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USE OF THE UNIVERSAL STAGE IN SEDIMENTARY PETROGRAPHY

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ABSTRACT. The universal stage is of particular value in the investigation of certain sedimentary petrographic problems. Customary universal stage technique is readily applied to sedimentary petrography, but the following special applications are recommended and discussed: goniometric procedure for the determination of habit and interfacial angles in idiomorphic and sub-idiomorphic minerals, investigation of mutual relations of cementing minerals or secondary growths, determination of feldspar composition and recognition of authigenic feldspar, distinction between quartz and clear plagioclase, and identification of calcite and dolomite by optical methods.

INTRODUCTION

THE purpose of this paper is to draw the attention of sedimentary petrographers to some of the uses of the universal stage in routine petrographic examination of sedimentary rocks. As a result of their own experience, the writers believe that a universal stage is a piece of apparatus essential for a modern sedimentary laboratory and offer the following suggestions for its use.

1) One good petrographic microscope should be reserved for this work. On it a universal stage should be mounted permanently to avoid the waste of time otherwise involved in repeatedly setting up centering and adjusting the instrument prior to each investigation.

2) For all routine measurements of such properties as optic orientation, optic sign, axial angle, extinction angles, and interfacial angles, whether in uniaxial or biaxial minerals, a stage with three rotation axes (innermost vertical, north-south horizontal, and east-west horizontal) is thoroughly satisfactory. Our preference is for the three-axis stage of Silge and Kuhne, San Francisco, or the standard four-axis stage of Leitz.

3) The classic Federow procedure described in such standard German works as those of Berek (1924), Reinhard (1931) and Nikitin (1936) is recommended. Various aspects and modifications of the Federow method will be found in a number of papers written in English (Barber, 1936, pp. 221-289; Nemoto, 1938; Haff, 1941; Turner, 1940, 1942, 1947), and

in addition, a clear, concise outline of the essential procedure has been given by Haff (1942). The Federow method involves plotting all measured directions and planes on a stereographic or an equal-area projection net. In the writers' opinion this is an advantage rather than otherwise, because a clear picture of the optic and crystallographic orientation of the measured mineral develops as measurement proceeds, and any error in measurement or identification of a given direction is readily perceived and may be corrected. Moreover, use of a projection net is essential in identifying crystal faces and zones, and is the simplest method of measuring interfacial angles with a universal stage. Those unfamiliar with the use of a projection net in this connection are referred to a paper by Haff (1940) which gives a clear account of the essential procedures involved.

4) Material adapted to investigation with a universal stage includes thin sections and grain preparations permanently mounted in plastic, Canada balsam, hyrax, or some other resin.

5) The beginner is reminded that the chief advantage of the universal stage is that certain properties (e.g., axial angle, optic orientation, intercleavage angles) may be measured directly in a single crystal; whereas with an ordinary petrographic microscope such properties are usually determined by comparing optical reactions observed in a number of crystals presumed to be identical in composition. But the precision of the universal stage is still limited by the degree of accuracy with which a position of extinction or the sharpness of a cleavage surface can be estimated visually. Most measurements involve errors of the order of one or two degrees; so that the universal stage, although a convenient instrument, yields data in many cases little more precise than those determined by ordinary petrographic means.

GENERAL TECHNIQUE APPLIED TO SEDIMENTARY PETROGRAPHY

In sedimentary, just as in igneous or metamorphic petrography, the most generally useful optical data for the rapid measurement of which the universal stage is specially suited are, 1) the positions of the indicatrix axes X, Y, and Z in relation to visible crystallographic planes and directions and 2) the optic axial angle and optic sign. It is not within the scope of this paper to describe the Federow procedure for obtaining these data, but the use of this procedure is

invaluable in the solution of problems that commonly arise in sedimentary petrographic work.

One of the special difficulties of sedimentary petrography arises from the great variety of relatively rare minerals that are likely to be present in heavy concentrates. Such, for example, are lawsonite, diaspore, scheelite, spodumene, etc. Where only one or two grains are available for study in a single mount, optic axial angle and optic sign are properties whose determination may be essential for identification of the minerals. Also with respect to some of the more abundant minerals found in sedimentary rocks optical data obtained by means of a universal stage may be invaluable, as, for example, in the precise determination of feldspar composition (Turner, 1947), the distinction between orthorhombic and monoclinic pyroxene by the relation of Z to the prismatic cleavage, the identification of varieties of monoclinic pyroxene by means of optic axial angle, and the distinction between apatite and colorless andalusite lying on the front pinacoid {100} cleavage.

Strongly colored minerals or minerals with strong dispersion are not suited to investigation by means of a universal stage because in such minerals it is impossible to locate precisely the positions of the indicatrix axes. This applies particularly to mounted grains (as contrasted with thin sections) since the effects of dispersion and absorption are increased by the relatively great thickness of grain. Epidote minerals, dumortierite, pumpellyite, and many amphiboles belong to this category.

Universal stage procedure is also essential in those special investigations in which measurement of preferred orientation of common constituents of sedimentary rocks (notably quartz, carbonates, and micas) is desirable (Ingerson, 1944, p. 640).

DETERMINATION OF CRYSTAL HABIT AND INTERFACIAL ANGLES

So many sedimentary minerals, especially those of heavy concentrates, occur as idiomorphic or subidiomorphic crystals, that crystal habit is an important diagnostic character. Although the prevailing habit of a given mineral may usually be judged by inspection of a number of typical grains with the ordinary microscope, it is advantageous to be able to tilt individual grains about an axis within the plane of the microscope stage. This is readily done if the slide is mounted on

a universal stage. The amount of additional detailed information readily available through this simple procedure alone is significant and lends perspective to other observations made with the ordinary microscope. Such a procedure may be

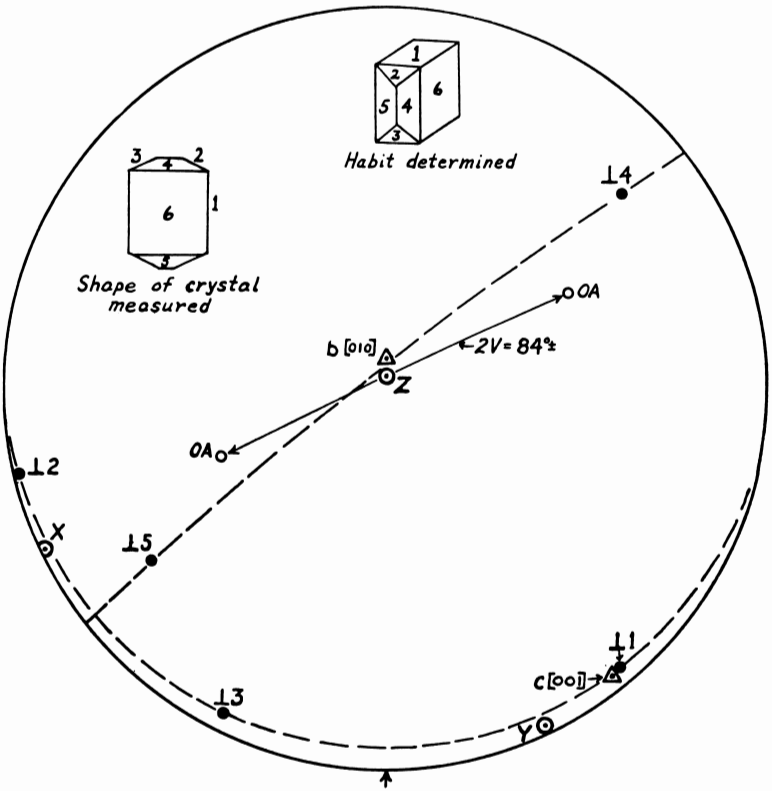


Fig. 1. Equal-area projection of heulandite (Example 1).

particularly desirable in cases where variation in habit or in mean dimensions of grains is investigated statistically in problems relating to paleogeography (Smithson, 1939, pp. 423-427; Hagerman, 1933).

