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THE TWO-CIRCLE GONIOMETER

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INTRODUCTION

Crystallographic measurements were first made by simple contact instruments, which gave the angle between a pair of crystal faces. This method was soon improved by employing the crystal faces as reflecting surfaces, and measuring the angle thru which it was necessary to turn the crystal in order to bring successive faces of a zone to the same position of reflection. Measurement thus by zones, with a new adjustment of the crystal for each zone measured, was adopted by crystallographers as a general procedure, and used for many decades; and a variety of instruments was devised for this purpose, some of great accuracy. The use of such one-circle reflecting goniometers is fully described in numerous accessible works in English.

The next improvement in crystal measurement had for its object the determination of complete angular relationships between all the faces of the crystal, expressed in terms comparable to those employed in locating positions on the earth's surface,—latitude and longitude. This plan was first used by the English crystallographer W. H. Miller in 1874; and three instruments based upon it were independently described, almost simultaneously.¹ These were soon followed by others of still greater complexity² upon which both polar coördinate angles and complete zonal measurements could be made at a single setting of the crystal.

Goldschmidt's two-circle goniometer, one of the first to be described, has since been constantly improved, and is an essential part of a complete system of descriptive crystallography which

¹ V. Goldschmidt, *Z. Kryst. Min.*, 21, 210, 1892; E. Fedorov, *Verh. Min. Ges. Russia* 26, 458, 1889; *Z. Kryst. Min.*, 21, 574, 1893; S. Czapski, *Z. Instrumentenkunde*, 13, 1893; *Z. Kryst. Min.* 25, 620, 1896.

² G. F. H. Smith, *Mineral. Mag.*, 12, 175, 1899.

is coming into general use, especially in America. Most of the papers describing the use of this instrument and the methods of discussing the resulting measurements are, however, widely scattered in German publications. No complete instructions, in English, for the use of Goldschmidt's two-circle methods have ever appeared in print; such incomplete papers as exist³ are relatively inaccessible.

The advantages of these methods are, however, so great, and the number of workers using the instruments so considerable, that it seems desirable to publish a rather full account of the principles and methods of two-circle goniometry and of its graphic expression, the gnomonic projection. It is planned, accordingly, to have an article on some phase of this method appear in successive numbers of this journal for at least the next six months, and ultimately to reprint these in a single pamphlet for the use of teachers and students of crystallography.

THE INSTRUMENT

In the familiar spherical projection the crystal faces are represented by the points of intersection of the face-normals with the surface of a sphere described about the crystal center. The relations of these points upon the sphere are known, if we determine the angular distances between them (measurement of interfacial angles) or if we determine the position of each one with reference to a set of coördinates (measurement by angular coördinates). These operations are strictly analogous to well known geographical operations; the first is comparable to triangulation, or the measurement of angular distances between points on the earth's surface; the second is like the determination of localities by latitude and longitude—that is, by reference to an equator and a meridian as fixed coördinates. The latter operations are so nearly alike that it is found convenient to retain the geographical terms for the crystallographic coördinates, and we accordingly speak of the equator and meridian of the crystal.

Any great circle of the sphere of projection may be taken as equator and the pole will lie at a distance of 90° therefrom. Any great circle at right angles to the equator may be taken

³ C. Palache, *Am. J. Sci.*, 2, 279, 1896; A. J. Moses & A. F. Rogers, *Sch. Mines Quart.*, 24, 1, 1902; see also the brief account in: A. E. H. Tutton, *CRYSTALLOGRAPHY*, 462-481, 1911; and the textbook based on the method: T. L. Walker, *CRYSTALLOGRAPHY*, 1914.

as first meridian. In practice the choice of coördinates is limited to a few cases.

The means of applying this principle to crystal measurement is found in the *two-circle goniometer* of which fig. 1 is an illustration. Its construction is best explained by reference to the outline diagrams, figs. 2 and 3. H is the horizontal circle revolving about the axis *h*, graduated and provided with fine adjustment and vernier. Rigidly attached to H by an arm and at right angles to it is the vertical circle V revolving about the axis *v* and also graduated and provided with fine adjustment.

