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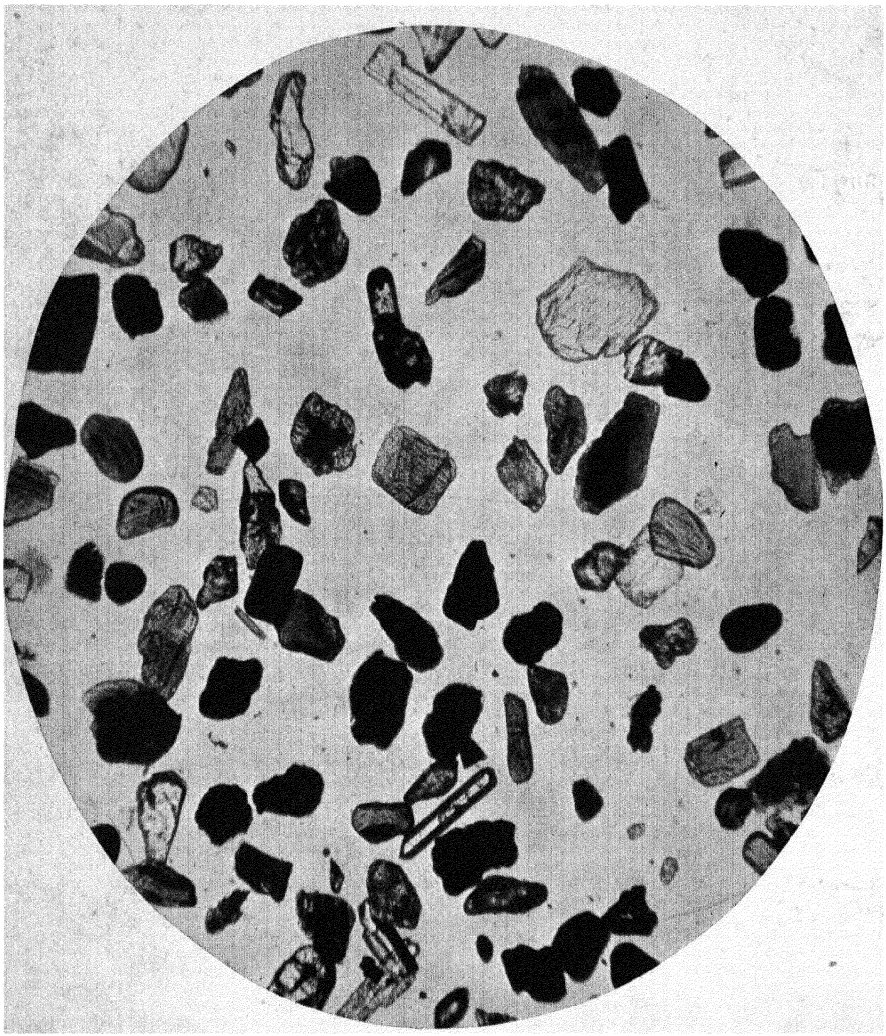
# THE EXAMINATION OF FRAGMENTAL ROCKS



HEAVY MINERAL GRAINS FROM GALVESTON, TEXAS, BEACH SAND (× 80)

Composed principally of augite, basaltic hornblende, kyanite, monazite, pargasite, tourmaline, and zircon

# *The* Examination *of* Fragmental Rocks

*Revised Edition*

*By*

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# PREFACE

THE examination of mineral fragments, whether in bulk or in grain, has claimed the attention of many workers in the applied physical sciences. Among those exhibiting interest in this subject, and contributing largely to it, are mineralogists, geologists, ceramists, hydrologists, petroleum engineers, metallurgists, and chemical engineers.

It is the purpose of this manual to present some of the investigative methods developed by these various specialists that may be of common interest and utility to all of them.

The methods of bulk analysis, such as for grain-size distribution, porosity, etc., have not been standardized, and it is highly desirable for the workers in one field to know the methods that have been perfected in other fields. Geologists and hydrologists, for example, may well profit by some of the methods worked out by ceramists. The author has endeavored to present some of the best methods from the various technologies, and the bibliography has also been selected with this end in view.

The treatment of this book is not one for elementary students, but it should be followed readily by one who has had the ordinary scientific fundamentals.

The section on the optical identification of mineral grains does not presuppose a knowledge of optical mineralogy, and the treatment is practical rather than theoretical. The mineral tables present a dichotomous classification which, together with the chapter descriptive of minerals, makes comparatively simple and rapid the recognition of the species commonly found in clastic mineral aggregates.

Some of the methods described were developed for a petroleum-research project, and the author wishes gratefully to acknowledge the assistance of the following companies which contributed financially to that research: Associated Oil Company, General Petroleum Corporation, Marland Oil Company, Pacific Oil Company, and Standard Oil Company of California.

F. G. T.

STANFORD UNIVERSITY, CALIFORNIA
March 1931

# PREFACE TO THIRD EDITION

This edition is mainly a reprinting of the second edition, except for a rewritten discussion of "degree of rounding" and the description of an improved apparatus for sedimentation analysis. Errors of the older text have been corrected.

F. G. T.

STANFORD UNIVERSITY
July 1947

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# THE EXAMINATION OF FRAGMENTAL ROCKS

## I

## INTRODUCTION

THE physical examination of clastic sedimentary rocks and of other crystalline aggregates is a necessary or desirable part of many technical investigations.

Some of the substances that may profitably be examined or tested by physical methods are:

1. Glass sand
2. Moulding sand
3. Ceramic raw materials and products
4. Portland cement
5. Mineral constituents or impurities in various manufactured substances
6. Building stone
7. Sedimentary rocks, in geological studies
8. Sedimentary rocks, in the correlation of strata penetrated by oil wells
9. Crystalline chemical compounds
10. Concrete mixtures
11. Filtration sands
12. Soils
13. Oil sands
14. Water sands
15. Rotary drilling muds
16. Ore and gangue minerals encountered in ore-dressing investigations
17. Sands and crushed materials for abrasives

The physical attributes of these materials that may, for one purpose or another, be examined are:

*a*) State of aggregation
*b*) Grain size
*c*) Grain shape
*d*) Density
*e*) Porosity
*f*) Permeability
*g*) Mineral content

Other properties, such as thermal and electrical conductivity, sorptive power, plasticity, mechanical strength, etc., are often of technical importance but do not come within the scope of this book.

The properties of significance and the methods of examination will necessarily depend upon the material to be studied and the object in view. A complete physical examination is very seldom required, the investigator usually being interested either in the properties of the rock as a whole or in the separate constituents of the rock.

The geologist or the petroleum engineer, in studying the movements of fluids through buried sediments, does not, as a usual thing, need more than a general knowledge of the minerals composing the sediments, but is interested principally in state of aggregation, porosity, and permeability. In studying the same sediments, however, for the purpose of ascertaining their source, tracing their continuity over a given area, or delineating the sub-surface geological structure, he is more likely to pay principal attention to the composition and shape of the constituents of the rock.

A selected bibliography of the subject is provided at the end of the book.

II

# SIZE ANALYSIS

## Grain size

The size of grains in a heterogeneous aggregate may be expressed in various ways, and the form chosen will depend upon the state of aggregation of the material and the purpose and method of the determination.

The size analysis is:

1. Visual
2. Mechanical
3. Both visual and mechanical

Visual analysis is useful for determining:

*a*) Maximum and/or minimum grain size
*b*) Average grain size
*c*) Degree of rounding

Visual analysis is usually performed with the aid of a microscope, a camera, or both. Simple inspection with a microscope and a micrometer eyepiece will suffice to determine maximum or minimum grain size, and will give a qualitative idea of the degree of rounding; and micrometer measurements on a fairly large number of grains will give an approximation of average grain diameter.

In the technology of pigments, fillers, filtration clays, and other very finely divided substances, the microscope is used successfully for the determination of average particle size and of particle size distribution.

A method used by Green[1] was to photograph a slide, evenly strewn with the particles, and to project the negative upon a ruled screen so as to give a total magnification of about 20,000 diameters; the average diam-

[1] Green, Henry, "A Photomicrographic Method for the Determination of Particle Size of Paint and Rubber Pigments," *Jour. Franklin Inst.*, 192: 637–66. (1921.)

eters of the individual grains are then read with a millimeter scale and a size-frequency distribution is made.

Where the grains are prismatic and elongated, the best value for the average diameter of a grain is the harmonic mean; that is,

$$d_{av} = \frac{3lbt}{lb + lt + bt}$$

where $l$, $b$, and $t$ are the length, breadth, and thickness, respectively. In this case, $b$ and $t$ may be taken as equal. For more equant grains, however, the formula $d_{av} = \sqrt{l \times b}$ may be used; or it is probably as accurate to estimate by eye the diameter of a circle whose area is equal to that of the grain. Another method is to measure the diameter of the particles always in one direction with respect to the microscopic field.

A grid-micrometer ocular was used by Perrott and Kinney[2] and by Weigel.[3] By this method a count is made of the grains in each square of the grid that lies within a certain size range. Another count is then made for the next smaller size range, and so on down to the smallest grains, higher-power objectives being used as occasion demands. For sized material, where all of the particles can be measured with a single objective, the process may be shortened by measuring all particles in a field at the same time. A mechanical stage is very helpful in moving from one field to another so as to cover the whole slide, where this is desirable, without repeating measurements on any of the grains.

The particle size record is made on some such form as is shown in Fig. 1, the grouping of the tally marks indicating roughly the form of the frequency distribution curve. The character of this distribution may be calculated by the methods described on page 22.

### *Averages of Particle Size*

In Fig. 1, the average particle size is computed by five different formulas.[4] The values would all be the same for material having particles all of the same size, and they become less concordant as the size uniformity of the material decreases.

The *arithmetical mean* is the one most commonly employed, but it has little physical significance for heterogeneous material, and a small proportion of large grains has small effect on influencing the average.

[2] Perrott, G. St. J., and Kinney, S. P., "The Meaning and Microscopic Measurement of Average Particle Size," *Jour. Amer. Ceramic Soc.*, **6**: 417–39. (1923.)

[3] Weigel, W. M., "Size and Character of Grains of Non-metallic Mineral Fillers," *U.S. Bureau of Mines Tech. Paper 296.* (1924.)

[4] Weigel, *op. cit.*, p. 21.

The *length mean* is based on the surface presented to the observer, and the total surface or volume of the particle does not affect it.

**PARTICLE SIZE DISTRIBUTION**

MATERIAL, Diatomite.

SOURCE, Bradley, Calif.

1 micrometer scale division = 12.5 microns.

| Scale Div. | | Count | Freq | Products | | | |
|---|---|---|---|---|---|---|---|
| Range | d | | n | nd | $nd^2$ | $nd^3$ | $nd^4$ |
| 0.5-1.0 | .75 | | - | - | - | - | - |
| 1.0-1.5 | 1.25 | /// | 3 | 4 | 5 | 6 | 7 |
| 1.5-2.0 | 1.75 | //// | 4 | 7 | 12 | 21 | 37 |
| 2.0-2.5 | 2.25 | //// //// | 10 | 22 | 51 | 114 | 257 |
| 2.5-3.0 | 2.75 | //// //// //// | 15 | 41 | 114 | 312 | 860 |
| 3.0-3.5 | 3.25 | //// //// //// //// //// | 48 | 156 | 507 | 1645 | 5340 |
| 3.5-4.0 | 3.75 | //// //// //// //// //// //// // | 52 | 195 | 732 | 2640 | 10140 |
| 4.0-4.5 | 4.25 | //// //// //// //// //// //// //// / | 51 | 216 | 923 | 3915 | 16630 |
| 4.5-5.0 | 4.75 | //// //// //// //// //// //// /// | 38 | 180 | 859 | 4070 | 19350 |
| 5.0-5.5 | 5.25 | //// //// //// / | 16 | 84 | 441 | 2315 | 12150 |
| 5.5-6.0 | 5.75 | //// //// //// / | 16 | 92 | 529 | 3045 | 17500 |
| 6.0-7.0 | 6.5 | //// //// /// | 13 | 84 | 550 | 3570 | 23200 |
| 7.0-8.0 | 7.5 | //// //// | 10 | 75 | 562 | 4219 | 31600 |
| 8.0-9.0 | 8.5 | /// | 3 | 25 | 217 | 1840 | 15700 |
| 9.0-10. | 9.5 | /// | 3 | 28 | 271 | 2570 | 24400 |
| 10.0-11. | 10.5 | | - | - | - | - | - |
| | | TOTALS | 282 | 1212 | 5773 | 30582 | 177172 |

Arithmetical Mean $= \frac{\Sigma nd}{\Sigma n} = \frac{1212}{282} = 4.3$ div. $= 53.8$ microns

Length Mean $= \frac{\Sigma nd^2}{\Sigma nd} = \frac{5773}{1212} = 4.8$ " $= 59.5$ "

Average Volume $= \left[\frac{\Sigma nd^3}{\Sigma n}\right]^{\frac{1}{3}} = \left[\frac{30582}{282}\right]^{\frac{1}{3}} = 4.8$ " $= 59.5$ "

Surface Mean $= \frac{\Sigma nd^3}{\Sigma nd^2} = \frac{30582}{5773} = 5.3$ " $= 66.3$ "

Weight Mean $= \frac{\Sigma nd^4}{\Sigma nd^3} = \frac{177172}{30582} = 5.8$ " $= 72.5$ "

FIG. 1.—Log and computation sheet for particle size determination with the microscope

The *average volume mean* may be considered as that diameter whose corresponding volume divided into the total volume equals the total num-

ber of grains. It gives results larger than the arithmetical or length mean, but the large grains of a mixture, where small grains greatly predominate, scarcely affect the average.

The *surface mean* is based on the total surface of the particle, and is thought to give the best value for non-metallic minerals that are to be used as fillers, pigments, or filters.

The *weight mean* is based on the volume of the particles and gives, as shown in Fig. 1, larger results than any of the other expressions. It is of use in the study of pulverized coal and in ore-dressing problems. Suppose, for example, that a mill tailing consists of quartz with some galena attached to the quartz grains. The adherent galena will be, in general, proportional to the fineness of grinding. If a particle size distribution is obtained for a sample ground to a certain size, the weight mean will represent a diameter of particle of just the size to have the same proportionate amounts of quartz and galena as the chemical analysis shows for the bulk sample.