Approximate determination of interfacial angles and of zonal relations of faces bounding idiomorphic crystals is another technique specially useful in sedimentary petrography, both as a step towards identifying minerals and in interpretation of rock fabrics as observed in thin sections. The position of any well developed crystal face (or cleavage plane) is readily located within one or two degrees by bringing it into

the vertical north-south or east-west plane. The interfacial angles are measured between the poles of (normals to) faces plotted on the projection net and are subject to errors of several degrees, but the data obtained are in many cases sufficiently accurate to allow certain identification of both the mineral and the measured faces. Marked differences between refractive index of the mineral and that of the mounting medium (e.g., zircon in Canada balsam) increases the error owing to total reflection at surfaces adjoining the measured face.

Example 1.—The identification of minute crystals of authigenic heulandite in an upper Miocene sandstone (Santa Margarita formation) from Santa Cruz County, California (U.C. #51-8), is cited as an illustration of the use of interfacial angles and habit in identifying sedimentary minerals. The mineral was suspected of being a zeolite because of its low birefringence (.005±) and low refractive index (mean R. I. = 1.485 ± .003), but positive identification was not possible by ordinary microscopic means.

Figure 1 shows the indicatrix and poles of measured crystal faces of a single crystal plotted on the lower hemisphere of an equal-area projection net. The measurements made with a universal stage from which these points were plotted are[1]:

	X	25 → 1
	Y	115 → 2 ↓ 45 ↑ 39
⊥	face #1	310 ← 5
⊥	face #2	13 → 1
⊥	face #3	63 → 5
⊥	face #4	40 ← 21
⊥	face #5	36 → 24

[1] For all readings given in this paper the following convention is used. The first figure is the reading on the scale for the inner vertical axis of the stage; the arrow and second figure indicate the direction and amount of downward tilt (on the N.-S. axis). To plot these on the lower hemisphere of the projection net the following rules may be followed. Turn the zero position of the transparent overlay to the measured angle (first figure) indicated on the circumference of the net; plot the point at the angle of tilt (second figure) measured in from the circumference of the net along the east-west axis in the direction indicated by the arrow. In the case of measurement of Y, the third and fourth figures in the reading are the direction and corresponding amount of tilt around the horizontal east-west axis necessary to bring an optic axis into the vertical position. The optic axes are plotted on the net, along the great circle 90 degrees from Y, in the direction and amount indicated, starting at the horizontal east-west axis of the net.

The position of Z is located graphically at 90 degrees from both X and Y.

Examination of the plotted points reveals that the poles of three faces (#1, #2, and #3) all lie on a great circle (the dashed line through these three poles), and also that this great circle passes approximately through X and Y. Thus within the limits of accuracy to be expected in such measurements, all three of these faces are co-zonal and are normal to the plane including X and Y. The corresponding zone axis (labeled b{010} in Figure 1) and the optically determined point Z should thus coincide. Also these two points are very close to the great circle which includes the poles of faces #4 and #5. The two great circles are thus mutually perpendicular within the limits of experimental error. These data suggest strongly that the mineral is either monoclinic or orthorhombic.

The general habit of the crystal can be clearly seen by tilting it into various positions, and the interfacial angles can be read from the projection net. Comparison with published data (Dana, 1899, pp. 570-610) indicates that two zeolites, mordenite and heulandite, have the habit of the mineral in question; but the interfacial angles identify it as heulandite, with the following forms developed: #1 = {001}, #2 = {201}, #3 = {$\bar{2}$01}, #4 and #5 = {$1\overset{+}{1}0$}, and #6 = {010}. The following table gives the interfacial angles measured and, for comparison, the angles reported by Dana (shown in italics to the nearest degree).

	A ⊥ 2	A ⊥ 3	A ⊥ 4	A ⊥ 5
⊥ 1	63 *64*	66 *66*	88 *89*	89 *89*
⊥ 2		50 *50*	34 *33*	32 *33*
⊥ 3			35 *33*	32 *33*
⊥ 4				45 *44*

Interfacial angles and the identification of faces on the single crystal illustrated in this example have been checked, with an accuracy of two or three degrees, by measurements made on many other crystals from the same concentrate. The precision of these measurements is dependent on the sharpness with which the positions of crystal faces may be estimated visually, so that the operator can decide at the time of measurement which readings are likely to be most reliable. Obvi-

ously some crystals are more favorable for such measurements than others, and in general crystals with the most clearly defined faces should be chosen. The crystal chosen for this example is particularly favorable, but because it lay on its side pinacoid {010}, face #6, other grains must be measured to identify that face positively. Such measurements prove that face #6 is indeed the side pinacoid {010} and that it is strictly normal to Z.

In minerals of very low birefringence, such as the zeolites, relatively slight changes in refractive index (possibly caused by slight variations in composition or changes in temperature) may alter the optic sign and orientation or produce large changes in the optic axial angle. Crystal habit and interfacial angles are probably much more constant than such optical data, and are therefore valuable in identification of such minerals. In the present case, for example, the optical character of the heulandite immersed in Canada balsam and heated enough to harden the balsam is very different from the optical character observed when the mineral is mounted in plastic (Castolite) hardened without heating. (The optical orientation reported in this example is for the unheated mineral.) The heating necessary to harden the Canada balsam caused the optic sign to be reversed and the positions of X and Z to be interchanged. The interfacial angles and habit of the mineral are identical in the two media.

MUTUAL RELATIONS OF CEMENTING MINERALS AND SECONDARY OUTGROWTHS

The universal stage is particularly adapted to establishing the existence of secondary outgrowths on detrital mineral grains and to bringing out the mutual relations of cement minerals and authigenic minerals in general. Contrary to what might be expected, a random section across a grain partly bounded by sharply defined crystal faces in many cases yields irregular outlines, so that the existence of crystal faces is not suspected until these have been tilted into a vertical plane. For example, in mounted light fractions of some samples of the Santa Margarita sandstone of southern Santa Cruz County, California, most of the numerous grains of feldspar appear to be angular and irregular. Yet tilting in the appropriate direction on a universal stage reveals the surprising

fact that approximately half of these grains are at least partly bounded by crystal faces, and in many grains these can be shown to be clear secondary outgrowths developed around somewhat cloudy detrital grains originally irregular.