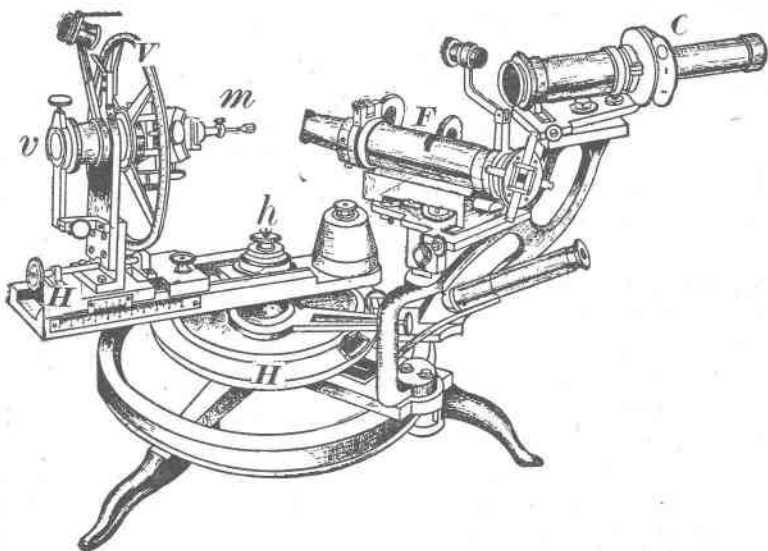


FIG. 1.

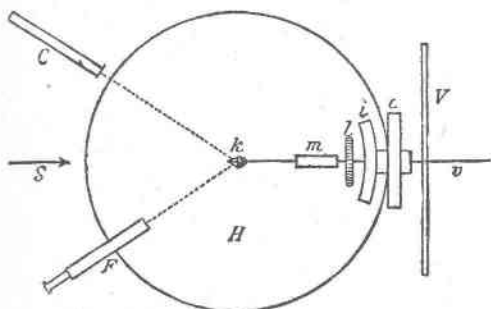


FIG. 2.

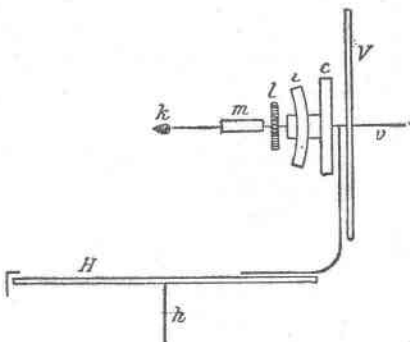


FIG. 3.

The axis v supports an adjusting device such as is found on the ordinary goniometer and upon it the crystal is mounted by means of a carrier m capable of independent adjustment.

The collimator C and telescope F are horizontal; they may be moved relative to each other and the angle between them measured.

By revolution of V (from an arbitrary zero thru an angle φ) each face of the crystal may be brought perpendicular to H. By revolution of H (thru angle ρ from an arbitrary zero) the face may be brought perpendicular to S, the bisectrix of the angle CkF, also, and will then reflect the signal upon the crosshairs of the telescope. The angles v and h , read upon the vertical and horizontal verniers respectively, determine the position of the crystal face with reference to the arbitrary coördinates. They may be termed the angular coördinates (Winkelcoördinaten) of the face. If the equator is taken parallel to V and if H is the first meridian, then angle φ corresponds to the geographical longitude, angle ρ to the pole elevation (complement of the geographical latitude).

In practice, whenever possible, the crystal is so mounted that the prism zone is perpendicular to V; or, what is the same, the plane perpendicular to the prism zone, a cube face in isometric system, a pinacoid in hexagonal, tetragonal, and orthorhombic systems, is taken as the *pole*. A face of the prism zone, preferably a pinacoid, is then taken as first meridian.

If this normal position cannot be used owing to absence or imperfection of the prism zone, another plane is taken as *pole* and preferably a face perpendicular to one of the other two axial zones. The elements and symbols so obtained are readily transformed to the normal form by interchange of axes.

It is evident that for a given position of collimator and telescope the value of $\rho = h_0$ for the polar position of the vertical circle will be constant and will serve for any plane adjusted parallel to V. This value, h_0 , is found as follows: A reflecting surface is mounted, centered, and brought to reflection by turning H and V. Let the reading on H be h_1 . V is then turned through 180° and the surface again brought to reflection by turning H. Let this reading be h_2 . The required value, $h_0 = \frac{1}{2}(h_1 + h_2)$. This value may be checked and improved by repeated measurements on other surfaces.