### *Degree of Rounding*

Degree of rounding may be given a numerical expression according to methods proposed by several authors. The roundness numbers shown in Fig. 2 were obtained by application of the following formula:

$$\text{roundness number} = \frac{\text{grain area}}{\text{area of smallest circle that will circumscribe the grain}}$$

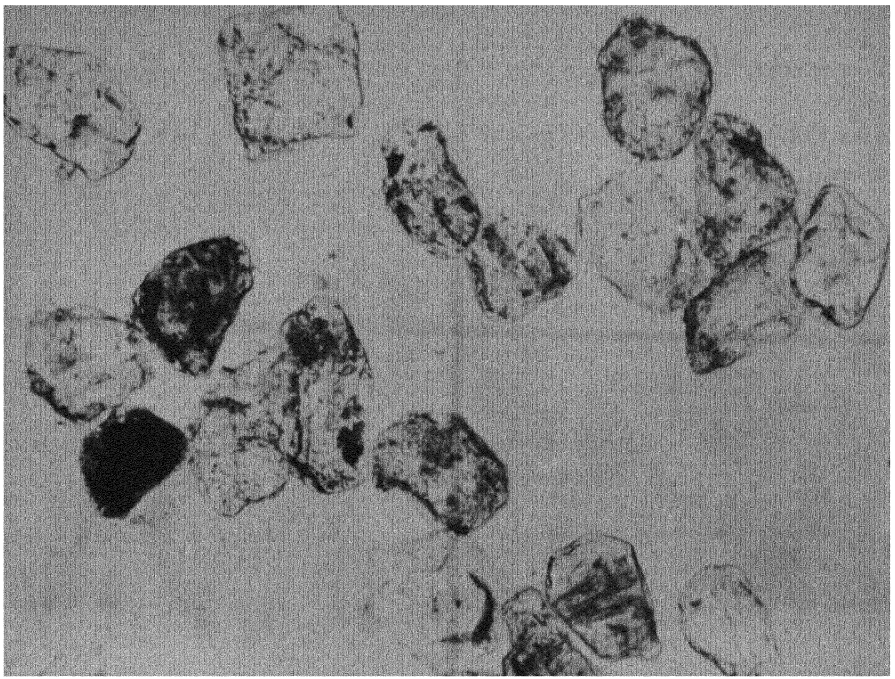
Tracings of the grain outlines may be obtained either by the use of an Abbé drawing apparatus attached to the microscope or by the employment of photomicrography. The grain areas may most conveniently be found by use of a planimeter.

A method proposed by Riley[5] requires the measurement of the diameters of the smallest circles that may be inscribed within and circumscribed about the grain projection. The roundness number is defined as follows:

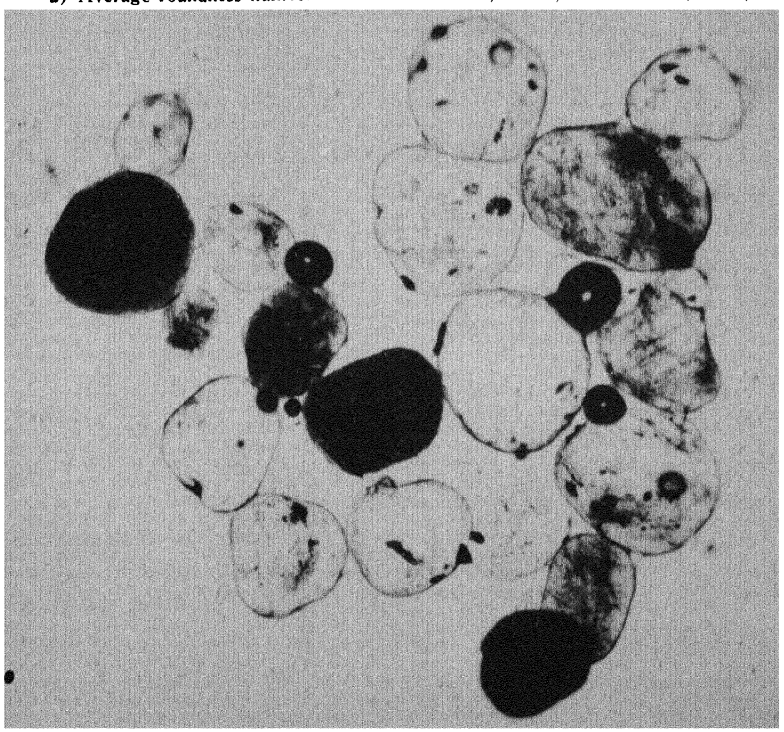
$$\text{sphericity} = \sqrt{\frac{d_i}{d_c}}$$

$d_i$ and $d_c$ are the diameters of the inscribed and circumscribed circles.

[5] Riley, N. A., "Projection Sphericity," *Jour. Sed. Petr.*, **11** (No. 2): 94–97. (1941.)



*a*) Average roundness number = 0.69. Galveston, Texas, Beach Sand (× 110)



*b*) Average roundness number = 0.80. Whitehorse Sandstone, Oklahoma (✕ 35)

FIG. 2.—Roundness of grains

It should be borne in mind that both of these roundness numbers are used upon the assumption that the grains are not lying on a greatly flattened side, as is the case with mica, etc. If, for example, the grains are predominantly feldspars, and are rounded cleavage flakes, they should be imbedded in balsam and a polished surface made. This surface may be photographed by reflected light and the grains will have random orientations.

The grain-circle area method may be extended in its application to pebbles. In this case, the roundness number may be expressed more accurately as to the ratio of the volume of the grain to the volume of the smallest enveloping sphere, the diameter of which will be the largest dimension of the pebble. The volume of the pebble may be obtained by the usual method of weighing in air and in water. Of course, this roundness number could not be identified with the grain-circle area number obtained from any cross-section of the same pebble. For example, the roundness number of a cube would be 0.368, whereas the least roundness number that could be obtained for any sectional area of a cube (the square section) would be 0.65. That is to say, the numbers are comparable only with other numbers obtained in a like manner.

### *Sizing*

Mechanical analysis gives an estimate of grain size distribution, the most complete statement of which is some form of the frequency curve. The analysis is made by a procedure usually called "sizing."

Sizing is an operation that is useful for two purposes: (1) to determine the frequency distribution of the various sized particles, and (2) to obtain grains of the material of the right size for microscopic examination.

These purposes may be attained by one of two methods of sizing: (1) screening; (2) water classification. Employment of the last-named method rests upon the assumption that all particles in the sample have the same density.

**Screen analysis.** Mechanical analysis by means of screens is a matter of everyday practice in ore dressing, cement testing, and other industrial operations. The screens that are manufactured in this country for these purposes have attained a considerable degree of standardization and perfection, and it would seem desirable to make use of these standardized screens for the sizing of mineral grains if such is compatible with the requirements. It has been pointed out by Gardescu[5a] that the use of uncalibrated screens may lead to erroneous results but, on the other hand,

[5a] Gardescu, I. I., and Billings, M. H., "Use of Mechanical Sand Analyses for Correlation Purposes," *Bull. Amer. Assoc. Petr. Geol.*, **2**: 1311–32. (1937.)

Krumbein[5b] found that the error of sampling is likely to be much greater than the error of testing.

For the description of sediments, the Wentworth scale (Table 1)[6] has gained rather wide adoption.

TABLE 1

THE WENTWORTH SCALE FOR GRADES OF SEDIMENTS

| Sediment | Size of Particles (mm.) | Sediment | Size of Particles (mm.) |
|---|---|---|---|
| Boulder gravel | | Coarse sand | |
| | 256 | | ½ |
| Cobble gravel | | Medium sand | |
| | 64 | | ¼ |
| Pebble gravel | | Fine sand | |
| | 4 | | ⅛ |
| Granule gravel | | Very fine sand | |
| | 2 | | 1/16 |
| Very coarse sand | | Silt | |
| | 1 | | 1/256 |
| | | Clay | |

The United States Bureau of Soils[7] has also defined the limits of grades as in Table 2.

TABLE 2

UNITED STATES BUREAU OF SOILS, SIZE CLASSIFICATION OF SOILS

| Sediment | | Size of Particles (mm.) |
|---|---|---|
| Pebbles | Over | 10 |
| Gravel | | 10–1 |
| Coarse | | 10–2 |
| Fine | | 2–1 |
| Sand | | 1–.05 |
| Coarse | | 1–.5 |
| Medium | | .5–.25 |
| Fine | | .25–.05 |
| Silt | | .05–.005 |
| Clay | Under | .005 |

[5b] Krumbein, W. C., "The Probable Error of Sampling Sediments," *Amer. Jour. Sci.*, **27**: 204–14. (1934.)

[6] Wentworth, C. K., "A Scale of Grade and Class Terms for Clastic Sediments," *Jour. Geol.*, **30**: 377–92. (1922.)

[7] *U.S. Dept. Agric. Bur. of Soils Bull. No. 4.*

The standard screens of American practice (Table 3) are based upon the 200-mesh screen, with openings 0.074 mm. in width, and with a constant ratio between the successive sizes of $\sqrt{2}$. This means that the area of the openings of a given screen is just twice that of the next finer screen. For closer sizing, the series has a constant ratio of $\sqrt[4]{2}$ between sizes.

TABLE 3

AMERICAN (TYLER) STANDARD SCREEN SIZES

| Mesh | Openings (mm.) | Mesh | Openings (mm.) |
|---|---|---|---|
| 2½ | 7.925 | 28 | 0.589 S |
| 3 | 6.680 S | 32 | 0.495* |
| 3½ | 5.613 | 35 | 0.417 S |
| 4 | 4.699 S | 42 | 0.351 |
| 5 | 3.962* | 48 | 0.295 S |
| 6 | 3.327 S | 60 | 0.246* |
| 7 | 2.794 | 65 | 0.208 S |
| 8 | 2.362 S | 80 | 0.175 |
| 9 | 1.981* | 100 | 0.147 S |
| 10 | 1.651 S | 115 | 0.124* |
| 12 | 1.397 | 150 | 0.104 S |
| 14 | 1.168 S | 170 | 0.088 |
| 16 | 0.991* | 200 | 0.074 S |
| 20 | 0.833 S | 250 | 0.061* |
| 24 | 0.701 | 270 | 0.053 |

In the table above, the sizes marked "S" are those of the standard $\sqrt{2}$ series, the others being interpolated in the $\sqrt[4]{2}$ ratio. The sizes marked with an asterisk conform very nearly to the Wentworth scale; that is, a two-to-one ratio, beginning with 4 mm. as the largest.

This comparison is shown in the following table:

TABLE 4

COMPARISON OF WENTWORTH AND TYLER SIZES

| Wentworth Scale mm. | Nearest Corresponding Tyler Screen mm. | Mesh |
|---|---|---|
| 4 | 3.962 | 5 |
| 2 | 1.981 | 9 |
| 1 | 0.991 | 16 |
| ½ (= 0.5) | 0.495 | 32 |
| ¼ (= 0.25) | 0.246 | 60 |
| ⅛ (= 0.125) | 0.124 | 115 |
| 1/16 (= 0.062) | 0.061 | 250 |

For the grades between "pebble gravel" and "very fine sand," then, we have standard screens that very nearly conform with the various grades, and we may interpolate other sizes between for closer sizing. We may then propose a scale that makes possible the use of standard screens and, at the same time, conforms to the Wentworth scale within the limits of error of ordinary screening practice. This scale is provided in Table 5:

TABLE 5

SCALE FOR GRADES OF SEDIMENTS

| Sediment | Screen Mesh |
|---|---|
| Pebble gravel | + 5 |
| Granule gravel | − 5 + 9 |
| Very coarse sand | − 9 + 16 |
| Coarse sand | − 16 + 32 |
| Medium sand | − 32 + 60 |
| Fine sand | − 60 + 115 |
| Very fine sand | − 115 + 250 |
| Silt and clay | − 250 |

(+) indicates "retained on"
(−) indicates "passes through"

The separation into its constituents of the −250-mesh material is best accomplished by a method other than screening. Holmes[8] even contends that screening cannot be carried out satisfactorily with grains smaller than about 0.25 mm. (−60-mesh), but this is not borne out by modern screening practice.

**Water classification.** Water classification of small particles is based upon *Stokes' Law,* which states that a sphere will sink in a liquid at a velocity directly proportional to: (1) the square of the diameter; (2) the difference in density of sphere and liquid, and inversely proportional to the absolute viscosity of the liquid. A shape factor is important in this relationship if it is to be applied to mineral grains instead of spheres.

Stokes' equation may be stated as follows:

$$r^2 = \frac{9}{2} \frac{\mu h}{(\Delta - \delta) g t}$$

where:

$r$ = radius of settling particle (cm.)
$\mu$ = absolute viscosity (poise)
$h$ = distance settled (cm.)
$t$ = time (seconds) for particle to fall $h$ cm.

[8] Holmes, Arthur, *Petrographic Methods and Calculations* (1921), p. 204.

$\Delta$ = density of falling particle ($g$/cc.)
$\delta$ = density of settling medium
$g$ = acceleration due to gravity (980)

For particles whose density may be assumed to average 2.63, settling in water ($\delta = 1$; $\mu = 0.01$), and allowing for a shape factor, the equation reduces to the following:

$$d = \sqrt{\frac{v}{700}}$$

where

$d$ = diameter of settling particle (mm.)
$v$ = velocity of particle (mm./second)

The equation has been found to be substantially correct for quartz grain sizes between 0.15 and 0.015 millimeters.

Water classification is accomplished either by undisturbed settling or by rising current classification. The first of these usually involves decantation or siphoning of part of the grains held in suspension after a given time of settling. The second principle is applied with some form of rising current classifier (*elutriator*), in which, for a given water velocity, the larger particles settle and the smaller ones are carried into the discharge.

Both of these methods have serious shortcomings, and the simpler of them is perhaps as accurate as any. This is the method of undisturbed settling. It is accomplished in one way by mixing a weighed sample in a large beaker of water, allowing settling to take place until a drop removed from the middle of the column is found, by examination under the microscope (with micrometer ocular), to contain no grains larger than the predetermined size. The suspension is then removed from that same depth in the column by means of a siphon. The residue is diluted and the process repeated three or four times, after which the residue is filtered, dried, and weighed. The suspension may be reclassified by the same process.

Another method of undisturbed settling is based upon Stokes' Law and the work of Odén,[9] Svedberg,[10] and Schramm and Scripture.[11] This method may be described as follows:

The sedimentation apparatus is shown in Fig. 3, in which $A$ is a $1'' \times 12''$ pyrex tube, to the open end of which an annular brass disk is affixed by means of a suitable cement (such as litharge and glycerin).

[9] Odén, S., *Proc. Royal Soc. Edinb.*, **36**: 219. (1916.)

[10] Svedberg and Rinde, *Jour. Amer. Chem. Soc.*, **45**: 943 (1923.)

[11] Schramm, E., and Scripture, E. W., Jr., "The Particle Analysis of Clays by Sedimentation," *Jour. Amer. Ceramic Soc.*, **8**: 243–58. (1925.)