During the examination of thin sections of some Eocene reservoir sands from the Kettleman Hills-Coalinga area, California, the writers found that, in general, quartz and feldspar grains appear to be irregularly bounded where they project into or adjoin cavities. Here, too, appropriate tilting of these free edges, even through ten or fifteen degrees, reveals the presence of sharp secondarily developed crystal faces that would otherwise remain undetected. By measuring and plotting several such faces and one or more optical directions in any grain, it is commonly possibly to identify the individual faces and so to obtain a picture of the exact crystal form that tends to develop by secondary enlargement of the detrital grains. Moreover, it may be possible to obtain reliable information as to the order of development of outgrowths and cementing minerals during lithification of the sediments in question (Gilbert, 1948). Several instances are cited below as examples of this technique.

Example 2.—This illustration of the identification of crystal forms developed on a secondary outgrowth of quartz is taken from the Eocene McAdams sand of the Kettleman Hills area, California (U.C. #S3/3C). Figure 2 shows the optic axis and poles of faces measured on a secondarily enlarged quartz grain. In the inset sketch representing the general form of the grain measured (Q_1), stippled areas are detrital quartz and diagonal lines indicate secondary outgrowths on several detrital grains; cross-hatched areas are detrital feldspar. The sketch is highly idealized to indicate the number and relative positions of the faces on several outgrowths, but it should be understood that at any one tilt of the stage only one or two of these faces are clear. With no tilt at all, faces #1 and #4 alone are distinct.

With the universal stage the positions of the optic axis (c axis) and the pole of each suspected crystal face are measured in the usual manner and with the following results:

Optic Axis	39 ← 20		
⊥ face #1	348 → 4	⊥ face #4	350 → 3
⊥ face #2	260 ← 20	⊥ face #5	28 → 32
⊥ face #3	315 → 16	⊥ face #6	258 ← 19
		⊥ face #7	317 → 14

Each of these readings is plotted on the lower hemisphere of an equal-area (or stereographic) projection net, and the angle between the optic axis and the pole of each face is read from

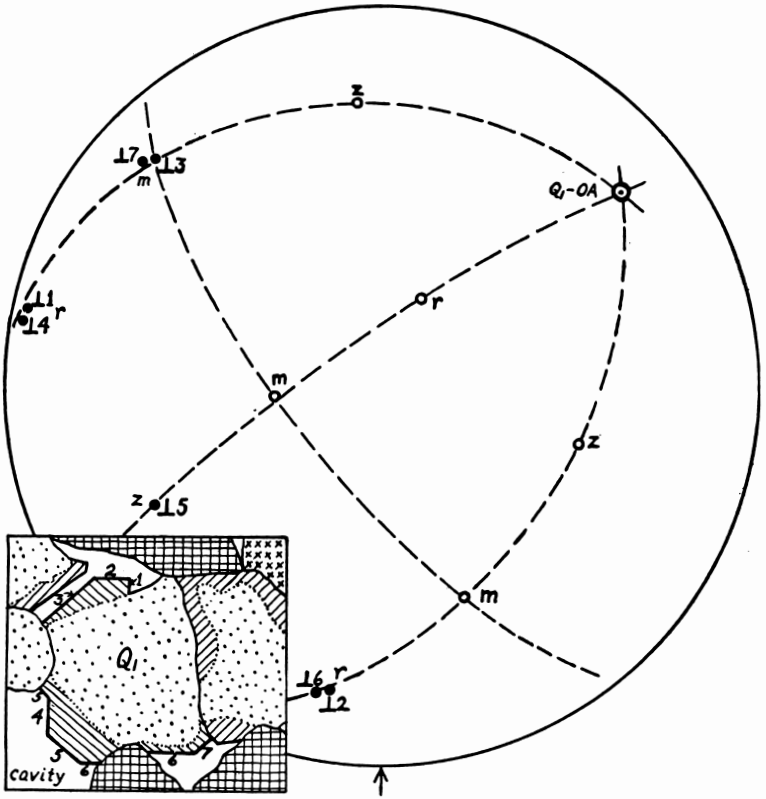


Fig. 2. Equal-area projection of quartz (Example 2).

the net. These angles are then compared with published angles for quartz to give a tentative identification of the various faces, as follows:

	Λ Optic axis	Suggested form	Correct angle (to nearest degree)
⊥ face #1	56°	r {10$\bar{1}$1} or z {01$\bar{1}$1}	52°
⊥ face #2	56°	r {10$\bar{1}$1} or z {01$\bar{1}$1}	52°
⊥ face #3	90°	m {10$\bar{1}$0}	90°
⊥ face #4	53°	r {10$\bar{1}$1} or z {01$\bar{1}$1}	52°
⊥ face #5	54°	r {10$\bar{1}$1} or z {01$\bar{1}$1}	52°
⊥ face #6	54°	r {10$\bar{1}$1} or z {01$\bar{1}$1}	52°
⊥ face #7	92°	m {10$\bar{1}$0}	90°

These results and an inspection of the points plotted on the projection suggest that among the seven faces three forms are represented; namely #3, #7 = $\{10\bar{1}0\}$; #1, #4 and #2, #6 = $\{10\bar{1}1\}$; #5 = $\{01\bar{1}1\}$. Alternatively #1, #4 and #2, #6 could be identified with $\{01\bar{1}1\}$ and #5 with $\{10\bar{1}1\}$. The above identification can be checked by two independent means, 1) the zone relationships of faces and 2) interfacial angles.

Zone relations: The poles of all prism faces must lie on a great circle (zone) 90 degrees from the optic axis. This great circle is drawn on Figure 2 and includes face #3 while face #7 is only slightly off the zone. Assuming that face #3 is the common unit prism $\{10\bar{1}0\}$, the poles of the other unit prism faces can be located on the same great circle by measuring 60 degrees on either side of face #3 and are shown as open circles labeled m. Now if the other faces are indeed unit rhombohedrons, each must be co-zonal with one of the prism faces and the optic axis. This condition is satisfied in this case as shown by the diagram where each of the faces in question lies on or very near one of these great circles. For reference, the poles of the other three faces of positive and negative unit rhombohedron forms are shown by open circles labeled r and z.

Interfacial angles: The angle between each pair of faces is measured from the projection net and compared with the correct interfacial angles for the forms identified. The results are as follows, where the correct angle is given in italics:

	Λ 2 (r)	Λ 3 (m)	Λ 4 (r)	Λ 5 (z)	Λ 6 (r)	Λ 7 (m)
1 (r)	89 *86*	34 *38*	2 *0*	47 *46*	89 *86*	32 *38*
2 (r)		65 *67*	89 *86*	48 *46*	2 *0*	66 *67*
3 (m)			36 *38*	67 *67*	67 *67*	2 *0*
4 (r)				47 *46*	87 *86*	34 *38*
5 (z)					46 *46*	66 *67*
6 (r)						68 *67*

Within the limits of accuracy obtainable with the universal stage, the angles check and the faces can be considered as satisfactorily identified.

Because the angles between optic axis and each of the various faces are independent of the interfacial angles, and both are independent of the zone relations, identifications checked by all three methods can be considered certain. Where only

two or three faces occur on a crystal the identification is possible in the same manner although it may be less convincing than with a larger number; but if a single face is present the only character available is the angle between the optic axis and the face, in which case identification is considered tentative or inconclusive.