Every face may be brought to reflection in two positions which yield, however, the same values of φ and ρ . If v and h are the

angles read for a face when v stands in that quadrant of H near the observer and the telescope (h less than h_0) and v' and h' the angles when V stands in an opposite quadrant of H then:

$$v = 180^\circ - v',$$

$$h - h_0 = h_0 - h' = \rho.$$

Averaging these two readings increases the accuracy of measurement but all ordinary requirements of accuracy are fully met if a single reading is taken for each face, preferably in the first position.

The angle between collimator and telescope, once fixed at a convenient position (about 70 degrees), must not be altered during the measurement of a crystal. In practice it need not be changed often. Since all readings on H have to be subtracted from the constant h_0 in order to obtain ρ for each face, it is convenient to have the value of h_0 an even number of degrees. This may be attained by the method of trial, shifting the angle and determining h_0 until the condition is fulfilled. The clamp of the telescope should then be set and the fine adjustment screw also clamped tight, lest it be moved inadvertently during a measurement. This proceeding is laborious, but saves much time in calculation; on the writer's instrument this angle, and accordingly the value of h_0 , has not been changed for twenty years.

Should the instrument get out of adjustment, it may be placed in order again in accordance with directions furnished by the maker.

ADJUSTMENT OF THE CRYSTAL

The value of the constant h_0 having been determined,¹ the next step in the measurement of a crystal is its correct adjustment on the goniometer. The method to be used depends upon the symmetry of the crystal and the faces present. Most crystals will fall into one of four cases, which may be defined as follows:

Case I. The pole face present and reflecting.

Case II. The pole face defined by a zone perpendicular to it, (prism zone).

Case III. The pole face defined by a "ring" (group of faces making equal angles to the base, as a pyramid or rhombohedron).

¹ According to the graduation of H , the value of the reading h_0 may be 90° greater or less than the h for a prism face. In the latter case in what follows, for ($h_0 - 90^\circ$) read ($h_0 + 90^\circ$) and for ($h_0 - \alpha$) read ($h_0 + \alpha$).

Case IV. The pole face defined by a zone and a face in the zone making a known angle to the pole face.

Case I. The pole face (f) present and giving a good reflection.

The crystal is fixed upon the adjustment table with hard cement as near the desired position as may be and a corner of the face is centered. H is now brought to the reading h_0 and the reflection from f centered on the crosshairs by use of the adjusting tables. When properly adjusted, that is when parallel to V, the reflected signal should remain stationary on the crosshairs during a revolution of V.

Case II. The pole face (f) defined by a zone perpendicular to it (prism zone in any system).

An edge of the prism zone is centered and adjusted to the horizontal crosshair. H is clamped at $h_0 + 90^\circ$ and the reflections from two adjacent faces of the zone are brought to the center of the crosshairs by means of adjusting tables. H is then loosened, the edge again centered and the whole repeated as often as necessary. Other faces of the zone are then examined and if necessary the adjustment bettered. When the prism zone is thus adjusted at ($h_0 + 90^\circ$), f , the pole face, is at h_0 and if present its reflection should be on the crosshairs when H is brought to h_0 . This case is important since the plane at right angles to the prism zone is the normal plane of projection in all systems and this position gives simple and direct results in the calculation. The prism zone is rarely lacking entirely and even when its faces are poor or striated its correct adjustment is possible.

Adjustment by the prism zone is more accurate than that by the pole face and should be used in preference to the latter where both are possible on a crystal.

Case III. The pole face (f) defined by a "ring."

(a) The angle (α) made by the faces of the "ring" to (f) is known.

The crystal is placed on the goniometer with one face of the ring (F) opposite a tilting screw (T_1 , see below, p. 31) and H is clamped at ($h_0 + \alpha$). The image of F is brought upon the cross hairs of the telescope by movement of V and T_1 . Another face of the ring is then brought to reflection, H again clamped at ($h_0 + \alpha$), and the image brought upon the crosshairs by movement of V and T_2 . By one or two repetitions the two faces

will be adjusted, when images from the remaining faces of the ring should fall on the vertical crosshair at the same position of H.

(b) The angle (α) made by the faces of the "ring" to the pole face (f) is unknown.

The crystal is set on the adjusting table with its vertical axis as nearly upright as possible, and three or more faces of the ring are successively brought to reflection by motion of V and H. The angle of each on the vernier of H is recorded, and h_0 subtracted from each. The average of these values is an approximate value of (α) and may be used for an approximate adjustment as in (a) above. Repetition of this procedure once or twice will give an accurate value for (α) and a final adjustment.

