable certain conclusions to be reached which are of considerable practical significance.

(1) A general indication of the size of the error likely to be encountered in a universal stage measurement of optic axial angle can be obtained by inserting the Bertrand lens and observing the movement of the image of the light source when the stage is tilted. If this movement is large the error in both orthoscopic and conoscopic measurements is likely to be appreciable, and if it is towards the downtilted side of the stage—as is normally the case, the values for 2V obtained from the universal stage measurements will be too small.

(2) Higher accuracy will be obtained with both the orthoscopic and conoscopic techniques if segments and a center plate having refractive indices corresponding to those of the cement and glass components of the microscope slide (*i.e. ca.* 1.54), and not to that of the mineral, are used.

(3) Higher accuracy will be obtained with both techniques if the substage diaphragm apertures are such that the illuminating beam fills the aperture in the objective diaphragm when the latter is fully stopped down. For orthoscopic measurements it is generally advisable to keep the objective diaphragm fully stopped down, but there appears to be no need to impose any restrictions on the setting of this diaphragm for conoscopic measurements.

(4) The total error in repeated conoscopic measurements when 2V is small to moderate (0–65°) will be negligible if segments of low refractive index are used with the normal center plate of the stage and suitable substage diaphragm apertures (see (3)), but will be about 0.5° if 2V is larger. If segments with a retractive index differing greatly from those of the components of the central assembly are used the corresponding errors will be approximately 0.5° and 1°.

(5) The total error in repeated orthoscopic measurements made with an objective of low magnification and small numerical aperture (such as U.M.1) in conjunction with segments of low refractive index, the normal center plate and with the substage diaphragm stopped down will again be negligible when 2V is small to moderate, but will be about 0.5–1° if 2V is large. If an objective with a high magnification and a large numerical aperture (such as U.M.3) is used with segments differing greatly in refractive index from the components in the central assembly, the error in a measurement may be about 2.5° if the optic axial angle is moderate, and about 5–6° if the angle is large.

(6) In view of these errors it may be impossible to deduce the com-

position of a mineral (*e.g.* olivine, orthopyroxene) simply by measuring 2V with the universal stage, unless the technique and equipment employed are similar to those used in the derivation of the curve linking 2V and composition, and, indeed, it may be necessary to redetermine many of these curves using standard equipment and technique.

ACKNOWLEDGMENTS

The author is indebted to Professor T. C. Phemister and to Drs. W. E. Fraser and F. E. Tocher for reading the manuscript and offering much useful advice and criticism. Particular reference must be made also to the great skill and patience displayed by Mr. G. G. Brebner in making the crystal spheres as this investigation could not have been carried out without this assistance.

APPENDIX: TECHNIQUES USED IN THE PRODUCTION OF CRYSTAL SPHERES

G. G. BREBNER

The spheres used in the investigation described above were made from small fragments of the crystals. These were mounted with Canada balsam on a glass rod and were then ground with carborundum powder on a lap normally used in the making of thin sections. When the exposed end of the specimen had been ground to a roughly hemispherical shape, the specimen was remounted so that the unground portion was now exposed, and grinding was continued until a rough sphere had been produced.

A thin-walled brass cylinder with an internal diameter slightly less than the estimated diameter of the final sphere (generally 2.5–5 mm) was then made. This cylinder was rotated by means of an electric motor and the specimen, which had been liberally coated with a paste of carborundum powder and water, was loosely applied against its open end. Medium grained powder was used at first, followed by fine powder in the later stages of grinding. The final surface was imparted to the specimen by using a similar cylinder of bakelite and optical rouge.

After a little experience had been gained, it was found that a specimen could be converted into a nearly perfect sphere with comparative ease. During the earlier stages of the grinding the approach to perfect sphericity was measured by rotating the specimen on a one circle goniometer fitted with an ocular graticule. When the specimen had become a nearly perfect sphere a more sensitive test was employed—the points of emergence of the optic axes were located, using the goniometer microscope and crossed polaroids. Ideally each axis should emerge in points 180° apart, and this degree of perfection was actually attained in the olivine specimen used in the previous investigation. In the topaz specimen the axes were located at points which were 179°58′ and 180°12′ apart.

Attempts were made to produce spheres, not only from the two specimens described above, but also from additional specimens of olivine and from specimens of albite, epidote and staurolite. It was found that a sphere which was nearly perfect geometrically could be made even when the specimen possessed a good cleavage (topaz, albite). However, if hard inclusions were present (*e.g.* iron ore grains in olivine) it was found that the specimen tended to disintegrate when these inclusions appeared at the surface as a result of the grinding. It was also found that in the deeply colored minerals (epidote, staurolite) strong absorption prevented the observation of interference figures, even in spheres with a diameter of less than 1 mm.

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Manuscript received, August 10, 1962; accepted for publication, January 30, 1963.