It should also be apparent that the identification of crystal faces in this manner refers to crystal forms only and not to individual faces. Thus the positive (r) and negative (z) unit rhombohedrons in quartz cannot be distinguished. The writers follow the convention that if only one unit rhombohedron form is present it is called the positive one (r); if both are present either may be called positive (r) and the other negative (z).

Example 3.—The relationship between calcite and secondary quartz outgrowths in the Eocene McAdams sand of the Kettleman Hills area (U.C. #S3/7C) is illustrated by Figure 3. The inset sketch is highly idealized and illustrates a portion of a thin section showing a triangle of calcite (C) surrounded by a detrital quartz (stippled) with secondary outgrowths (diagonal lines). The cross-hatched areas are feldspar. The optic axes of two quartz grains (Q_1 and Q_2) and of calcite (C), together with the poles of faces #1, #2, #3 and the pole of a calcite cleavage, were located in the usual manner with the universal stage and plotted on the lower hemisphere of the equal-area projection net. The readings made with the stage were as follows:

Calcite optic axis	200 ← 56	⊥ face #1	196 ← 26
$Quartz_1$ optic axis	254 ← 24	⊥ face #2	126 ← 34
$Quartz_2$ optic axis	195 ← 65	⊥ face #3	339 → 13
Calcite cleavage	182 ← 14		

The angle between the optic axis of calcite and the pole of the calcite cleavage as measured from the projection net is 43 degrees. Since this angle agrees as well as can be expected with the correct angle ($44\frac{1}{2}°$) between the c axis and rhombohedral cleavage of calcite, it can be assumed that the fracture plane measured is indeed the rhombohedral cleavage $\{10\bar{1}1\}$. With the pole of this cleavage and the optic axis (c axis) plotted on the projection, the positions of the other common rhombohedron faces of calcite can be located and are shown by open triangles labeled r ($\{10\bar{1}1\}$) and e ($\{01\bar{1}2\}$). None of these approximates the positions occupied by the poles of

faces #1 and #2, so that clearly neither of these faces is a common rhombohedron of calcite.

The angles between the optic axis of quartz$_1$ and the poles of faces #1 and #3 are 52 degrees and 89 degrees respectively,

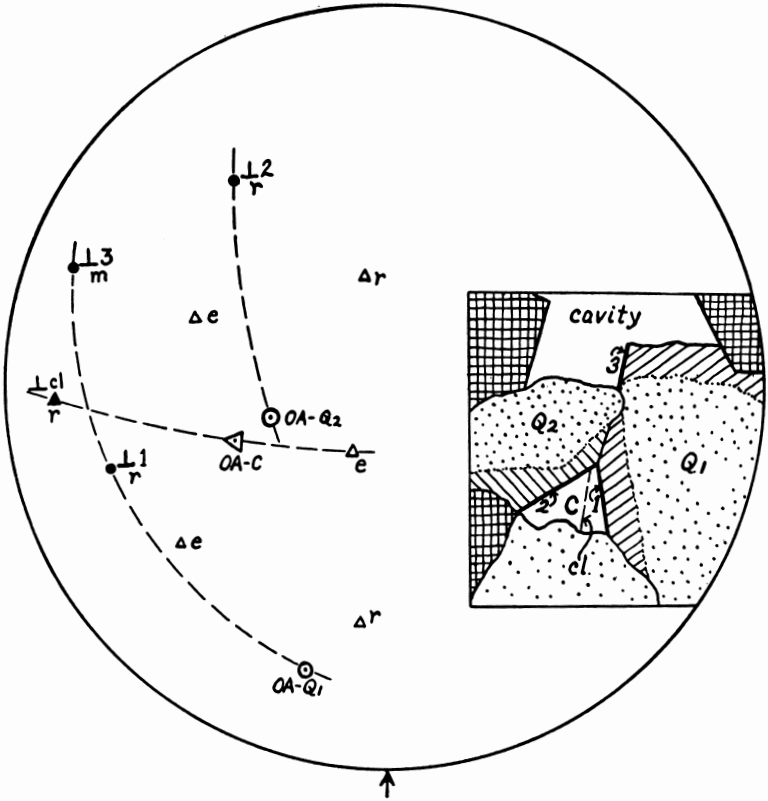


Fig. 3. Equal-area projection of calcite, C, and quartz, Q_1 and Q_2 (Example 3).

which agree with the correct angles for the unit rhombohedron r ($\{10\bar{1}1\}$) and unit prism, m ($\{10\bar{1}0\}$) of quartz. Also these two faces are co-zonal with the optic axis (c axis). Thus face #1 is determined as the rhombohedron of quartz$_1$ and is not a rational face of calcite. The optic axis of quartz$_2$ is inclined to the pole of face #2 at an angle of 51 degrees, a value that agrees with identification of face #2 as the unit rhombohedron, r $\{10\bar{1}1\}$, of quartz$_2$. This determination appears reasonable but is not positive since only one face is to be found on quartz$_2$ and zonal relations and interfacial angles cannot be used as a check on the identification.

It is concluded that faces #1 and #2 are unit rhombohedrons on quartz outgrowths, Q_1 and Q_2 respectively, and are not rational faces of calcite as at first they would appear to be. Therefore, the calcite must have crystallized later than the quartz outgrowths and has filled a void bounded by previously developed faces of secondary quartz. This conclusion is borne out by similar observations made throughout this and other thin sections from the same formation. The same technique can be used to investigate the boundary between two different quartz outgrowths, such as the one shown in the inset sketch of Figure 3. Such boundaries generally approximate to plane surfaces; but results obtained by the writers indicate that most of them are not rational faces of either grain of quartz. This was the result in the case illustrated here and probably indicates that the two quartz outgrowths developed simultaneously.

Reference data.—For convenient reference the following crystallographic angles of quartz and calcite are given to the nearest degree.

TABLE I

Common crystallographic angles of quartz

c	axis	∧	⊥m	(10$\bar{1}$0)	90°
c	axis	∧	⊥r	(10$\bar{1}$1)	52°
c	axis	∧	⊥z	(01$\bar{1}$1)	52°
⊥m	(10$\bar{1}$0)	∧	⊥r	(10$\bar{1}$1)	38°
⊥m	(01$\bar{1}$0)	∧	⊥z	(01$\bar{1}$1)	38°
⊥m	(01$\bar{1}$0)	∧	⊥r	(10$\bar{1}$1)	67°
⊥m	(10$\bar{1}$0)	∧	⊥z	(01$\bar{1}$1)	67°
⊥r	(10$\bar{1}$1)	∧	⊥r	($\bar{1}$101)	86°
⊥z	(01$\bar{1}$1)	∧	⊥z	(1$\bar{1}$01)	86°
⊥r	(10$\bar{1}$1)	∧	⊥z	(01$\bar{1}$1)	46°

TABLE II

Angles to rhombohedron faces of calcite

c	axis	∧	⊥r	(10$\bar{1}$1)	45°
c	axis	∧	⊥e	(01$\bar{1}$2)	26°
⊥r	(10$\bar{1}$1)	∧	⊥r	($\bar{1}$101)	75°
⊥e	(01$\bar{1}$2)	∧	⊥e	($\bar{1}$012)	45°
⊥r	(10$\bar{1}$1)	∧	⊥e	($\bar{1}$012)	71°
⊥r	(10$\bar{1}$1)	∧	⊥e	(01$\bar{1}$2)	38°

DETERMINATION OF COMPOSITION OF FELDSPAR

For methods of determining the composition of twinned grains of feldspar as seen in thin sections the reader is referred to Nikitin (1936) and Turner (1947).