This case is important, and is commonly met with in rhombohedral crystals and in pyramidal crystals of the three rectangular systems in which the prism zone is lacking or poorly developed.

Case IV. The pole face (f) defined by a zone and a face (F) in the zone making a known angle (α) to the pole face.

The crystal is set on the adjusting table with the given zone opposite to one of the tilting screws (T_1 , see below, p. 31), H is clamped at ($h_0 + \alpha$) and F is brought to reflection by movement of V and T_1 . H is now unclamped and successive faces of the zone are brought to reflection by movement of H and V. In general the images will lie above or below the horizontal crosshair. Movement of V and of T_2 will correct their position until by movement of H all faces of the zone come to reflection on the horizontal hair without movement of V. H is again clamped at ($h_0 + \alpha$), and the process repeated until F is at the angle ($h_0 + \alpha$) and the zone is vertical, when the crystal is adjusted.

This case is most frequently met with in monoclinic crystals in which the prism zone is absent or poorly developed.

Abnormal positions.—

It is always desirable that the crystal should be measured in its normal position, that is, with vertical axis normal to V. If the habit of the crystal prevents this choice or makes such adjustment difficult, the next simplest proceeding is to choose one of the other axial zones as the equatorial (prism) zone. This case arises not infrequently in the monoclinic system with crystals of the epidote habit in which the zone of orthodomes is the major zone. If this zone be taken as prism zone, the clinopinacoid becomes pole face. Adjustment and measurement

proceed as in normal position; discussion of the results will be described on a later page.

Abnormal orientation for measurement is often useful in cases of symmetrical distortion in isometric crystals where an octahedron or dodecahedron face may be taken as pole face instead of the normal cube. In the case of twin crystals, unless the twin plane is a face of the prism zone, two measurements are sometimes desirable, one with one unit of the group in normal position for determination of the forms present, a second with the twin plane vertical and some zone containing it and common to both crystals in equatorial position to enable a simpler discussion of the twin relation in projection.

It sometimes happens with crystals of lower symmetry, or where there is extreme distortion, or but a fragment of the crystal at hand, that it is impossible to orient the crystal without a preliminary measurement. Generally it suffices to measure a few interfacial angles, which may be done rapidly as follows: Any good face is adjusted as pole face (Case I), that is, its reading on H is h_0 . As many other faces as may be necessary are then successively brought to reflection and readings on H taken for each. Subtracting h_0 from each reading, the interfacial angle between each face and the pole face is obtained. It is also evident that the readings on V for a zone adjusted as prism zone, and those on H for vertical zones, furnish interfacial angles which may likewise be used for orientation of the crystal.

PRACTICAL DETAILS OF CRYSTAL MEASUREMENT

The crystal to be measured should be studied under the hand lens, loupe or binocular, and its symmetry determined, if possible. One or more sketches should then be made on such a scale and with such accuracy that each face may be surely recognized when seen thru the telescope of the goniometer, even when inverted, as it is with most of the lens systems. The sketch should be made on the top of the sheet of quadrated paper which is to be employed to record the measurements, and each face in the sketch should receive a serial number, the order of numbering being quite arbitrary. In the case of very small crystals the sketch can sometimes be made more easily on the goniometer itself, but it should never be omitted.

The crystal having been studied, and the zone, face or "ring" selected which is to be used for its adjustment on the instrument,

it is mounted with hard wax on a brass pin fitting the adjustment table, with its long axis as nearly parallel to the length of the pin as possible. The pin is then placed in the socket, but before clamping it there some face of the prism zone or the "ring" should be brought as nearly as possible opposite to one of the tilting screws of the adjusting table, by rotating the pin in its socket. Let this screw be indicated in what follows as T_1 , the other one as T_2 . The more exactly this position is attained, the more rapidly will the whole adjustment proceed; and in case of zones or "rings" with but few faces, close approximation as described below is indispensable.

The pin is clamped and the crystal centered. The chosen face is then brought to the required position (according as it falls in Case I, II, III, or IV above) by movement of V and T_1 . If when this is accomplished it is found that T_1 is not horizontal it is well to slightly loosen the pin in its socket and, holding the pin with one hand so that the image from the face remains near the crosshair, to turn the vertical circle with the other hand until T_1 comes into the horizontal position. The pin is then clamped and the adjustment of the first face repeated. The reason at the base of this operation is that if the face is opposite to one tilting screw, T_1 , it is parallel to the other, T_2 , and will be rotated by any movement of T_2 required to adjust a second face only in its own plane, and thereby but slightly disturbed in its position relative to T_1 .