*B* is a brass cup attached to an identical brass disk, the two disks being ground together with fine abrasive until water will not leak through their junction. During sedimentation the assembly stands with the glass tube pointing upward. It is then advisable to stand it beneath a coil spring or weight, which presses on top of the tube and insures a tight joint between the two disks. The assembly may stand in a temperature-controlled water bath or in an atmosphere of constant temperature.

1. Fill the glass tube about three-quarters full of distilled water (or other liquid medium of sedimentation).
2. Weigh an amount of the —250 mesh aggregate sufficient to make a concentration of about 2 percent suspension. Transfer the sample to the tube, adding a deflocculent if required.
3. Fill the tube to the brim with water (or other suspension medium); apply the cup part by sliding one disk over the other, and then, holding the two parts together, shake vigorously. If prolonged shaking is required to effect dispersion, a rubber stopper may be inserted into the neck of the tube before it is completely filled with liquid, and it may then be placed in a mechanical shaker.
4. Invert the assembly and, at the same time, start a stop watch. Place the assembly under spring or other device for pressing the disks together, and leave it undisturbed until the chosen settling time has elapsed.
5. Hold the assembly upright and slide off the glass tube part without disturbing the contents of the brass cup beneath. This operation is an important improvement over other methods for the separation of the sedimented from the unsedimented portions, inasmuch as it is effected with the least disturbance of the liquid. It is generally conceded that the principal error of the test-tube method lies in the turbulence caused when the unsedimented portion is withdrawn by pipette or siphon.
6. Concentrate the sediment in the brass cup by decantation, filtration, or evaporation; dry and weigh.
7. The procedure outlined above should be repeated for various sedimenting times, the time preferably being in geometrical sequence, such as: 1, 2, 4, 8, 16, . . . , minutes.

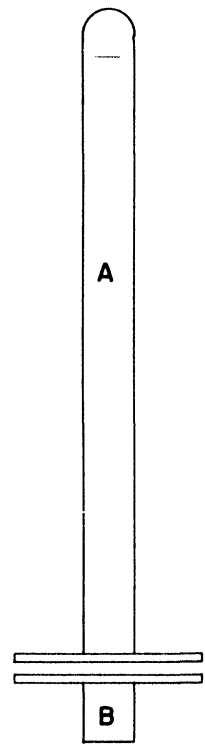



FIG. 3. — Apparatus for sedimentation method of analysis.

In order to interpret the results, the following calculations are made:

Let $w$ = number of grams of solid matter contained in the part $A$ at the instant of its inversion, as in 4 above.

$w_1$ = number of grams of solid matter contained in the part $B$ at the same instant of inversion.

$w_2$ = number of grams of solid matter contained in the part $B$ at the liquid column, as in 5 above.

Then, $w_2 - w_1 =$ grams of solid matter sedimented in the time $t$.

and $\frac{w_2 - w_1}{w} \times 100 =$ percentage of solid matter that settled from the liquid column above the cup $B$.

These percentages are plotted against their respective times (time on the abscissa), and a smooth curve is drawn through the points. From each of these points, a tangent to the curve is drawn and extended to intersect the ordinate. It is well to make this graph to a large scale in order to draw the tangents accurately. The scaled distances, then, between the successive intercepts are the percentages of the material of the size range given by Stokes' equation for the corresponding velocities indicated by the abscissas of the points from which the tangents were drawn.

The amount of material ($P$) sedimented in a given time ($t$) is composed of: (1) particles whose size would have insured their reaching the bottom zone of the tube even if they had started from the top, and (2) particles that reached the bottom zone because they started from a point below the top but would not have reached it if they had started from the top. Since each particle has a constant velocity (Stokes' Law), the amount of sediment composed of particles of the second group will be $t\frac{dP}{dt}$, and of the first group, $S$. We may, therefore, write:

$$P = S + t\frac{dP}{dt}.$$

In Fig. 4, for a time ($t$) the total amount sedimented is $P$. A tangent drawn from this point on the $P$-$t$ curve makes an angle $\alpha$ with the abscissa. The slope of this tangent is $\frac{dP}{dt}$ and the distance on the ordinate from the tangent intercept to $P$ is equal to $t\frac{dP}{dt}$, and the distance to the origin is $S$. The distance $S$, then, represents the amount of sediment composed of particles of the first class that accumulated in the time $t$. The rate of accumulation of these particles is $v = \frac{S}{t}$; and their diameter, by the Stokes' equation, is

$$D = \sqrt{\frac{v}{700}}$$

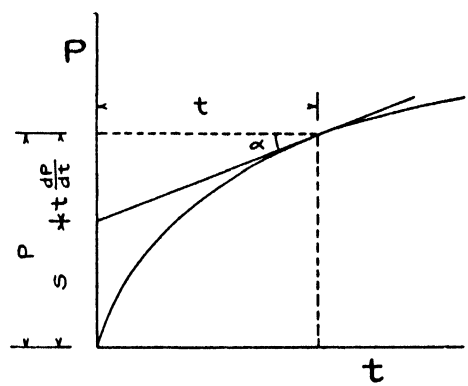



FIG. 4.—Graphical method for solution of the Odén sedimentation equation.

For example, two points, $m_1$ and $m_2$, on a curve give the following measurements:

| | $m_1$ | $m_2$ |
|---|---|---|
| Time (from the origin) | 20 | 55 |
| Total percentage settled | 45 | 68 |
| Tangent intercept | 30 | 50 |
| Difference between tangent intercepts | 20 | |

If the distance beween the liquid meniscus in $A$ (after inversion) and the bottom of tube $A$ were 230 mm., the velocities corresponding to the points $m_1$ and $m_2$ would be $\frac{230}{20} = 11.5$ and $\frac{230}{55} = 4.2$, respectively. From the simplified Stokes equation.

$$\left(d = \sqrt{\frac{v}{700}}\right),$$

the particle sizes ($d$) corresponding to these velocities ($v$) would be

$$d_1 = \sqrt{\frac{11.5}{700}} = .128 \text{ mm.}$$

and

$$d_2 = \sqrt{\frac{4.2}{700}} = .077 \text{ mm.}$$

The conclusion, then, is that there is 20% (difference between tangent intercepts) of material between the sizes 0.128 mm. and 0.077 mm.

Two curves depicting the results of this method are shown in Fig. 5. The data for Sample No. 3 are as follows:

SAMPLE NO. 3

CRETACEOUS SANDSTONE

| Settling Time (Minutes) | Percentage Sedimented ($P$) | Tangent Intercept ($S$) | Velocity (mm./sec.) $\left(\frac{230}{t}\right)$ | Diameter (mm.) $\left(\sqrt{\frac{v}{700}}\right)$ |
|---|---|---|---|---|
| 2 | 58.0 | 30 | 1.917 | 0.0523 |
| 4 | 70.6 | 58 | 0.958 | 0.0370 |
| 8 | 78.4 | 68 | 0.479 | 0.0262 |
| 16 | 83.5 | 75 | 0.240 | 0.0185 |
| 32 | 87.7 | 84 | 0.120 | 0.0131 |
| 64 | 89.0 | 87 | 0.060 | 0.00925 |
| 128 | 90.2 | .. | 0.030 | 0.00654 |

STATEMENT FROM CURVE

| Size Range (mm.) | Percentage |
|---|---|
| Greater than 0.074 | 0 (on screens) |
| 0.074 -0.0523 | 30 |
| 0.0523-0.0370 | 28 |
| 0.0370-0.0262 | 10 |
| 0.0262-0.0185 | 7 |
| 0.0185-0.0131 | 9 |
| 0.0131-0.00925 | 3 |
| Less than 0.00925 | 13 |

Sample No. 4 is a white china clay with no material coarser than 200-mesh.

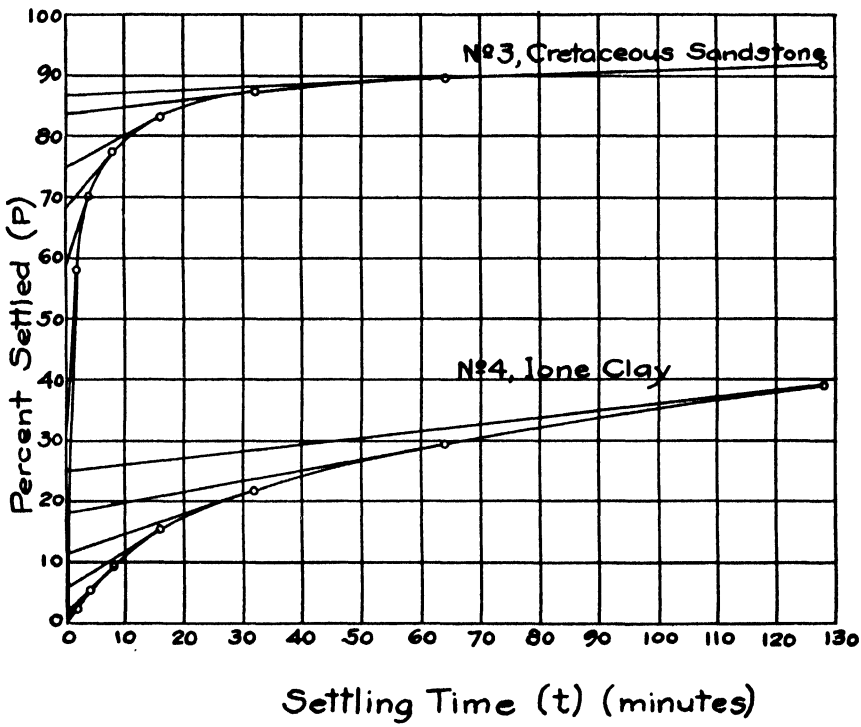



FIG. 5.—Sedimentation curves, showing graphical method of interpretation

The cumulative percentage curves for these two samples are shown in Fig. 6 (p. 17), the results of the screen analysis for Sample No. 3 being combined with those from the sedimentation test. It will be noted from the extrapolation of these curves (dotted lines) that Sample No. 3 prob-

ably has no material as fine as .004 mm. (no clay), while Sample No. 4 probably has 40% that is finer than .001 mm.

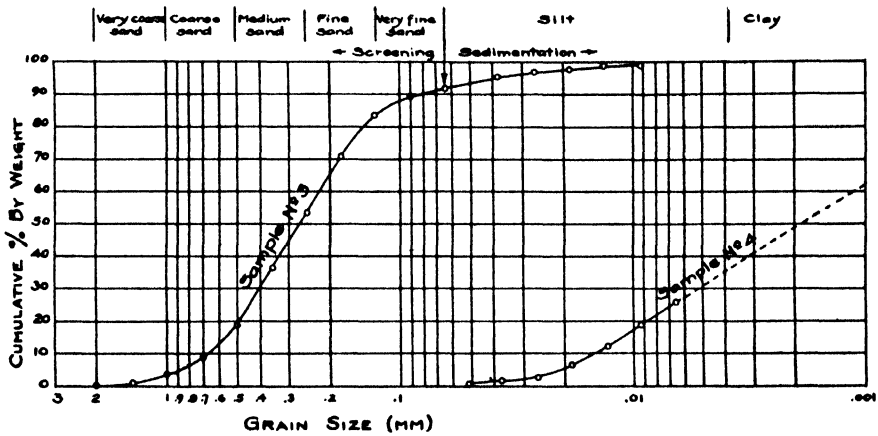



FIG. 6.—Cumulative percentage sizing curves, based upon both screening and sedimentation

**Statement of mechanical analysis.** The statement of a mechanical analysis may include the data of screen analysis, water classification, or both, according to the material and the purpose in view.

In the following two screen analyses, columns (1), (2), and (4) are the ones customarily included in the analytical statement. Column (1) states the openings in millimeters as given approximately by the screens selected from the Tyler series to fit the Wentworth scale.

**Screen Analyses of Sands**

SAMPLE NO. 1

CORE SAMPLE FROM OIL WELL

Field, Huntington Beach, California.
Well, Calpet—Macklin No. 1.
Depth, 3,828 feet.

| | (1) Screen openings (mm.) | (2) % | (3) Log % | (4) Σ % | (5) Log Σ % |
|---|---|---|---|---|---|
| Retained on | 8 | 1.0 | 0.301 | 1.0 | 0.301 |
| Retained on | 4 | 6.2 | 0.792 | 7.2 | 0.857 |
| Retained on | 2 | 10.6 | 1.025 | 17.8 | 1.250 |
| Retained on | 1 | 15.2 | 1.182 | 33.0 | 1.518 |
| Retained on | ½ | 18.2 | 1.260 | 51.2 | 1.709 |
| Retained on | ¼ | 20.9 | 1.320 | 72.1 | 1.858 |
| Retained on | ⅛ | 15.9 | 1.201 | 88.0 | 1.945 |
| Retained on | 1/16 | 6.1 | 0.785 | 94.1 | 1.974 |
| Passed through | 1/16 | 5.9 | | 100.0 | |

## SAMPLE NO. 2

CORE SAMPLE FROM OIL WELL

Field, Seal Beach, California.
Well, Marland—Bixby No. 2.
Depth, 4,423 feet.

| | (1) Screen openings (mm.) | (2) % | (3) Log % | (4) Σ % | (5) Log Σ % |
|---|---|---|---|---|---|
| Retained on | 2 | 2.8 | 0.447 | 2.8 | 0.447 |
| Retained on | 1 | 3.7 | 0.568 | 6.5 | 0.813 |
| Retained on | ½ | 6.7 | 0.826 | 13.2 | 1.121 |
| Retained on | ¼ | 20.3 | 1.307 | 33.5 | 1.525 |
| Retained on | ⅛ | 36.8 | 1.566 | 70.3 | 1.847 |
| Retained on | 1/16 | 17.1 | 1.233 | 87.4 | 1.942 |
| Passed through | 1/16 | 12.6 | | 100.0 | |

The *histograms* of Fig. 7 show the same statement of these analyses in graphic form, and from them the percentages of the various grades (pebbles, sand, silt, etc.) established by the Wentworth scale may be read.