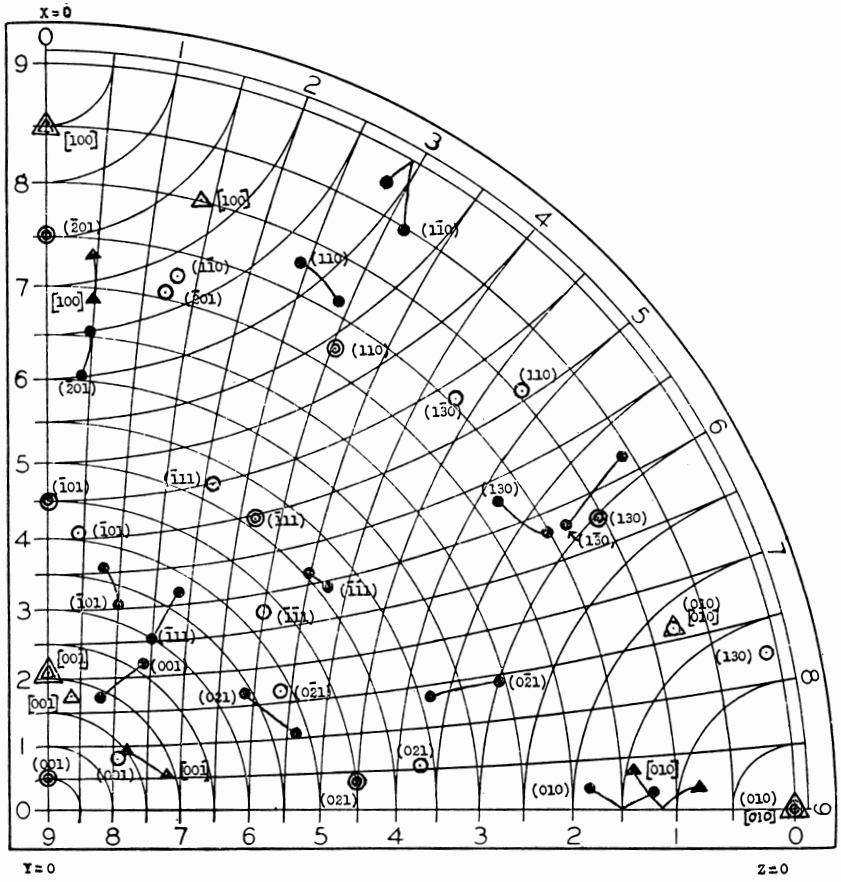


Fig. 4. Inclination of X, Y, and Z to axes and poles of faces in orthoclase, microcline, and albite. Triangles are axes; circles are poles of faces. Solid black points are albite (Ab_{100}-Ab_{90}) with label at pure albite; single circles and triangles are microcline; double circles and triangles are orthoclase.

A special case, of great importance in problems of diagenesis and cementation, is the determination of narrow rims (outgrowths) of secondary feldspar surrounding detrital feldspar grains, and of minute idiomorphic crystals of authigenic

feldspar. In such grains or outgrowths, whether seen in thin section or in individual grain mounts, it is commonly possible to locate approximately with a universal stage the positions of a number of crystal faces and the directions X, Y, and Z. These are plotted on a projection net (as in previous examples) and the three angles between the pole of each face and X, Y, and Z respectively are measured from the net and recorded. These angles are plotted from the appropriate corners of the stereographic diagram (after Nikitin, 1936, Pl. VII)reproduced as Figure 4, each set of three angles defining a point on the diagram. Even with the most favorable conditions and reliable measurements, the points thus obtained

TABLE III

Interfacial angles in feldspar to the nearest degree

		Orthoclase Microcline	Albite
(001) Λ (010)	zone of a axis	90	86°24′
(001) Λ ($\bar{1}$01)	zone of b axis	50	52
(001) Λ ($\bar{2}$01)	zone of b axis	80	82
(010) Λ ($\overset{+}{1}\bar{1}$0)	zone of c axis	59+	60+
(010) Λ ($\overset{+}{1}\bar{3}$0)	zone of c axis	29+	30+
(001) Λ ($\overset{+}{1}\bar{1}$0)		68	Λ (110) = 65; Λ (1$\bar{1}$0) = 69
(001) Λ ($\bar{1}$11)	co-zonal	55	Λ ($\bar{1}$11) = 56; Λ ($\bar{1}\bar{1}$1) = 58
($\bar{1}$11) Λ (1$\bar{1}$0)	co-zonal	57	55
($\bar{1}$01) Λ ($\bar{1}$11)		27	26
(010) Λ ($\overset{+}{\bar{1}}\bar{1}$1)	co-zonal	63	Λ ($\bar{1}$11) = 60½; Λ ($\bar{1}\bar{1}$1) = 66
($\bar{1}$11) Λ ($\bar{1}\bar{1}$1)	co-zonal	54	53
($\bar{2}$01) Λ (110)		46	46
($\bar{2}$01) Λ ($\bar{1}$11)	co-zonal	39	39
(110) Λ ($\bar{1}$11)	co-zonal	85	85
(001) Λ ($\overset{+}{1}\bar{3}$0)		78	Λ (130) = 74; Λ (1$\bar{3}$0) = 80
($\bar{1}$01) Λ ($\overset{+}{1}\bar{1}$0)		69	Λ (110) = 70; Λ (1$\bar{1}$0) = 66
($\bar{1}$01) Λ ($\overset{+}{1}\bar{3}$0)		78	Λ (130) = 80; Λ (1$\bar{3}$0) = 74
($\bar{2}$01) Λ ($\overset{+}{1}\bar{3}$0)		67	Λ (130) = 68; Λ (1$\bar{3}$0) = 62
($\bar{1}$11) Λ (130)		78	Λ (130) = 77; Λ (1$\bar{3}$0) = 52
($\bar{1}\bar{1}$1) Λ (130)		54	Λ (130) = 57; Λ (1$\bar{3}$0) = 82
(110) Λ ($\bar{1}\bar{1}$1)		57	57
(1$\bar{1}$0) Λ ($\bar{1}$11)		84	81

are not likely to coincide with labeled points representing the principal faces of feldspar, but by their proximity to labeled points they will serve to identify the faces measured and the nature of the feldspar. This identification can then be checked by means of interfacial angles and zone relations between faces. Particularly useful in this regard is the common face (and cleavage plane) {010}, since the angles between its pole and X, Y, and Z respectively vary significantly with the composition of the feldspars. Likewise, if the positions of any of the three crystallographic axes (a[100], b[010], c[001]) can be located on the projection net, the three angles between each of these axes and X, Y, and Z respectively can be plotted on Figure 4 and compared with the labeled axial points as a check on the identification of the feldspar in question. The axes are particularly useful in this connection because their mutual relations to X, Y, and Z vary considerably in the different feldspars.