A second face, chosen as nearly as may be at right angles to the first, is now adjusted, T_2 alone now being used, together with V . Returning to the first face, its position is verified and readjusted with T_1 , and in turn the second face is reexamined and adjusted with T_2 ; and this is continued until both faces are correct. The zone or "ring" is then tested in its entirety and any slight alterations made that may be needed, care being taken to use at any time only that tilting screw which is most nearly horizontal.

The adjustment should now be tested by examination of other "rings" or vertical zones that may be present, or in any other way possible, and if it prove satisfactory, the crystal is ready for measurement.

Measurement is effected by bringing each face in succession to reflection, identifying it upon the sketch, clamping both circles, setting the image with the tangent screws exactly upon

the crosshairs of the telescope, and reading both verniers. The order in which the faces are measured is a matter of indifference. It is common practice to measure first the prism zone in its entirety, especially if it be rich in faces. Rings may then well be measured, or each series of vertical zones between prismatic faces and the base. Much depends upon the crystal, its size and complexity, and upon how much is known of its symmetry before measurement. If it be so large that only a part of it is visible in the telescope at one time, it is generally best to measure all visible faces without regard to zones and then, shifting by means of the sliding screws to another area, to repeat until the circuit is complete.

The lens systems employed in Goldschmidt goniometers of different models are so different that it is impossible to give exact instructions for their varying use. In general, measurements should be made with the system of lowest magnification practicable. If a crystal have both large smooth faces and minute ones it is well to measure all the larger faces with a low power and large image and then, shifting to a higher power, to go over it again for the smaller faces, with less reflecting surfaces. In the case of very small crystals it is necessary to use the higher magnifying systems thruout, altho the measurements so obtained are of inferior accuracy.

The measurement of each face is entered on a single line of the paper. Leaving a blank of several squares on the left hand margin, for the entry of the symbol when determined, there should be entered first a quality index indicating the perfection of the signal. The writer employs for this purpose five greek letters, α denoting a perfect signal; ϵ an image so faint or blurred that little dependence can be placed upon the reading; with three intermediate grades. The number of the face occupies the next column. Next comes the angle (v) read on the vertical circle and after it the angle (h) read on the horizontal circle. For each of these a space of three squares is needed. If it is desired to make any further notes on the reading they should be confined to a small space at the extreme right-hand side of the line, leaving the intermediate space for calculations connected with the projection and discussion of the measurements. The notes of successive measurements may occupy successive lines if figures are made small and distinct. Quadrated paper with 5 mm.

spaces is convenient, and two figures may be easily written in each square.

It is of great importance that the measured face be absolutely identified in the sketch, so that it may receive its proper number; otherwise much confusion ensues in projection and the discussion of results. The crystal should always be left on the instrument without disturbing its adjustment, at least until a projection has been made; then if any discordance appears between sketch and measured (plotted) position, or any doubt arises as to the correctness of entered angles, the face in question may be at once reexamined and verified. On setting off, on the two verniers, the two angles entered in the notes, the face corresponding to them should come again to reflection on the crosshairs.

The instrument permits all the faces of one end of the crystal, including prism faces, to be measured at one setting. Should the other end also be developed, it is necessary to invert the crystal, adjusting it with the same zone as prism zone and the same face as first meridian, thus establishing the relation between the faces of the two ends.

The measurement of faces which are smooth but too dull to reflect the signal is a special difficulty, to meet which several methods have been devised. One simple one is sometimes effective for crystals which have enough reflecting faces to permit adjustment. The dull face is brought as nearly to reflecting position as may be done by observing maximum illumination. It is then touched with a drop of alcohol, or even water, from the tip of a small soft paint brush. The liquid at first forms a curved surface, but as it evaporates there is an instant when the film is practically a plane, adhering to the surface of the face; this film may reflect an image of the signal long enough to permit of the accurate setting of the signal on the crosshairs. Large dull faces may sometimes be measured by causing slips of thin cover glass to adhere to them by a drop of oil.

The measurement of faces giving multiple reflections involves another set of problems. All images should be measured and if possible, by means of the eyepiece provided with a blende (shutter), the portion of the face yielding each should be identified, and the facts entered in a special sketch of the face. The position of the typical or normal facet will probably be best recognized when the measurements are plotted in the projection and the zone lines drawn.