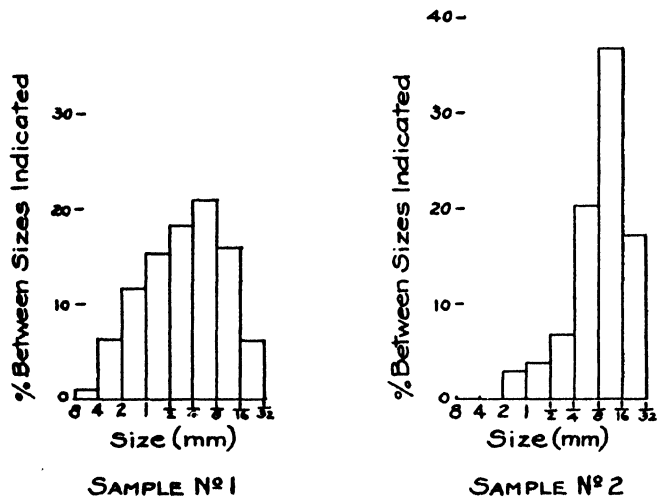



FIG. 7.—Histograms

In Fig. 8 (p. 19) are plotted the cumulative percentages that would be retained on the various screens. From these curves (called *ogives*) may be read directly the percentage that would be retained on a screen of given size. The curves are plotted to arithmetical,. semi-logarithmic, and double logarithmic scales. It should be noted that the logarithmic (base = 2) divisions of the abscissas of the two logarithmic curves are made simply by

spacing equidistantly the screen sizes of the 2:1 ratio. In the double logarithmic curves, the log $_{10}$% is scaled on the ordinate.

The logarithmic curves have the advantage of saving space, and the semi-log ruling is to be preferred to the double-log, because it requires less computation and is more quickly read. The semi-log ruling of Figs. 6 and 9 is still more convenient, because the abscissa may be read at any point.

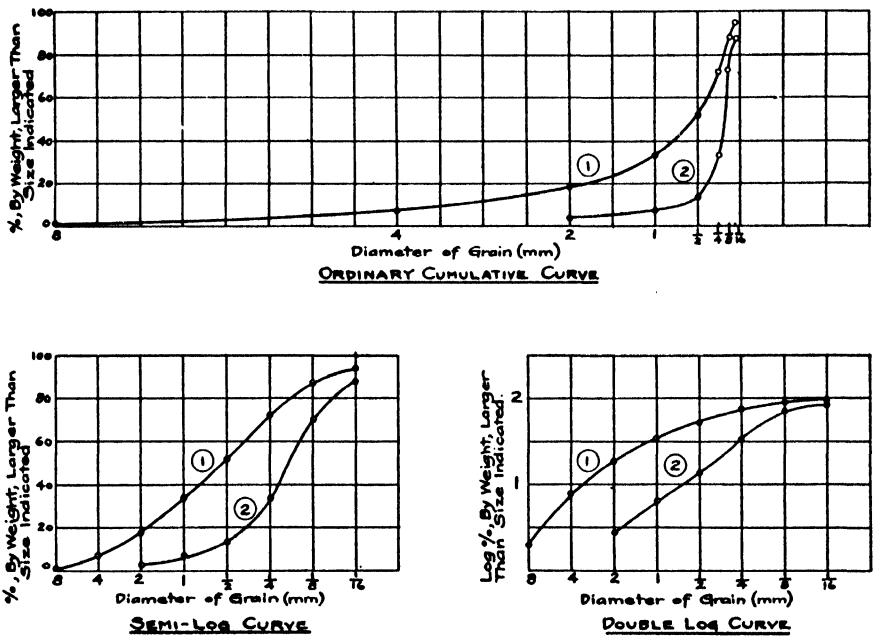



FIG. 8.—Types of cumulative frequency curves

From the data of columns (2) of the analytical statements are constructed the curves of Fig. 10. These are the so-called *frequency distribution curves* of mathematical statistics.[12] The frequency curve represents the limit that would, by the theory of probabilities, be reached by a histogram if the grain size intervals were made smaller and smaller and the scale of the ordinate increased in the same proportion. Numerical data cannot be taken from these curves (the ordinates are scaled in relative frequencies), but they facilitate the visualization of the type of sample represented and reveal its characteristics.

The high peak of the frequency curve is called the *mode*. It represents the size of grain that is (by weight) most abundant. The relative height of

[12] Kelley, Truman L., *Statistical Method*, 1924.

the mode and the way in which the frequencies are grouped on each side of it are characteristic of the material. Some types of curves and the interpretation for clastic materials are shown in Fig. 11 (p. 21).

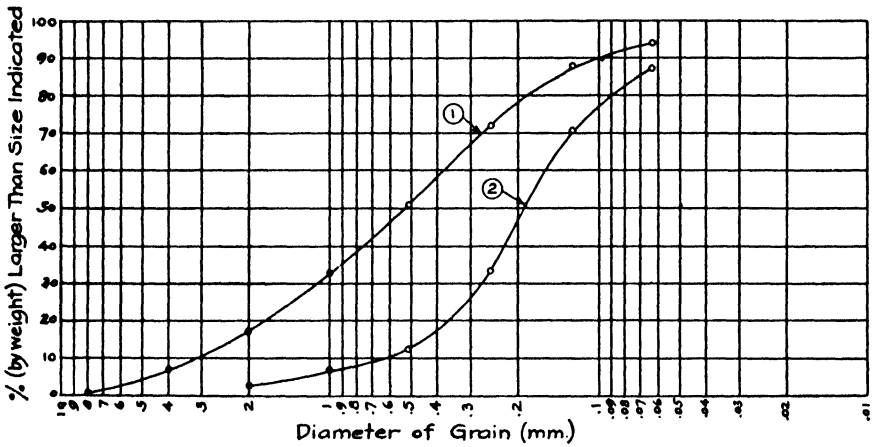
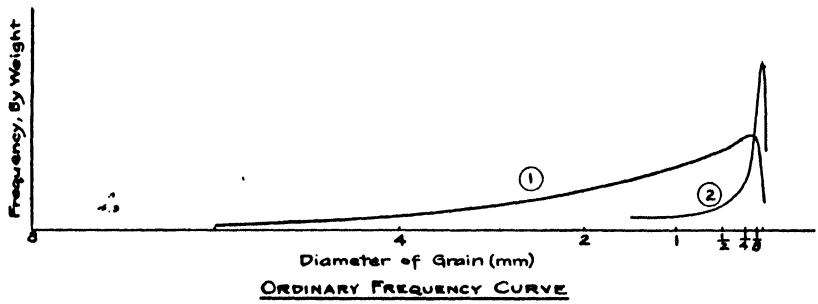
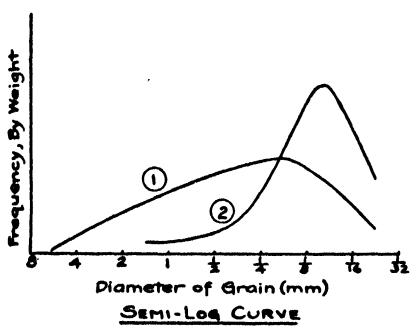


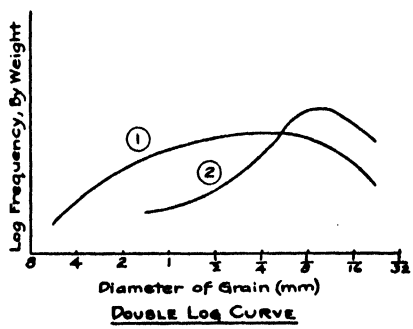

FIG. 9.—Cumulative frequency curves, semi-log ruling




ORDINARY FREQUENCY CURVE



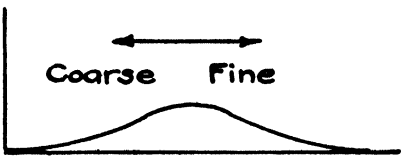

SEMI-LOG CURVE




DOUBLE LOG CURVE

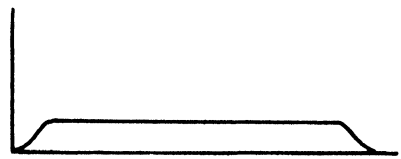
FIG. 10.—Types of frequency curves

Rivière[12a] has proposed a method of plotting by polar co-ordinates for which he claims a more rational interpretation and greater significance of results. In order to plot by this method, let:



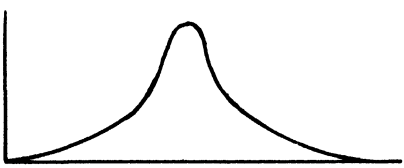

**NORMAL CURVE**

**Represents a purely random distribution**



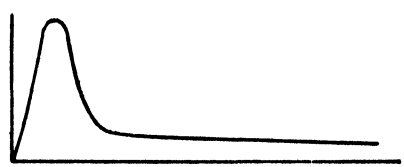
**FLAT SYMMETRICAL CURVE**

**Represents a nearly perfect assortment**



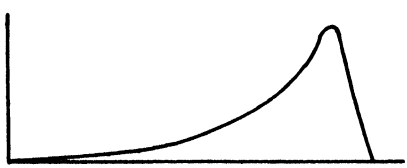
**STEEP SYMMETRICAL CURVE**

**Represents an abundance of medium grades, with equal distributions of the coarse and fine grades**



**STEEP ASYMMETRICAL CURVE**

**Represents an even assortment of fine and medium grades, contained in the interstices of a preponderance of coarse material**



**STEEP ASYMMETRICAL CURVE**

**Represents a preponderance of fine material, but no extremely fine grains**

FIG. 11.—Types of frequency curves

$x_1$ and $x_2$ = any two consecutive mesh dimensions $(x_1 > x_2)$

$x_m = \frac{1}{2}(x_1 + x_2)$ = mean of any two mesh dimensions

$\Delta x = x_1 - x_2$

$\Delta m$ = weight of material passing through $x_1$ and retained by $x_2$.

[12a] Rivière, M. André, "L'interprétation rationelle des *spectres* de tamisage des sédiments sableux et la signification géologique des diagrammes," *Comptes Rendus*, **204** (No. 6) : 441–43. (1937.)

The co-ordinates are:

$$\sqrt{\frac{\Delta m\%}{\Delta x}} \text{ on the radii}$$

and successive values of $x_m$ (in radians) from any assumed radius.

Points on contiguous radii are connected by lines, and the resulting figure is judged by its size, shape, orientation, and by the fact that the areas subtended are proportional to the weights of material.

Lack of symmetry about the mode is called *skewness,* and a close bunching of frequencies at the mode (high narrow peak) is called *kurtosis.* A curve may be characterized by these two. The numerical measure of skewness and kurtosis has been given by Kelley,[13] and the data may be taken from the cumulative percentage curve (Fig. 9). In the normal curve, skewness = 0; kurtosis = 0.263. A kurtosis greater than 0.263 signifies a steep curve.

$$\text{Skewness} = P_{50} - \tfrac{1}{2}(P_{10} + P_{90})$$

$$\text{Kurtosis} = \frac{P_{25} - P_{75}}{2(P_{10} - P_{90})}$$

where:

$P_{50}$ = the 50 **percentile**; or the size of grain where 50% are larger and 50% smaller

$P_{10}$ = the 10 percentile; or the size of grain where 10% are larger and 90% smaller

$P_{90}$ = the 90 percentile

$P_{25}$ = the 25 percentile

$P_{75}$ = the 75 percentile

For Sample No. 1, Fig. 9, the values are:

$P_{50} = 0.52$

$P_{10} = 3.10$

$P_{90} = 0.10$

$P_{25} = 1.40$

$P_{75} = 0.22$

$$\text{skewness} = .52 - \tfrac{1}{2}(3.10 + 0.1) = -1.03$$

$$\text{kurtosis} = \frac{1.4 - .22}{2(3.1 - 0.1)} = 0.197$$

It should be noted that negative skewness indicates that more of the material is fine-grained than is coarse-grained.

[13] *Op. cit.*, p. 77.

The values for the three samples are as follows:

| Sample | Skewness | Kurtosis |
|---|---|---|
| 1 | −1.03 | 0.197 |
| 2 | −0.14 | 0.655 |
| 3 | −0.10 | 0.965 |

Another measure of skewness and a mathematical method of smoothing frequency curves of screen analyses has been given by Van Orstrand.[14]

Another statement of deviation from the normal curve is the *"uniformity coefficient"* proposed by Hazen.[15] This is defined as follows:

The uniformity coefficient is the ratio of the diameter of a grain that has 60% (by weight) of the sample finer than itself to the diameter of a grain that has 10% finer than itself. A sand composed of grains all of the same size would have a uniformity coefficient = 1. In terms of the percentiles described above, the formula is:

$$u.c. = \frac{P_{40}}{P_{90}}$$

For samples 1, 2, and 3 the uniformity coefficients are 7, 5, and 4.5, respectively.

Another measure of kurtosis is the "spread" of the curve, which is its width at half the maximum height.

The relationship of these measures of variability to porosity and permeability are discussed in chapter iii.

Krumbein[16] has pointed out that the histogram may give a false idea of the skewness and kurtosis of the distribution. He has devised a graphical method for constructing the frequency curve from the cumulative curve (ogive), and advocates the use of curves constructed in this manner for the comparison of size analyses.

### *State of Aggregation*

Examination of the natural texture of a sedimentary rock may be made on a thin section by transmitted light, or on a polished surface by reflected

[14] Van Orstrand, C. E., "Note on the Representation of the Distribution of Grains in Sands," *National Research Council, Report of the Committee on Sedimentation* (1925), pp. 63–67.

[15] Hazen, Allen, quoted by Meinzer, O. E., "The Occurrence of Ground Water in the United States," *U.S. Geol. Surv. Water Supply Paper 489* (1923), p. 7.

[16] Krumbein, W. C., "Size Frequency Distribution of Sediments," *Jour. Sed. Petr.*, 4 (No. 2) : 65–77. (1934.)

light. If the grains are not extremely small, as in a shale, the polished section is to be preferred because of the greater ease of preparation.

The sample usually needs support before a surface can be ground and polished without disturbing the grains. This support may be supplied in the following manner:

1. The dry sample is boiled in xylene to drive air from the pores.

2. The sample is cooked in Canada balsam for a time that depends upon the texture. Fine-textured rocks may need up to twelve hours' boiling in order to become entirely saturated with balsam.

3. A polished surface is made, using FFF carborundum on a lap to flatten the face, followed by rubbing with No. 904 corundum powder[17] on a glass plate, and finally by polishing on stretched broadcloth wet with rouge and water.

Material, like clay, that is wet and friable may be tied in a rag and boiled in alcohol to drive out the water, followed by boiling in xylene, balsam, etc.

Where it is desirable to make a thin section from friable material, it becomes necessary to employ a binder having more strength than balsam. The best substance for this purpose is a synthetic resin such as Bakelite No. AR-0013 (a varnish of thick consistency) or No. AR-0014 (a varnish of thinner consistency).[18] The refractive index of the hardened bakelite is 1.63.