Reference data.—Crystallographic and optical data used in determining low temperature feldspars by this method are

TABLE IV

Angles between X, Y, and Z and poles of common feldspar faces to nearest degree (After Nikitin, 1936, pp. 94-101)

	Orthoclase			Microcline			Albite (Ab_{100})			Albite (Ab_{90})		
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
⊥(010)	90	90	0	74	82	18	88	72	18	88½	78	12
⊥(001)	85	5	90	82	13	79½	68	26	76	73	19	82
⊥(110)	36	72	59½	49½	80½	42	28	78	66	33	76	61
⊥(1$\bar{1}$0)	36	72	59½	22	72½	77	32	85	58½	28½	87½	61½
⊥($\bar{1}$01)	45	45	90	49	41	86	60	32	80	54½	36	82
⊥(021)	86	45	45	85	53	37	73½	34	61	79½	38	54
⊥(0$\bar{2}$1)	86	45	45	73½	38	56½	75½	64½	30	76	56	37
⊥($\bar{2}$01)	15	75	90	23	70½	78	30	60½	86	25	65	85
⊥(130)	63	80	29½	78	89	12	57½	72½	38	62	75	32½
⊥(1$\bar{3}$0)	63	80	29½	46½	75½	47	62	77	31½	58½	84	32
⊥($\bar{1}$11)	50½	51	63	45	52	69	65	30	75	58½	37½	72
⊥($\bar{1}\bar{1}$1)	50½	51	63	62½	43	60	61	51	52½	58½	50½	55
c [001]	69	21	90	73	17½	87	85	19	72	81	15	78
a [100]	5	85	90	17½	80	76	22	69	85	17½	73	85
b [010]	90	90	0	74	82	18	86½	76	14	88	82	8

tabulated in Tables III and IV. The interfacial angles cited are measured between the normals to (poles of) faces in question. Within the limits of error involved in universal-stage measurements, the angle between any two faces may in most cases be regarded as identical for feldspar of any variety or composition.

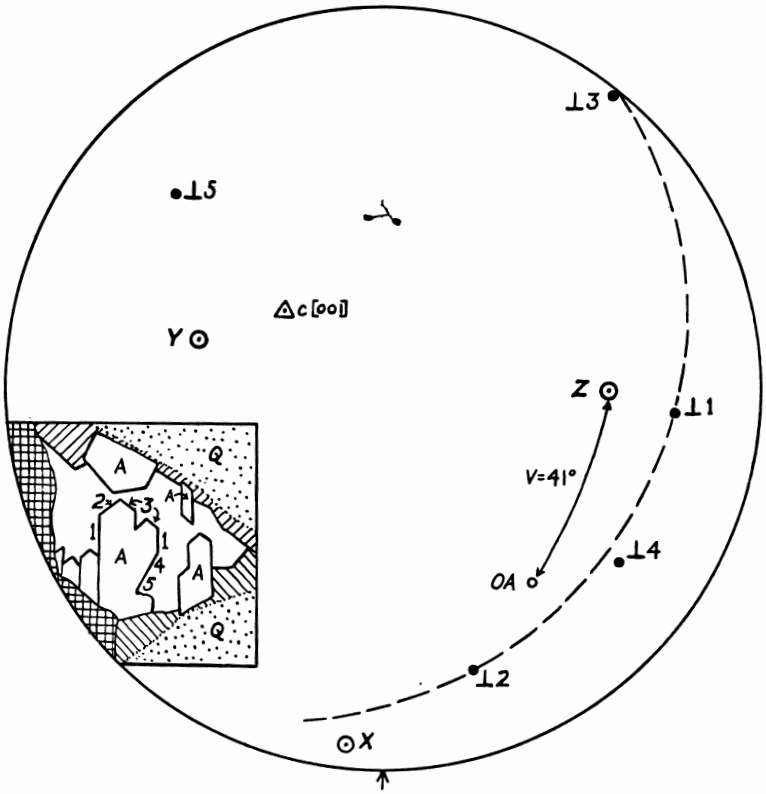


Fig. 5. Equal-area projection of albite (Example 4).

Example 4.—Authigenic albite from the Eocene McAdams sand of the Kettleman Hills area (U.C. #S3/10C) is illustrated by the equal area projection and inset sketch reproduced as Figure 5. In the sketch, the stippled areas are detrital quartz (Q) with secondary outgrowths shown by diagonal lines; cross-hatched areas are detrital feldspar, and euhedral crystals (A) are albite projecting into a cavity. The shapes of the albite crystals and the faces developed on them and

secondary quartz are not apparent unless the section is tilted; nor are they all apparent at any one position of tilt.

Measurements of X, Y, and Z, an optic axis, and the poles of all visible faces, made with a universal stage on the largest albite crystal, are as follows:

X	84 → 6	⊥ face #1	356 ← 24
Y	345 → 48 ↓ 29	⊥ face #2	288 ← 24
Z	0 ← 40	⊥ face #3	52 ← 2
		⊥ face #4	324 ← 24
		⊥ face #5	317 → 26

Plotted on the lower hemisphere of a equal-area projection net, these readings appear as the points shown in Figure 5. The three angles between X, Y, and Z and the pole of each face are read from the projection net and the faces tentatively identified by plotting these angles on the diagram reproduced as Figure 4, with the following results:

	∧X	∧Y	∧Z	Crystal form represented
⊥ face #1	88	72	17	(010) of Ab_{100}
⊥ face #2	28	88	61	(1$\bar{1}$0) of Ab_{91}
⊥ face #3	34	76	60	(110) of Ab_{90}
⊥ face #4	60	75	34	(130) of Ab_{95} or (1$\bar{3}$0) of Ab_{100}
⊥ face #5	61	31	77	($\bar{1}$01) or ($\bar{1}$11) of Ab_{100}

If the first four faces are correctly identified they must lie on a single great circle since they are all in the zone of the c axis (see Table III); as can be seen in Figure 5 this condition is satisfied. A further independent check on the identity of the faces can be made by determining the interfacial angles from the projection net and comparing these with the proper angles given in Table III. Face #5 in particular is not certainly identified by the angles between its pole and X, Y, and Z respectively, which indicate that it may be either (($\bar{1}$01) or ($\bar{1}$11); but the ambiguity is removed by referring to the interfacial angles. These prove that face #5 is the unit pyramid ($\bar{1}$11). Similarly angles to faces #2 and #3 prove that face #4 is (1$\bar{3}$0), not (130). The following tabulation shows the measured interfacial angles and, for comparison, the correct angles in italics.

	Λ⊥#2 (1$\bar{1}$0)		Λ⊥#3 (110)		Λ⊥#4 (1$\bar{3}$0)		Λ⊥#5 ($\bar{1}$11)		($\bar{1}$01)
⊥ #1 (010)	62	*60*	59	*60*	29	*30*	62	*61*	*86*
⊥ #2 (1$\bar{1}$0)			60	*59*	33	*30*	58	*55*	*66*
⊥ #3 (110)					87	*89*	85	*85*	*70*
⊥ #4 (1$\bar{3}$0)							50	*57*	*80*

With the faces thus certainly identified, the c axis [001], can be located on the projection net since it is parallel to faces #1, #2, #3, and #4; that is, it is the pole of the great circle through the poles of these faces. Located as it is from four faces considered conjointly, the position of the c axis [001], is probably more reliable than the position of any single face. Its inclination to X, Y, and Z plotted on Figure 4 agrees closely with that of pure albite.