One method of preparation is partly to imbed a small fragment of the rock in plaster of Paris. After the plaster has set, the fragment is coated with the resin and baked for two hours at 85°C., and for eight hours at 95°–100°C. After cooling slowly, a thin section may be cut just as if from a solid rock. A somewhat different method of preparation has been described in considerable detail by Leggette.[19]

**Making of thin sections.**[20]—The making of a thin section involves considerable practice and skill. The essential steps, however, are:

1. A face is flattened on a lap with No. 90 carborundum and then with FFF carborundum.

[17] Procurable from the Bausch & Lomb Optical Company, or from opticians' supply houses.

[18] Procurable from Bakelite Corporation, New York.

[19] Leggette, Max, "The Preparation of Thin Sections of Friable Rock," *Jour. Geol.*, **36** (No. 6) : 549–57. (1928.)

[20] For more extended directions, the reader is referred to "The Technique of Preparing Thin Sections of Rock," by R. E. Head, *Utah Eng. Exper. Sta., Tech. Paper No. 8*, 1929.

2. The face is smoothed with No. 904 or 906 corundum powder on a glass plate.

3. The dry surface is cemented to a glass slide by means of Canada balsam or Kollolith.[21] A small fragment of the resin is placed on a glass slide and the latter put on a hot plate until the resin has melted and bubbles have disappeared. The rock fragment is pressed firmly on the slide, which is then removed from the hot plate.

4. The opposite side of the specimen is ground on a lap with No. 90 carborundum until it appears to be about 1 mm. thick. It is then thinned further with the FFF powder and given its final thinning with No. 904 or No. 906 corundum powder on a glass plate. When sufficiently thin, the grains should reveal the fact by their interference colors when examined between crossed nicols of the microscope. Where quartz grains are present, they should show colors not higher than low first order yellow. (See page 80.)

5. The section has a cover-glass placed thereon in a manner similar to that described in section 3 above.

The clay minerals may be distinguished in either thin section or polished surface by soaking for about ten minutes in malachite green dissolved in xylene.[22] The clay minerals become colored by the stain, while the others do not.

Crushed or other incoherent material may also be studied after imbedding in bakelite or other synthetic resin. This procedure requires a steel briquetting mold, surrounded by a resistance heater, and mounted in a hydraulic press. The mixture of grains and powdered resin is placed in the mold, heated to about 150° F. under a pressure of 1,000 lb. per sq. in. until resin has melted. The temperature is then raised to about 290° F., and the pressure to 2,500 lb. per sq. in. to "cure" the melt. The briquet is then expelled from the mold, and from it may be made thin sections or polished surfaces for microscopic study.

[21] Kollolith is somewhat preferable to balsam and may be procured, either solid or dissolved in xylene, from the E. Leitz Company, New York. Other synthetic thermoplastic resins are (1) "Lucite," made by E. I. du Pont de Nemours and Co., Arlington, N.J., and (2) "Vinylite," series AYAF, made by Carbide and Carbon Chemicals Corp., New York.

[22] Holmes, Arthur, *Petrographic Methods and Calculations* (1921), p. 276.

# III

# POROSITY AND PERMEABILITY

## POROSITY

The subject of porosity and permeability of porous media has been one of much technical interest, first in the fields related to ceramics, metallurgy, and geology, and later to petroleum engineering in connection with the problems of subterranean fluid movement. Petroleum engineers have been aided by the development of the core-drill, with which undisturbed specimens of deeply buried rocks could be brought to the surface for examination with respect to their physical and chemical composition.

There has been much discussion, in the technical fields mentioned, as to the proper methods for the determination and expression of porosity and permeability. The only possible conclusion is that what is sufficient for the needs of one technology may be inadequate for those of another; but this is not always the case, and the worker in one field of mineral technology may benefit greatly from methods devised in another. The choice of method requires considerations of accuracy consistent with: (*a*) interpretive possibilities, (*b*) accuracy of sampling, and (*c*) cost of apparatus and its operation. Needless accuracy is met as commonly as its opposite.

From a quantitative standpoint, the porosity of a rock or other substance is the ratio of the volume of internal open spaces to the total volume of the specimen. The open spaces are variously referred to as *pores, interstices,* or *voids.*

The pores of a substance may be isolated from one another, or they may be intercommunicating, and it is in this latter sense that we speak of "available pore space" or "effective porosity" in contradistinction to "total pore space" or "total porosity."

Many substances have both intercommunicating and isolated pores, and a determination of the porosity must take into consideration which of these classes of pores are to be measured. A sandstone, for example, might have 90% of its pores accessible to liquids, 5% accessible to gases, and the

remainder totally sealed in the form of intragranular voids. The determination of porosity and the method used will, therefore, depend upon the purpose in view.

TABLE 6

AVERAGE POROSITIES OF ROCKS[1]

| | Porosity (Percentage) |
|---|---|
| Holocrystalline igneous rocks | 1 |
| Slate and shale | 4 |
| Limestone and dolomite | 5 |
| Sandstone | 15 |
| Sand | 35 |
| Clay | 50 |
| Chalk | 53 |
| Soils | 55 |
| Diatomite | 90 |

Table 6 gives typical porosities of various rocks. Fraser[2] gives the porosities of various spheroidal and crushed substances under different types of packing.

The porosity of an aggregate is determined by the following factors:

1. Size distribution of grains
2. Shapes of grains
3. Solidity of grains
4. Orientation of grains
5. Degree of compaction
6. Amount of nongranular material (colloids, or cement) in pores or coating the grains

The separate effects of these factors have been experimentally investigated[3] for the cases of two- and three-component mixtures.

## Bulk Volume

### *Incoherent Materials*

All methods for porosity measurement require the separate determination of the bulk volume of the specimen. In the case of incoherent ma-

[1] Meinzer, O. E., "The Occurrence of Ground Water in the United States," *U.S. Geol. Surv. Water Supply Paper 489* (1923), p. 10.

[2] Fraser, H. J., "Porosity and Permeability of Clastic Sediments," *Jour. Geol.*, **43** : 936. (1935.)

[3] Fraser, *op. cit.;* and Tickell, F. G., Mechem, O. E., and McCurdy, R. C., "Some Studies on the Porosity and Permeability of Rocks," *Trans. Amer. Inst. Min. Met. Eng.*, **103** : 250–60. (1933.)

terial, such as sand, the sampling and manipulation result in disturbing the natural or original state of aggregation. It then becomes necessary to attempt to restore the material to an approximation of its original state of aggregation, or to subject it to a standard treatment that will permit valid comparisons between different specimens. Such treatments may include agitation, vibration, compression, tamping, or sedimentation in a container of suitable size and shape. Originally water-sedimented sand, for example, may conveniently be sedimented by puddling with a stick in a two-liter graduate, adding the sand a little at a time, together with just enough water to cover it. This process will liberate entrapped air and may be continued until the cylinder is full. The volume of water added should be recorded as it gives a measure of the pore volume.

In cases where compression is thought to be the best method of preparing standard specimens, a cylindrical briquetting mold actuated by a hydraulic press will provide a means for uniform compaction, and the bulk volume determination then requires only the measurement of the cylindrical specimen.

### *Coherent Materials*

For bulk volume determination of coherent porous substances, such as indurated rocks and ceramic bodies, broken fragments are used.

#### Gravimetric Methods.

A method proposed by Melcher[4] is described by him as follows:

> The method selected is based on the principle that the volume of the sand [sandstone] minus the volume of its individual grains equals the volume of the pore space. The volume of the pore space divided by the volume of the fragment gives the per cent pore space by volume.
>
> ***Dipping samples in paraffin.***—Sometimes the texture of the samples is so loose that it is difficult to keep the grains of sand from rubbing off while handling them; other fragments are firmer and more compact. It was because of this looseness of texture and the small size of some of the samples that the method of dipping in paraffin was adopted. After the surface of a sample was thoroughly cleaned of foreign material with an assay brush and loose particles brushed off, it was broken into two parts; one part was used for finding the volume of the fragment and the other was used for finding the volume of the individual grains making up the fragment.
>
> The pieces that were to be used for finding the volume of the fragment were weighed and then dipped into paraffin heated to a temperature a little above its melting point. The layer of paraffin around the sample was then examined for air bubbles and

[4] Melcher, A. F., "Determination of Pore Space of Oil and Gas Sands," *Mining and Metallurgy*, April 1920; and *Trans. Amer. Inst. Met. Eng.*, **65** : 469–97. (1921.)

pinholes. If any were found, they were removed by remelting the paraffin at that point with the end of a hot wire.

The fragments are best dipped by holding them with the fingers. First, the half of the sample opposite the fingers is dipped; then the sample is turned around and the other half is dipped. The samples should never remain in the melted paraffin longer than two or three seconds, and very small samples or very porous ones should be immersed for shorter periods. Bubbles should not be permitted to come out of the samples, as they usually indicate that the paraffin is beginning to enter the pores. If there is any doubt about the paraffin entering the pores of the sample, the specimen may be broken, after it is weighed in distilled water, and examined with a hand lens or microscope, depending on the size of the pores. It will be found that, after a little practice, if the samples are cold, there will not be much difficulty in dipping them so that the paraffin will not enter the pores, as the paraffin almost immediately hardens when it comes into contact with the cold surface of the sand. When the paraffin cools, the sample with its coating is weighed to determine the weight of the paraffin.

***Determining volume of fragment.***—The sample with the coating of paraffin is suspended in distilled water by a No. 30 B. & S. gauge platinum wire and weighed; a fine wire is used so that the error due to surface tension will be as small as possible. The water should have been boiled and its temperature taken to one-tenth of a degree at the time of the weighing. The sample is then removed from the water, dried by pressing the surface against bibulous paper or a smooth towel, and weighed in air. This weighing is made to see whether the sample absorbed any water. If any appreciable quantity of water is absorbed, a correction can be made to the weight of water displaced from the difference between the last weighing and the former weighing of the sample plus the paraffin in air.

From the weight of the water displaced, its temperature and density, the volume of the sample plus the volume of the paraffin can be obtained. The tables by P. Chappuis on the change of density with the temperature of pure water free from air were used. From a previous determination of the density of paraffin, which in this case is 0.906, and the weight of the paraffin covering the sample, its volume can be obtained. Subtracting this volume from the total volume of the sample, plus the volume of the paraffin, gives the volume of the fragment of stone used.

An improvement on this procedure was introduced by Nutting[5] by the use of a special weighing bottle about 30 mm. in diameter and depth with a 6-mm. wide flanged top, ground and polished to fit a thick circular plate cover. Weighings of the bottle, specimen, paraffin- or lacquer[6]-coated specimen, water-filled bottle, and water-and-coated-specimen-filled bottle give data for calculating the bulk volume of the specimen.

A more rapid, but less accurate, method is to use mercury as the submergent. This obviates the necessity for paraffin coating.

[5] Nutting, P. G., "Physical Analysis of Oil Sands," *Bull. Amer. Assoc. Petr. Geol.*, **14** : 1337–49. (1930.)

[6] Brankstone, H. R., Gealy, W. B., and Smith, W. O., "Improved Technique for Determination of Densities and Porosities," *Bull. Amer. Assoc. Petr. Geol.*, **16** : 915–23. (1932.)

TABLE 7

BULK VOLUME DATA AND CALCULATION (GRAVIMETRIC).
SAMPLE NO. 3 (SEE FIG. 6)

| Item No. | Items | Observation or Calculation |
|---|---|---|
| 1. Bottle, empty | | 21.5751 g. |
| 2. Bottle + water | | 36.2179 g. |
| 3. Weight of water | (2 — 1) | 14.6428 g. |
| 4. Water temperature 22°C. | | |
| 5. Water density (from Table 8) | | 0.9978 g. per cc. |
| 6. Volume of water | (3 ÷ 5) | 14.6751 c.c. |
| 7. Sample | | 7.8432 g. |
| 8. Sample + paraffin | | 9.0131 g. |
| 9. Paraffin | (8 — 7) | 1.1699 g. |
| 10. Paraffin density | | 0.89 g. per c.c. |
| 11. Paraffin | (9 ÷ 10) | 1.3145 c.c. |
| 12. Bottle + water + sample (weighed) | | 39.2874 g. |
| 13. Bottle + water + sample | (2 + 7) | 44.0611 g. |
| 14. Water displaced by sample | (13 — 12) | 4.7737 g. |
| 15. Sample + paraffin | (14 ÷ 5) | 4.7842 c.c. |
| 16. Bulk volume of sample | (15 — 11) | 3.4697 c.c. |
| 17. Bulk density of sample | (7 ÷ 16) | 2.2605 g. per c.c. |

TABLE 8

DENSITY OF WATER AND MERCURY

| Temp. (°C.) | Water (g. per c.c.) | Mercury (g. per c.c.) |
|---|---|---|
| 15 | 0.99913 | 13.5584 |
| 16 | .99897 | 13.5560 |
| 17 | .99880 | 13.5535 |
| 18 | .99862 | 13.5511 |
| 19 | .99843 | 13.5486 |
| 20 | .99823 | 13.5461 |
| 21 | .99802 | 13.5437 |
| 22 | .99780 | 13.5412 |
| 23 | .99756 | 13.5388 |
| 24 | .99732 | 13.5363 |
| 25 | .99707 | 13.5339 |
| 26 | .99681 | 13.5314 |
| 27 | .99654 | 13.5290 |
| 28 | .99626 | 13.5265 |
| 29 | .99597 | 13.5241 |
| 30 | .99567 | 13.5216 |

## Volumetric Methods.

***Goodner Volumeter.***—A very rapid method, but one applicable only to specimens sufficiently coherent to withstand handling without loss of

grains, is by the use of the **Goodner Volumeter**[7] as shown in Fig. 12. The apparatus is adjusted by adding mercury to the well (*a*) and raising or lowering the burette (*b*) and the gauge (*c*) until the point of the latter just touches the surface of the mercury and the reading on the burette is zero. At the same time, the level of the mercury in the well must be high enough to submerge the grooves on the bottom of the plug (*d*). The apparatus is constructed so that the area of the annular space between the well and the plug equals the inner cross-sectional area of the burette.

The rock specimen is placed in the well and the plug inserted over it, completely submerging the specimen. The burette is lowered by means of the rack and pinion until the gauge point again just touches the surface of the mercury. The reading of the burette is then the volume of the sample. The operation takes about thirty seconds.

**Russell Volumeter.**—A method proposed by Russell[8] involves the use of acetylene tetrachloride in a specially designed flask[9] (Fig. 13, *b*). Sutton[10] describes the use of this method as follows:

***Preparation of sample.***—A chunk sample, 3 to 4 cc. in volume, of the sand to be tested is selected, and the physical appearance and characteristics are noted.

Preparation of two samples of each specimen is advisable as the subsequent operations may damage the original, and if a second piece is at hand the test can be carried on without delay.

Although the removal of the oily and waxy material in the specimens before the determination of the volume of the sand grains is not essential to the accuracy of the test, it prevents discoloration of the liquid and provides for a continuous run after the test is started. Heating the sample in a gas oven over a Bunsen flame for 1 to 4 hours will usually remove most of the oily material. Temperatures obtained by these methods probably range between 400 to 600° F. (204 to 316° C.).

If the sample contains considerable oil, an electric oven can be used most effectively to remove it. The temperature should be between 600 and 800° C. (1112° to 1472° F.), and the sample should be removed as soon as ignition ceases.

The specific time and temperature data for a particular sample depend upon the quantity of oil in the specimen, the size of the piece being tested, the character of the rock, and the amount of organic or mineral matter it contains.

After heating the specimen and allowing it to cool, it should be carefully examined for cracks or fractures and all loose grains or projecting particles dislodged.

[7] Goodner, E. F., "A Mercury Volumeter," *Jour. Amer. Ceramic Soc.*, Vol. 4, No. 4 (April 1921).

[8] Russell, W. L., "A Quick Method for Determining Porosity," *Bull. Amer. Assoc. Petr. Geol.*, **10** (No. 10) : 931. (1926.)

[9] Made by Eimer and Amend, New York.

[10] Sutton, C. E., "Use of the Acetylene Tetrachloride Methods of Porosity Determination in Petroleum Engineering Field Studies," *U.S. Bureau of Mines, Repts. of Invest.* No. 2876 (June 1928).

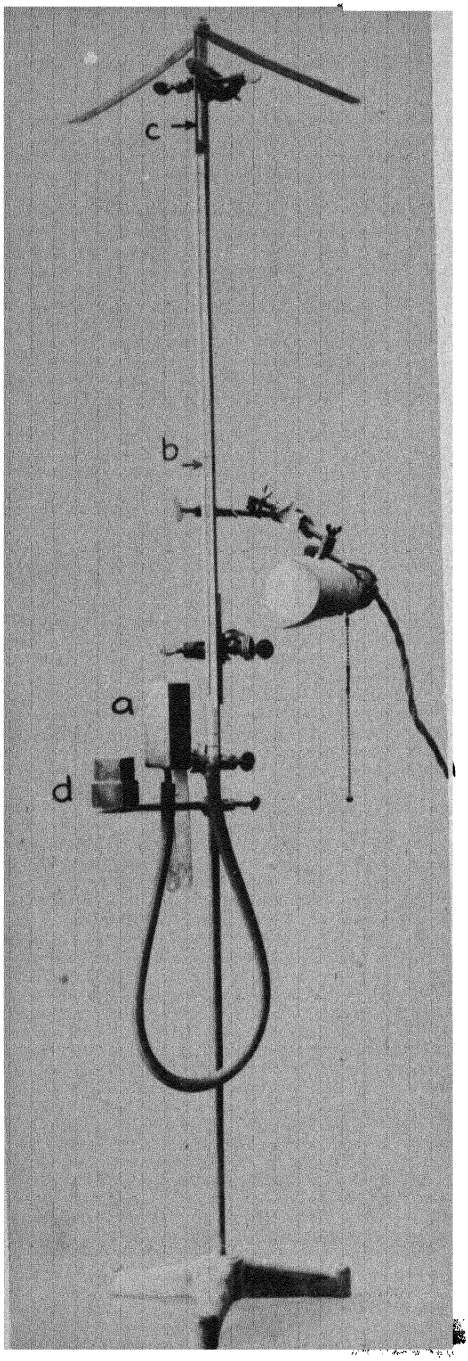



FIG. 12.—Mercury volumeter

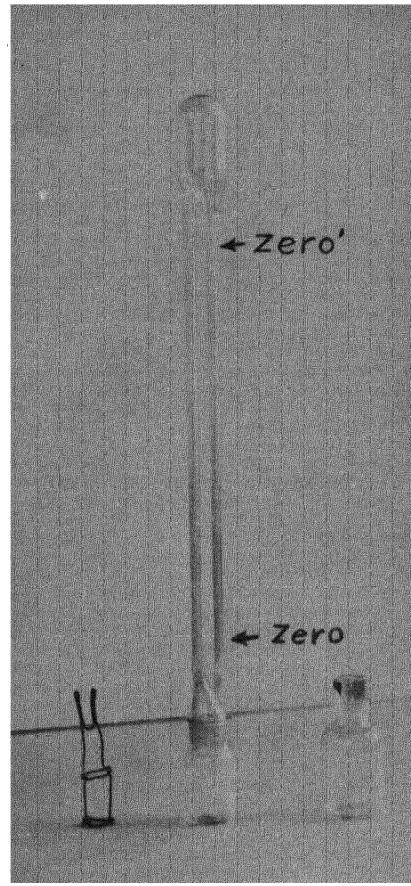



FIG. 13

(Right to left)

*a*) Wide mouth pycnometer

*b*) Russell porosity apparatus

*c*) Wire cage for use in Gealy modification of Russell method.

A sample that is cracked or fractured should be discarded, as the liquid that accumulates in the crack cannot be removed, and the test will not be reliable. The piece selected for the test should be compact and not easily broken if slightly jarred. When soft and disintegrating sands are being tested, extreme care must be used in handling the sample or the results will not be accurate.

After the sample has been prepared, it should be immersed in a beaker or graduate of acetylene tetrachloride and under a fluid head approximately equal to that which will be obtained when in the apparatus. The actual head will depend upon the size of the sample and the bore of the graduated tubes of the apparatus. For a sample 3 to 4 cc. in volume and the apparatus shown in Fig 13, *b*, a fluid head of 4 to 5 inches was found satisfactory.

While immersed in the liquid, the sample should be agitated or shaken frequently until all air bubbles have ceased to issue from it.

***Determination of volume of aggregate.***—In making the determination the stopper is removed and the apparatus inverted and filled with acetylene tetrachloride to the zero′ graduation, or slightly above. The apparatus, with the stopper in place, is designed to have the volume above the zero′ graduation exactly equal to the volume below the zero point. As this equality is not usually obtained in practice, a correction factor, known as "correction for zero point," is ordinarily necessary and should be determined from a number of tests before actual determinations are begun. The amount of this correction is determined by filling the apparatus, in the inverted position, to the zero′ graduation, placing the stopper over the tubes, and rotating the apparatus to the upright position. The correction will be plus or minus, depending upon the position of the fluid level with respect to the zero point.

If the fluid level in the upright position is below the zero point, the correction is positive and must be added to the readings taken with the specimen in the stopper. If the level is above the zero point, the correction is negative and must be deducted.

The factor will be constant for each instrument at a given temperature, that is, at the temperature for which it is determined.

Test runs have shown that although the acetylene tetrachloride drains quite rapidly and does not adhere to the sides of the glass tubes, a drainage period of 8 to 10 minutes should be allowed before a reading is taken.

After the fluid has been allowed to drain, with the apparatus in the inverted position, the zero′ ($Z_1$) is taken and the ground-joint surface coated with stopcock grease. The sample is then taken from the beaker and the liquid adhering to its surface removed. This particular phase of the test should be done with extreme care, as therein lies one of the most likely sources of error in the determination. As the acetylene tetrachloride drains rapidly, it has been found best to remove the sample with a pair of small tweezers, hold it momentarily in such position that a corner or projection is pointing downward, and then remove the droplet draining to this corner with bibulous paper or cloth. Wiping the entire surface of the sample is likely to withdraw some of the fluid from the surface pores and thus give too low a value for the aggregate volume.

When a number of tests are being run on the same sand the error due to estimating the surface of the specimen is probably compensative; that is, it will be positive in one case and negative in another so that the error in the averaged result will be small.

The specimen is then placed in the stopper, and the stopper fitted over the tubes. The apparatus is turned to the upright position, and after allowing a drainage period of 8 to 10 minutes a reading ($R_1$) is taken.

After applying the correction for zero point to $R_1$, as explained above, the zero' reading ($Z_1$) is subtracted from the corrected $R_1$ reading. The remainder is the volume of the solid or aggregate sample.

Gealy[11] recommends the use of mercury for determining the volume of the rock chunk, the latter being submerged in the mercury by means of a wire cage (Fig. 13, *c*). The difficulty of manipulation with mercury in a piece of fragile apparatus is somewhat of a drawback to this method.

## Grain Volume

### Gravimetric Methods.

All gravimetric methods for the determination of grain volume demand the complete disaggregation of the sample. This is accomplished, in the case of coherent materials, by crushing to a fineness sufficient to insure complete separation of grain aggregates.

TABLE 9

GRAIN VOLUME DATA AND CALCULATION (GRAVIMETRIC). SAMPLE NO. 3 (SEE Fig. 6)

| Item No. | Items | Observation or Calculation |
|---|---|---|
| 1. Bottle, empty | | 21.5751 g. |
| 2. Bottle + water | | 36.2179 g. |
| 3. Weight of water | (2 — 1) | 14.6428 g. |
| 4. Water temperature 22°C. | | |
| 5. Water density (from Table 8) | | 0.9978 g. |
| 6. Volume of water | (3 ÷ 5) | 14.6751 c.c. |
| 7. Bottle + grains | | 29.4183 g. |
| 8. Grains | (7 — 1) | 7.8432 g. |
| 9. Bottle + liquid | | 44.7033 g. |
| 10. Weight of liquid | (9 — 1) | 23.1312 g. |
| 11. Density of liquid | (10 ÷ 6) | 1.5797 g. per c.c. |
| 12. Bottle + grains + liquid (weighed) | | 47.7426 g. |
| 13. Bottle + grains + liquid | (7 + 10) | 52.5495 g. |
| 14. Liquid displaced by sample | (13 — 12) | 4.8069 g. |
| 15. Grain volume | (14 ÷ 11) | **3.0429** c.c. |
| 16. Grain density | (8 ÷ 15) | **2.5775** g. per c.c. |

The whole sample used for the determination of bulk volume may be used but, in the case of friable material, it is difficult to avoid loss of grains. This may be taken into account by reweighing the sample after crushing.

[11] Gealy, W. B., "Use of Mercury for Determination of Volume of Rock Specimens in Russell Porosity Apparatus," *Bull. Amer. Assoc. Petr. Geol.*, 13 (No. 6): 677. (1929.)

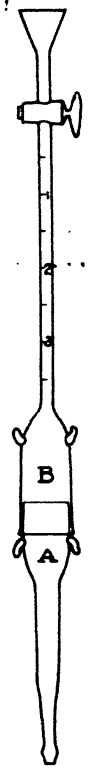



FIG. 14.—Washburn-Bunting Volumeter

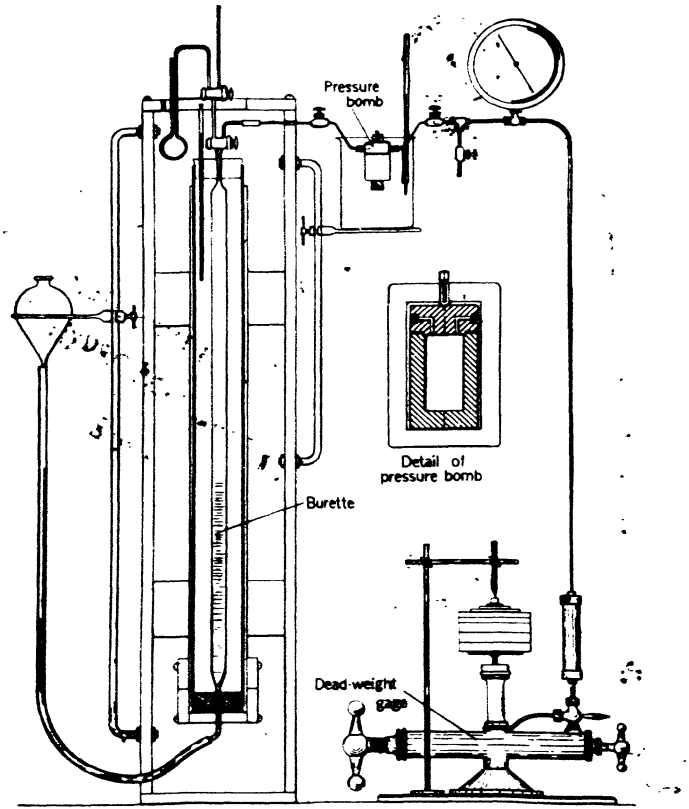



FIG 15.—Hydrogen Volumeter

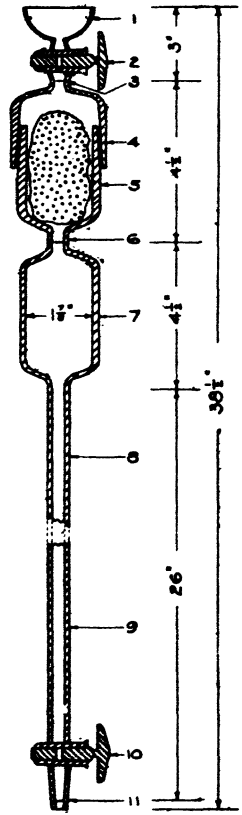



FIG. 16.—Air Porosimeter

The original Melcher Method accomplished the determination of grain volume in a narrow-necked pycnometer, with the grains submerged in water. Entrapped air was removed by gentle heating under a partial vacuum. This method was improved by Nutting's modification of using a wide-mouthed pycnometer and immersing the grains in tetrachlorethane (acetylene tetrachloride) or tetrahydronaphthalene (tetralin). Kerosene has also found favor for this purpose. These liquids have high capillarity, and air entrapped in the sample may readily be removed by stirring. The weighing bottle described on page 29 may be used; or a wide-mouthed pycnometer with a bored glass stopper, as pictured on the right of Fig 13, will be found convenient.

**Volumetric Methods.**

The Russell Volumeter may be used for the determination of grain volume in the same manner as for bulk volume. The entire sample used in the bulk volume determination is preserved, however, but there is likelihood that material may be lost during drying and grinding of the specimen.

*Gas Porosimeters.*—Washburn and Bunting[12] and MacGee[13] have described instruments by the use of which direct determination, either of pore volume or of grain volume, may be made with a consolidated specimen. These instruments depend upon the application of Boyle's Law to gases, and offer an additional advantage for some purposes in that available pore space is measured rather than total pore space. Several of these instruments, or modifications of them, have gained considerable use and will be described in the following pages.

***Washburn-Bunting*[14] *Volumeter.***—This instrument is of the McLeod Gauge type and is shown in Fig. 14.[15] The bottom part, A, is of 50 c.c. capacity, and is attached to the upper part, B, by a ground joint lubricated with stopcock grease. Heavy rubber bands are stretched between the glass projecting lugs to hold the two parts together. The stem of *B* is graduated in 0.05 c.c. divisions from zero at the stopcock to 3.5 c.c. near the bottom. The volumeter should be attached in a vertical position to a ring-stand and connected from the bottom of A by means of 7 feet of rubber pressure-tubing to a 500-c.c. leveling bottle, which should rest in a

[12] Washburn, E. W., and Bunting, E. N., "The Determination of the Porosity of Highly Vitrified Bodies," *Jour. Amer. Ceramic Soc.*, **5** : 527–37. (1922.)