It is concluded that the idiomorphic feldspar crystal in question is nearly pure, untwinned albite having a Baveno habit. The smaller crystals present in the same cavity are similar but they have fewer faces developed. The accuracy obtained in these measurements is about all that can be expected with the universal stage, but great precision is not required for satisfactory identification, particularly if the angular relation between X, Y, and Z and one of the pinacoids or one of the crystallographic axis is known.

By the use of these methods and similar ones applied to quartz (see examples 2 and 3), the relationship between this albite and the secondary quartz outgrowths in contact with it can be determined. Quartz is molded around idiomorphic albite (particularly the upper left part of the sketch in Figure 5), but the albite crystals appear to have grown on top of thin quartz outgrowths. These latter bottom contacts of albite against secondary quartz are not rational faces of either mineral, and it is concluded that the two crystallized more or less simultaneously or that their periods of crystallization overlapped.

Example 5. — Authigenic feldspars are fairly numerous among the light minerals in the Santa Margarita sandstone, southern Santa Cruz County, California. Figure 6 is an equal-area projection of a crystal of authigenic orthoclase from this formation (U.C. #S1/29).

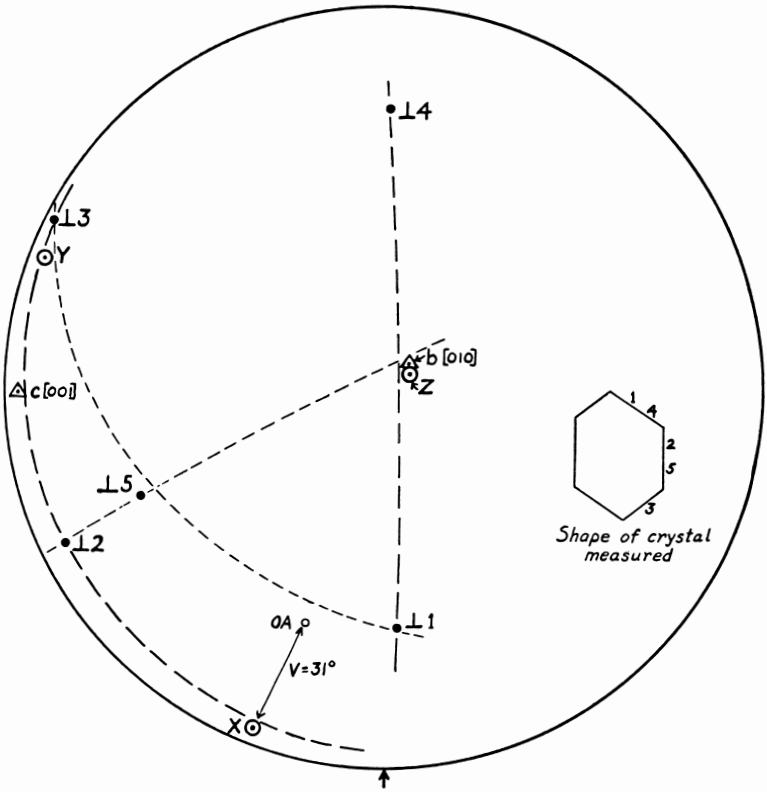


Fig. 6. Equal-area projection of orthoclase (Example 5).

The following measurements made with the universal stage were plotted on the projection net (Figure 6):

	X	69 → 4
	Y	339 → 4 ↓ 55
⊥	face #1	93 → 36
⊥	face #2	26 → 7
⊥	face #3	333 → 2
⊥	face #4	89 ← 28
⊥	face #5	24 → 30

The position of Z is plotted 90 degrees from X and Y. The angles between X, Y, and Z and the pole of each of the five faces is read from the projection net, and the probable form of each face is determined by plotting these angles on the diagram reproduced as Figure 4, with the following results:

	∧X	∧Y	∧Z	Crystal form represented
⊥ face #1	39	74	56	{110} of orthoclase
⊥ face #2	43	47	89	{$\bar{1}$01} of orthoclase
⊥ face #3	85	6	88	{001} of orthoclase
⊥ face #4	37	71	60	{110} of orthoclase
⊥ face #5	49	49	66	{$\bar{1}$11} of orthoclase

An independent check on this identification of the faces may be obtained by measuring the interfacial angles on the projection net and comparing them with the correct interfacial angles for orthoclase (Table III). The agreement is good as shown by the following tabulations where the correct angles are italicized.

	∧⊥#2 ($\bar{1}$01)		∧⊥#3 (001)		∧⊥#4 (110)		∧⊥#5 ($\bar{1}$11)	
⊥ #1 (1$\bar{1}$0)	68	*69*	68	*68*	61	*61*	57	*57*
⊥ #2 ($\bar{1}$01)			53	*50*	70	*69*	23	*27*
⊥ #3 (001)					66	*68*	56	*55*
⊥ #4 (110)							85	*84*

Another independent check is obtained by using the b and c crystallographic axes. Since faces #1 and #4 are two faces of the unit prism, the c axis [001] is the normal to the great circle passing through the poles of these two faces; likewise the b axis [010] is the normal to the great circle passing through the poles of faces #2 and #3, ($\bar{1}$01) and (001) respectively. The angles between each of these axes and X Y, and Z are read from the projection net and plotted on Figure 4. Furthermore, the angles between each crystallographic axis and the poles of faces (other than those used to locate the axis) can be measured and compared with the correct angles for an additional check if necessary. In the present case, the agreement is good between all of these angles and the corresponding correct angles for orthoclase.

The zone relations between poles of faces, crystallographic axes, and indicatrix axes should also be checked in connection with this identification, particularly where combinations of three or more co-zonal faces are present. In the present example, faces #1 (1$\bar{1}$0), #3 (001), and #5 ($\bar{1}$11) should be co-zonal if they have been correctly identified; Figure 6 shows that they are. Likewise, faces #2 ($\bar{1}$01) and #5 ($\bar{1}$11) and the b axis [010] should be and are co-zonal within the limits of error of measurement. Also if faces #2 and #3 respectively

are ($\bar{1}01$) and (001) of orthoclase, the great circle containing their poles should include X, Y, and the c axis [001], a condition which is satisfied in Figure 6.

RAPID DISTINCTION BETWEEN QUARTZ AND CLEAR FELDSPAR

Statistical investigation of the relative amounts of the principal light constituents in sandstones involves rapid distinction between alkali feldspars (with refractive indices below that of Canada balsam), plagioclase (oligoclase or a more calcic variety), and quartz. Clear grains of plagioclase without obvious twinning are not uncommon and are difficult or impossible to distinguish quickly from quartz by ordinary means. The universal stage is an efficient device for this purpose. Its use has previously been recommended by Doeglas (1940), but the procedure outlined by him, namely, that required for general distinction of uniaxial from biaxial minerals, is unnecessarily complex. The problem involved is the particular case of distinguishing a *positive* uniaxial mineral (quartz) from a biaxial mineral with large optic axial angle (feldspar), and can be solved simply and quickly as follows:

1) Set the north-south and east-west rotation axes of the stage near the zero positions. With the grain in question illuminated between crossed nicols, insert the gypsum plate and note whether the reaction is one of compensation or addition. Remove the plate and rotate on the innermost vertical axis of the stage so as to bring the grain into extinction with its slow direction (Z′) parallel to the north-south axis.

2) Tilt through any angle on the east-west axis of the stage. If the grain becomes illuminated (passes out of extinction), it is not quartz. If it stays in extinction for all positions of tilt on the east-west axis, it is probably quartz; but the same effect would result from a grain of feldspar oriented with X or Y parallel to the east-west axis of the stage—a most unlikely possibility.

3) To eliminate this latter possibility, tilt to any new angle on the north-south axis, and rotate on the innermost vertical axis until the grain is again in extinction with its slow direction (Z′) parallel to the north-south axis. If the grain again remains dark for all positions of tilt on east-west axis, it is uniaxial and positive (i.e., it is quartz).

If the grain is oriented with the optic axis nearly perpen-

dicular to the plane of the slide, the test may be more decisive if the gypsum plate is retained in position throughout. Extinction of the grain is then indicated not by darkness, but by the unmodified first order red color of the plate.

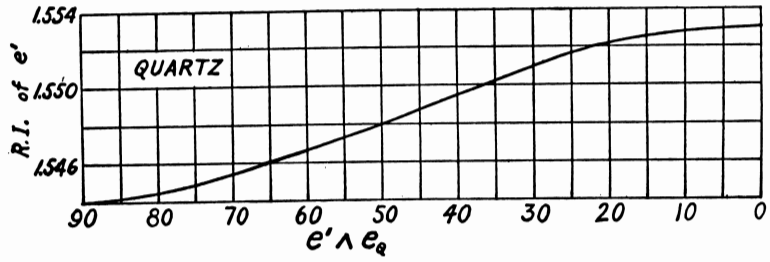
In practice the writers have found that a procedure involving steps #1 and #2 alone will yield reliable results in statistical work. The possible misidentification of quartz mentioned in step #2 is unlikely, but in any case the error arising from this cause is probably less than the sampling error in grain counts of 100 to 200 grains. Also the procedure described is used in practice only if a grain cannot be identified quickly by other means (refractive index, cleavage, or twinning). Carried out in this way the operation is very nearly as rapid as any other microscopic method involving counting, and is considerably more reliable.

OPTICAL DISTINCTION BETWEEN CALCITE AND DOLOMITE

Emmons (1943, p. 189) has described an optical method of distinguishing calcite from dolomite, based upon the difference in the refractive index of the extraordinary ray (epsilon) in these two minerals (1.50 in dolomite; 1.486 in calcite). With the north-south and east-west axes of the stage at zero, a section of carbonate bounded by Canada balsam is brought to extinction with the fast direction (e′) parallel to the north-south axis. The analyser is removed, and the section is tilted on the east-west axis until the refractive index of the carbonate exactly matches that of Canada balsam. Both the angular position around the inner vertical axis and the angle of tilt on east-west are read in order to locate e′ (for which R.I. = 1.540) on a projection net. The position of the optic axis (e) is now located in the usual way and plotted on the projection. The angle e Λ é (optic axis Λ é) is 29½ degrees in the case of dolomite, or 36 degrees for calcite. Smaller angles than 29½ degrees indicate ankeritic dolomite (e.g., 24½ degrees for dolomite in which there is 20% replacement of Mg by Fe).

The writers have found that a modification of this method may sometimes be applied in thin sections to grains of carbonate adjoining quartz—a condition commonly encountered where a sandstone is cemented by calcite or dolomite. The procedure is as follows:

1) Locate the respective optic axes in the carbonate grain (e_c) and in the adjoining quartz grain (e_q). On the projection net draw the great circles respectively normal to the two optic



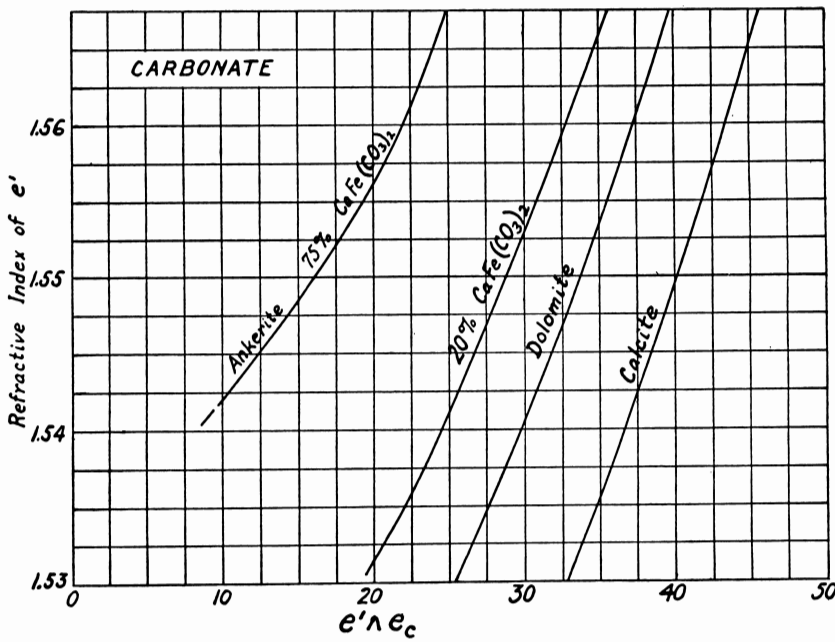


Fig. 7. Refractive index of é in quartz and carbonate.

axes. These great circles intersect in a point representing a common line lying in the basal planes of both crystals, and which is therefore a possible ordinary ray direction for both quartz and carbonate.

2) With the east-west axis at zero, rotate the section on the innermost vertical axis and tilt on the north-south axis so as to bring the common ordinary ray direction parallel to the east-west axis. (The appropriate angles of rotation and tilt are first read from the projection). If these two operations have been performed accurately, both grains will remain in extinction for any angle of tilt on the east-west axis.

3) With the analyser removed, tilt on the east-west axis until the refractive indices of the quartz and carbonate exactly match. Light in both crystals is now vibrating north-south in a common direction (e′), which is plotted on the projection net. The angle between e′ and the optic axis of quartz (e_q) is now read from the projection net and the refractive index of e′ determined from the upper curve of Figure 7. This index of refraction plotted against the angle between e′ and the optic axis of carbonate (e_c) on the lower set of curves in Figure 7 should identify the carbonate.

Quartz-carbonate pairs in which one of the two grains is oriented with its optic axis nearly normal to the plane of the section are most favorable for measurement, since only a small angle of tilt is then necessary to bring the common ordinary ray direction parallel to the east-west axis (step 2). The degree of reliability of this method, whether as originally described by Emmons or in the modified form just presented, depends mainly on the accuracy with which the refractive index of a mineral may be matched with that of the adjacent medium. In the writers' experience the range of determined values in the angle of $e_c \Lambda e'$ in grains of a single carbonate mineral is in some cases too great for reliable identification of the mineral as calcite or dolomite. In other cases where clear-cut boundary surfaces between the media were readily observed and a good research microscope was used, the results were found to be consistent and distinction between calcite and dolomite was made with some confidence. Distinction of ankeritic dolomite from calcite is more reliable on account of the higher refractive index of the former mineral as compared with pure dolomite.

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