[13] MacGee, A. E., "Several Gas Expansion Porosimeters," *Jour. Amer. Ceramic Soc.*, **9** : 814–22. (1926.)

[14] *Op. cit.*, p. 528.

[15] Procurable from Fisher Scientific Co., Pittsburgh, Pa.

movable support also attached to the ring-stand. The procedure is as follows:

1. Fill leveling bottle with mercury and adjust height until meniscus is in bottom part of A.

2. Place sample in A with a short piece of steel piano wire looped over it to prevent the sample from floating upwards when the mercury is introduced.

3. Attach B to A and fasten securely with rubber bands between the lugs.

4. Elevate the bottle until meniscus stands above the level of the stopcock.

5. Close stopcock. The only air in the chamber is now that which occupied the pores of the sample at atmospheric pressure.

6. Lower the bottle until the meniscus stands as in 1, and hold in that position for two or three minutes to permit the reduced pressure in the chamber to draw air out of the sample.

7. Elevate bottle until the menisci in bottle and graduated stem are on a common level. The air in the graduated stem is then at atmospheric pressure. Read the graduated stem at the meniscus level.

8. Open stopcock and repeat 4, 5, 6, and 7 so as to make sure that all air has been removed from sample. Read the stem again and add this reading to the one obtained in 7.

9. Remove sample from A and substitute therefor a solid piece of glass approximating in size and shape that of the sample. Repeat operations 1 to 7 and record the volume of air found as the instrumental correction to be subtracted from the reading obtained with the sample to give the pore volume of the sample. This instrumental correction is made necessary because of air adsorbed on the glass surfaces.

***Coberly Hydrogen Volumeter.***—Coberly and Stevens[16] developed this instrument particularly for the determination of porosity of core samples from oil wells. It has had considerable use by the petroleum industry, and is described in publications of the American Petroleum Institute[17] from which the following is quoted:

> In the gas-expansion method of determining the porosity of oil sands the volume of the pores in the specimen is determined by subtracting the volume of the sand grains from the bulk volume of the specimen. The volume of the sand grains is

[16] Coberly, C. J., and Stevens, A. B., "Development of Hydrogen Porosimeter," *Oil Weekly*, **68** (No. 6) : 17. (1933.)

[17] American Petroleum Institute, "Report of Subcommittee on Saturation Tests, Mid-Continent Committee on Petroleum Technology," *Amer. Petr. Inst. Production Bull.*, **217** : 50–57. (1936).

determined by noting the reduction of void space in a vessel or bomb of known volume when the specimen is placed in it. The volume of the bomb and the amount of this volume occupied by the sand grains in a sample specimen are determined by introducing compressed gas into the bomb, observing the pressure in the bomb, and later releasing this compressed gas and measuring accurately its volume at atmospheric pressure. When the test specimen is in the bomb, compressed gas is introduced—which fills not only that part of the bomb not occupied by the specimen, but also the pores or voids in the specimen.

With the above data the volume of the sand grains is calculated by use of the pressure-volume relationship expressed by Boyle's law, with a correction factor for the deviation from Boyle's law at the pressure and temperature of the test. When there is a difference in temperature between the compressed gas in the bomb and its expanded volume as measured in a burette, the expanded volume is converted to a volume at the temperature of the gas in the bomb, by application of the temperature-volume relationship expressed by Charles' law.

The total or bulk volume of the specimen may be determined with a pycnometer using mercury or with a Russell volumeter using acetylene tetrachloride. The difference between the bulk volume and the volume of the grains gives the volume of voids in the sample, and this volume divided by the bulk volume multiplied by 100 gives the porosity in per cent.

Fig. 15 shows the assembly of the apparatus as now used by the U.S. Bureau of Mines, and includes both a spring gage and a dead-weight gage for measuring the pressure. Other installations are in use where the pressure in the bomb is measured only with a carefully-calibrated spring gage. The pressure bomb consists of a steel cylinder of 1¾-in. outside diameter, 3¼ in. long; the inside dimensions are 1 in. by 1⅞ in. The cap or cover of the bomb is ground to fit, and is held tightly in place with a clamp. The actual volume of the bomb need not be greatly in excess of the volume of the specimen under examination, and a number of steel discs of the diameter of the bomb are inserted into the bomb to make its volume conform to the volume of the specimen under examination.

Different gases and pressures may be used in the determination; however, it has been found convenient for laboratory purposes to use air at pressures of 75 to 100 lb. per sq. in. After the compressed gas in the bomb has come to the temperature of the bath and the pressure determined accurately, it is released into the water-jacketed burette—where its volume is measured at the temperature of the bath surrounding the burette and at atmospheric pressure.

The data required for the determination of the volume of the bomb ($V_1$), along with the actual observations and calculations for such a determination using compressed air, are:

Pressure in the bomb ($P_1$) = 100.0 lb. per sq. in., gage.

Temperature of the air in the bomb ($T_1$) = 66.5 deg. F.

Barometric pressure ($P_2$) = 14.375 lb. per sq. in.

Volume of air after expansion (burette measurement) ($V_b$) = 92.02 ml.

Temperature of air in burette ($T_2$) = 73.9 deg. F.

The burette volume measured at 73.9 deg. F. is converted to a volume at 66.5 deg.

$$92.02\left(\frac{526.5}{533.9}\right) = 90.74 \text{ ml.}$$

The absolute pressure of the gas in the bomb is 100.0 + 14.375 = 114.375 lb. per sq. in. Air does not follow exactly the pressure-volume relationship expressed by

Boyle's law for an ideal gas ($P_1V_1 = P_2V_2$) and with a decrease in pressure is more expansible than an ideal gas. Accordingly, a correction factor is applied to the equation of Boyle's law to give:

$$\left(1 + \frac{n}{100}\right) P_1V_1 = P_2V_2 \text{ or, } V_2 = \frac{\left(1 + \frac{n}{100}\right) P_1}{P_2} V_1 \ldots \text{equation (1)}$$

where $n$ is the per cent deviation.

For the pressure and temperature of the air in this particular determination, the value of $n$ is 0.23, and the value of the term:

$$\frac{\left(1 + \frac{n}{100}\right) P_1}{P_2} \text{ becomes } 1.0023 \times \frac{114.375}{14.375} = 7.9748$$

The value 7.9748 may be considered as the number of atmospheres of compressed gas contained in the bomb before expansion. After expansion, one atmosphere of gas remains in the bomb; and, therefore, the volume measured by the burette is equivalent to only 6.9748 atmospheres of gas. In other words, after the gas in the bomb has expanded into the burette, the gas in the bomb is at atmospheric pressure, and the total volume of gas after expansion ($V_2$ in equation [1]) is equal to the volume measured in the burette plus the volume remaining in the bomb.

The simplified equation for determining the volume of the bomb ($V_1$) then becomes:

$$V_1 = \frac{V_b}{6.9748}, \text{ or } V_1 = \frac{90.74}{6.9748} = 13.009 \text{ ml.},$$

which is the volume of the empty bomb.

The same laboratory procedure and calculations as described above are followed when the sand specimen is placed in the bomb. For the specimens referred to in this discussion, the volume of space in the bomb occupied by compressed air with the specimen contained in it was 4.918 ml. Therefore, the volume of the sand grains in the specimen is the difference between 13.009 and 4.918, or 8.091 ml.

The bulk volume or the volume of the sand grains plus the voids in the specimen was determined by displacement of mercury from a pycnometer; the amount of displaced mercury is measured with a burette. The bulk volume of this particular specimen was 9.88 ml. The volume of voids in the specimen is the difference between the bulk volume (9.88 ml.) and the volume of the sand grains (8.091 ml.) or 1.789 ml. The volume of the voids divided by the bulk volume multiplied by 100 equals the porosity in per cent, or $\frac{1.789}{9.88} \times 100 = 18.1$ per cent.

Many of the details and experiments connected with this method have been studied by the U.S. Bureau of Mines, and a series of tests, covering a wide range of pressures, has been made. The results of these, together with extensive tables for use in the solution of the equations, are given in the report.[18]

[18] Taliaferro, D. B., Jr., Johnson, T. W., and Dewees, E. J., "A Method of Determining Porosity: A List of Porosities of Oil Sands," *U.S. Bur. Mines Rep. Invest. 3352* (1937).

***Author's Volumeter.***—A glass instrument operating on the same principle as the Coberly Volumeter, but of less bulky and cheaper construction,[19] is shown in Fig. 16. The procedure is as follows:

1. Suspend the instrument in a vertical position by means of a stand and clamps. The stem 8, 9 may be graduated, or a graduated scale may be mounted behind it.

2. Place a large evaporating dish of mercury beneath the tube in a manner such that the level of the mercury is opposite the graduation 11.

3. Remove cap 4, close stopcock 10, and fill tube with mercury up into the chamber 5.

4. Open stopcock 10 and draw mercury into the dish until meniscus is at graduation 6.

5. Place specimen in chamber 5 and replace cap 4. The specimen must have been thoroughly dried in an oven and placed in a desiccator to cool. It should be transferred quickly from desiccator to sample-chamber.

6. Close stopcock 2 and open stopcock 10, permitting mercury to drain into the dish until it comes to an equilibrium position in tube 8, 9.

7. Read graduation at meniscus in tube. It is a measure of the grain volume of the specimen, since the instrument has been calibrated with iron discs of known volume, and a curve constructed whereby the volume corresponding to any reading, when obtained according to the foregoing procedure, may be read from this curve.

This instrument has been elaborated and perfected by A. H. Nissan and coworkers.[20]

## Calculation of Porosity

Porosity may be defined in terms of volumes or of densities.

In terms of volumes,

$$\text{Porosity } (\%) = 100 \frac{\text{pore volume}}{\text{bulk volume}}$$

where pore volume = bulk volume − grain volume.

According to the data shown on pages 30 and 34, the calculated porosity is:

$$100 \left( \frac{3.4697 - 3.0429}{3.4697} \right) = 12.3\%$$

[19] Tickell, F. G., Mechem, O. E., and McCurdy, R. C., "Some Studies on the Porosity and Permeability of Rocks," *Trans. Amer. Inst. Min. Met. Eng.*, **103** : 256. (1933.)

[20] Nissan, A. H., *et al.*, "The Application of Physico-Chemical Principles to the Investigation of the Properties of Rocks," *Jour. Inst. Petr. Tech.*, **24** : 351–92. (1938.)

In these data the sample used for grain volume determination was the whole of the sample used for bulk volume determination, and no loss of weight was incurred during the crushing operation. If, however, only part of the original sample were used for the grain volume determination, it is simpler to express porosity in terms of densities:

$$\text{Porosity } (\%) = 100 \left( 1 - \frac{\text{bulk density}}{\text{grain density}} \right)$$

The calculation would be:

$$100 \left( 1 - \frac{2.2605}{2.5775} \right) = 12.3\%$$

## Porosity by Indirect Methods

The porosity of undisturbed samples of unconsolidated material, such as soils, may be approximated by the formula:

$$P = 100 \left( 1 - \frac{a}{s} \right)$$

where:

$P$ = percentage of porosity.
$a$ = specific gravity of dried sample.
$s$ = weighted average of the specific gravities of the constituent minerals.

The value of $a$ is the ratio of the weight of a measured volume of the material to the weight of an equal volume of water. The value of $s$ is determined either from the water displacement of a weighed sample of the solid particles, or from a microscopic determination of the relative abundance of the constituent minerals.

The *uniformity coefficient,* as defined in chapter ii, was proposed by Hazen[21] as an indication of the porosity of a sediment. Hazen makes the following statement:

> The amount of open space depends upon the shape and uniformity in size of the particles of sand, and is independent of their absolute size. The materials which have the sharpest rise in the diagram (cumulative percentage curves from size analyses), indicating the greatest uniformity in size, have the greatest open space, while the sands having a more gradual rise pack more closely; the finer particles occupy the spaces between the larger stones, greatly reducing the open space.

Meinzer gives a diagram in which observed porosities are plotted against uniformity coefficients. There is evidently some degree of correlation.

[21] Cf. Meinzer, *op. cit.,* p. 7.

As shown in chapter ii, Hazen's uniformity coefficient is only one measure of deviation from the normal frequency distribution curve. The percentile criteria of *skewness* and *kurtosis,* as defined in chapter ii, more completely and accurately characterizes the frequency distribution, and there are other criteria of still greater accuracy but of more difficult derivation.

It is beyond doubt that the distribution of grain sizes and the shapes of the grains influence the porosity of an aggregate, but whether or not prediction of porosity may be based upon a mechanical and visual analysis remains to be determined by experimentation. Degree of compaction enters largely into the problem.

An approach to experimental investigation of the effects of skewness, compaction, and grain shape has been made[22] by which it seems that a maximum value for porosity is reached for a skewness value of —0.03, and that this applies for various values of compaction pressure up to 4000 lb. per sq. in.

The upper limit of porosity for aggregates of solid rounded grains is 47.64%, this being the porosity of an aggregate of spheres, all of the same size and with cubical packing. For hexagonal packing (like stacked cannon balls), the porosity is 25.95%. It has been shown by Westman and Hugill[23] that if even-sized spheres, such as shot, are jigged, the packing will be cubical in vertical cross sections and hexagonal in horizontal cross sections, and the porosity will be 39.5%.

The compaction of natural sediments is probably due largely to rearrangement of the grains after deposition, although part may be due to compression. It is stated by Athy[24] that a sample of water deposited sand settled about 11% with continuous jarring under atmospheric pressure and, when subjected to a pressure of 4,000 pounds per square inch, settled about 2% more.

## PERMEABILITY

Aggregates are permeable to the passage of fluids by virtue of their porosities. They may, however, be porous without being permeable, as in the case of sealed pores. Permeability, in the general sense, expresses the

[22] Tickell, F. G., Mechem, O. E., and McCurdy, R. C., "Some Studies on the Porosity and Permeability of Rocks," *Trans. Amer. Inst. Min. Met. Eng.,* **103** : 250–60. (1933.)

[23] Westman, A. E. R., and Hugill, H. R., "The Packing of Particles," *Jour. Amer. Ceramic Soc.,* **13** (No. 10) : 769. (October 1930.)

[24] Athy, L. F., "Density, Porosity, and Compaction of Sedimentary Rocks," *Bull. Amer. Assoc. Petr. Geol.,* **14** (No. 1) : 8. (January 1930.)

idea of freedom of fluid motion within or through a porous body. The permeability of an aggregate is determined by the same set of factors, with the exception of solidity of grains, as was shown on page 27 to influence porosity. There is no quantitative relationship, however, between permeability and porosity, for two substances may have equal porosities but very different permeabilities, as might occur, say, in the case of clay and gravel. Nutting[25] states, however, that in one area a plot of permeability against mean grain diameter gave a smooth, parabolic curve.

In a technical and quantitative sense, permeability is the reciprocal of resistance to the *viscous* flow of unit quantity of a fluid of unit viscosity in unit time through a unit cube of material.

It has been shown[26] that permeability has the dimensions of an area,

$$\frac{[L^3T^{-1}]\ [ML^{-1}T^{-1}]\ [L]}{[L^2]\ [MLT^{-2}]\ [L^{-2}]} = [L^2].$$

In c.g.s. units, therefore, the unit of permeability is:

$$\frac{1 \text{ c.c./sec.} \times 1 \text{ poise} \times 1 \text{ cm.}}{1 \text{ sq.cm.} \times 1 \text{ dyne/sq.cm.}}$$

The American Petroleum Institute has adopted (tentatively) a unit of permeability called the *darcy*. This unit satisfies the dimensional criterion above, but is defined in terms as follows:

$$1 \text{ darcy} = \frac{1 \text{ c.c./sec.} \times 1 \text{ centipoise} \times 1 \text{ cm.}}{1 \text{ sq.cm.} \times 1 \text{ atmosphere/sq.cm.}}$$

In other words, a porous substance has a permeability of one darcy for all conditions of viscous flow, if a fluid having a viscosity of one centipoise will flow through a sample of it having a length of one centimeter and a cross-sectional area of one square centimeter, under a differential pressure of one atmosphere, at the rate of one cubic centimeter per second.

The customary unit is the millidarcy $= 0.001$ darcy. There is great variability in porous substances with respect to permeability. Open textured sands may give values as high as several thousand millidarcies, while close grained shales may give values as low as a few hundredths of a millidarcy.

For the purpose of permeability calculation from the data of laboratory observations, certain symbols are defined as follows:

[25] Nutting, P. G., "Physical Analysis of Oil Sands," *Bull. Amer. Assoc. Petr. Geol.*, 14 : 1349. (1930.)

[26] Tickell, Mechem, and McCurdy, *op. cit.*, p. 259.

$A$ = Cross-sectional area of sample, at right angles to which the fluid flows (sq. cm.)
$L$ = length of sample, parallel to direction of fluid flow (cm.)
$P_1$ = absolute pressure at the fluid intake (atmosphere)
$P_2$ = absolute pressure at the fluid outlet (atmosphere)
$\overline{P}$ = mean pressure in the system $= \left(\frac{P_1 + P_2}{2}\right)$ (atmosphere)
$\overline{Q}$ = rate of fluid flow, referred to pressure $\overline{P}$. (If an incompressible liquid is flowing, its volume does not vary with the pressure.)
$\mu$ = viscosity of the fluid (centipoise)
$k$ = permeability (darcy)

For the viscous regime, D'Arcy developed the empirical relationship which can most conveniently be expressed in the following form:

$$k = \mu \cdot \frac{\overline{Q}}{A} \cdot \frac{L}{P_1 - P_2}$$

If the flow is viscous, the velocity $\left(\frac{\overline{Q}}{A}\right)$ is a linear function of the pressure gradient $\left(\frac{P_1 - P_2}{L}\right)$, so that if from the experimental data values of $\frac{\overline{Q}}{A}$ be plotted against corresponding values of $\frac{P_1 - P_2}{L}$, a continuous graph will result which will pass through the origin and which, for the viscous regime (for double log paper), will be linear with a slope of 45°. As turbulence is approached the curve will flatten until a limiting slope of 26°5 is reached for complete turbulence. As a matter of fact, turbulent flow probably seldom occurs under the conditions ordinarily set up in testing apparatus because, according to the Reynolds criterion, the following velocities are necessary to produce turbulence in capillaries:

| Diameter of Capillary (mm.) | Velocity (cm. per sec.) Air | Water |
|---|---|---|
| 1.0 | 3,500 | 250 |
| 0.1 | 35,000 | 2,500 |
| 0.01 | 350,000 | 25,000 |

## Determination of Permeability

The American Petroleum Institute has adopted[26] a tentative standardization code for permeability determination, in order to define the condi-

[26] American Petroleum Institute, "Standard Procedure for Determining Permeability of Porous Media," *A.P.I. Code No. 27* (October 1935).

tions of test and point out sources of errors. A quotation from the code follows:

**Preparation of Samples**

12. **Size:** Theory imposes no limitation on the size of the sample to be used but it is evident that in order to minimize effects due to local inhomogeneities in the material such as concretions, small shale streaks, and the like, the samples should be of a generous size. When possible they are cut to a cross-sectional area of 5 to 10 $cm^2$ and 1 cm or more in length although frequently the size is much less because of the smallness of the original sample. Because of the desirability for measuring the permeability both parallel and perpendicular to the bedding plane, separate samples are cut in each of these directions and from as closely adjacent portions of the specimen as possible.

13. **Method of Cutting:** Samples may be cut to size either by fracture or the usual methods of coring with diamond bits or rotating tubes fed with coarse carborundum. Similarly the sample may be cut to proper length by fracture or with a suitable cutting disc (diamond or carborundum wheel).

14. All cutting methods involve the use of a liquid for cooling and removal of cuttings. If such methods are used the liquid must not cause appreciable disintegration of the cementing material and it is essential that the sample be saturated with the liquid prior to the cutting operation. Failure to so saturate the material will result in mudding of the faces due to capillary effects, which force fine cuttings into the pores and cause a serious reduction of the permeability. Numerous tests indicate that this precaution suffices to give results equivalent to those obtained when the faces are carefully and accurately fractured.

15. The sample is finally carefully cleaned and dried preparatory to mounting.

**Extraction of Oil from Samples**

16. Since many of the samples may contain oil, the sample must be carefully treated in order to remove, as far as possible, all traces of oil content. The usual Soxhlet extraction apparatus using carbon tetrachloride or benzol as a solvent is convenient and quite efficient. Since the samples are larger than those usually used in porosity determinations a considerably greater time is required to extract the contained oil properly. It is also desirable to modify the apparatus slightly so as to provide a definite head of fluid on the sample during extraction and thereby increase the effectiveness of the washing. By fitting the sample into one end of a tube 10 or 15 cm long and inserting the tube, sample end downward, in the extraction apparatus a head of 10–15 cm of liquid is maintained to force the liquid through the sample. This is much more effective than the usual surface washing.

**Mounting of Samples in Flow Tube**

17. The flow tube consists of a suitable holder so arranged that when the sample is properly mounted therein, the entire unit is gas tight and when pressure is applied at one end of the system all flow is through the porous medium. Care must be taken that no fluid bypasses the sample through an imperfect seal between the sample and the walls of the mounting. Suitable pressure taps are provided on the input and output sides of the sample so that manometers connected to these openings give the fluid pressures at these points. Since the resistance of the porous medium is exceedingly great compared with the resistance of the open tube on either side of the specimen, the

location of the pressure taps is not important, provided there are no constrictions in the flow system between them and the faces of the sample.

18. The specimen may be sealed into the flow tube by the use of pitch, sealing wax or other nonpermeable cement, or by the use of a well-fitted soft rubber plug which is drawn up to a tight seal on the walls of the sample by suitable compression glands. If cements are used, care must be taken that the cement is not dissolved to the slightest extent by liquids used as the test fluid. Needless to say, the cement should not penetrate the sample to any appreciable extent or encroach upon its faces for then the effective cross-section will be reduced. A slight encroachment on the faces is, however, less serious than penetration of the walls of the specimen or failure to seal properly right up to the faces of the sample. For specific designs of sample mountings, reference may be had to several recent papers mentioned in the bibliography.

### Arrangement of Apparatus

19. The exact arrangement of the apparatus is a matter of personal choice or convenience. The equipment must, however, adequately provide for:

*a*) Prefiltering of liquids used in the test in order to eliminate plugging due to presence of colloidal or other solid particles.
*b*) Removal of dissolved gases from the liquids used in order to prevent plugging by gas bubbles formed by the drop in pressure through the apparatus.
*c*) Removal of moisture and particles of dust from air or other gas by passing it through filter tubes before entering the apparatus.
*d*) The use of oils containing unsaturated hydrocarbons as test fluids only in the presence of a non-oxidizing atmosphere.
*e*) Suitable drying tubes (calcium chloride) in the lead lines to water manometers in order to eliminate any possible contamination of the gas by moisture.
*f*) The measurement of pressures by liquid manometers or devices of equivalent accuracy, i.e., dead-weight testers. In no case are the usual Bourdon gages (even test gages) to be relied upon for these measurements.
*g*) Means of knowing the absolute pressures (gage plus atmospheric) in the measurement of gas flow. Obviously, this necessitates that a good barometer be available wherever permeability tests are conducted.
*h*) Maintenance of a constant pressure on the inflow side. Standard low pressure "reducing valves" are satisfactory for this purpose. A simpler device, but one requiring more attention for satisfactory operation, is a manually controlled needle valve with an extension lever attached to the hand wheel.
*i*) Measurements of gas volume must be made at known pressure and temperature so that the measured volume may be reduced to the proper conditions of pressure and temperature (mean pressure when using equation [p. 44]) existing in the flow channel.
*j*) Measurement of the temperature of the fluid in the flow channel in order to apply the proper value for viscosity to equation [p. 44].

### Choice of Test Fluid

20. As a general rule it is somewhat safer to use gas (air) rather than a liquid (particularly water) as the test fluid since any possible deterioration of the material cementing the sand is eliminated thereby. Many sands are cemented with or contain material of a "bentonitic" type and the use of water as a test fluid in such sands will

result in a partial plugging or in extreme cases in the complete disintegration of the sample. Where partial plugging occurs it is impossible to detect that an erroneous measurement has been made unless a check measurement is made with gas. It is, therefore, a safe rule to make all tests with gas as the test fluid.

21. An exception to the above rule, is the case in which it is impossible to completely eliminate oil or other liquids present in the sample. It is then safer to use a liquid which is miscible with the liquid content of the sample but such test liquid must be carefully prefiltered and if oxidizable compounds are present, they should be eliminated from the test liquid by suitable chemical methods before use in the flow tests. It should be remembered that in all cases the presence of two immiscible fluids (water-oil, liquids-gas) simultaneously in a porous medium will result in a reduction in the permeability of the medium and this reduction may be very great even though only a small amount of the second fluid is present. . . . .

**Procedure in Making Measurements with Liquids**

22. When using liquids as a test fluid it is essential that all air be removed from the sample prior to the entrance of the liquid, otherwise gas bubbles may be locked in the pores resulting in a decrease in the effective cross section of the sample with a consequent reduction in permeability. The safest procedure is to evacuate the system before allowing the liquid to enter the sample holder.

23. Having observed this precaution, together with those already mentioned regarding the use of prefiltered and gas-free liquids, it is only necessary to observe the rate of flow and pressure gradient across the sample using several different rates of flow. A curve of flow-rate plotted against pressure gradient provides a convenient method of obtaining average values for computing the permeability and at the same time indicates whether the flow is viscous as required by definition. If the proper precautions have been observed, gradual changes in permeability during flow will not occur. The viscosity $\mu$ of the liquid at the temperature existing during the test must be used in calculating the permeability constant (equation [p. 44]).

**Procedure in Making Measurements with Gas**

24. Analogous to the care required in removing gas from the sample prior to flowing liquids is, in the case of gas flow, the necessity of removing all traces of liquid normally retained in the pores. This may be done by long careful drying in a suitable oven or even by application of vacuum to aid in volatilizing the liquid. In general, samples should never be heated to a temperature greater than 215° F. at any time if accurate results are to be obtained. In some cases even this temperature may be too high and the method of drying must be altered. This, together with proper filtering and drying of the gas already mentioned, effectively eliminates errors from this source and the permeability will remain constant regardless of the duration of flow. For routine measurements, the use of gas as the test fluid rather than liquids is strongly recommended.

25. As in the case of tests with liquids, data should be taken at several rates of flow so that a plot of pressure gradient vs. $\overline{Q}$ may be used in selecting average values for use in computation and at the same time the viscous nature of the flow verified from the curve as outlined in the preceding theoretical discussion.

26. In order to make the calculations clear the example shown in Table I is carried through from the original data obtained in the test to the final calculation of the permeability. While the porous medium in this case was a column of unconsolidated

sand having a permeability 100 times greater than a consolidated sand of good permeability, the data suffice to illustrate the method of computation.

From the data given in Table I are obtained the values given in Table II.

TABLE I

TEST DATA

Sample, 40–45 mesh sand, tube dia. 2.16 cm, area 3.66 cm², length 29.9 cm, viscosity ($\mu$) of air at 24° C. = 0.0183 centipoises.

| Vol. of Air at Atmos. Press. (ml) | Time (sec) | Inflow Pressure (cm $H_2O$) | Outflow Pressure (cm $H_2O$) | Barometric Pressure (cm $H_2O$) | Temp. (° C) |
|---|---|---|---|---|---|
| 250 | 58.0 | 5.1 | 0 | 1,013 | 24 |
| 250 | 42.5 | 6.9 | 0 | 1,013 | 24 |
| 250 | 33.5 | 8.8 | 0 | 1,013 | 24 |
| 250 | 27.0 | 10.8 | 0 | 1,013 | 24 |
| 250 | 23.2 | 12.8 | 0 | 1,013 | 24 |
| 250 | 20.1 | 14.7 | 0 | 1,013 | 24 |

TABLE II

| ml/sec/cm² at Atmos. Pressure | Inflow + Bar. Press. (cm. $H_2O$) | Outflow + Bar. Press. (cm. $H_2O$) | $\frac{P_1}{1033}$ ($P_1$ Atmos. Col. 2) | $\frac{P_2}{1033}$ ($P_2$ Atmos. Col. 3) | $\frac{P_1+P_2}{2}$ | $\overline{Q/A}$ (ml/sec/cm²) | $\frac{P_1-P_2}{L}$ |
|---|---|---|---|---|---|---|---|
| 1.18 | 1018.1 | 1,013 | 0.9855 | 0.9806 | 0.9830 | 1.20 | $1.64\times10^{-4}$ |
| 1.61 | 1019.9 | 1,013 | 0.9873 | 0.9806 | 0.9839 | 1.64 | $2.24\times10^{-4}$ |
| 2.04 | 1021.8 | 1,013 | 0.9891 | 0.9806 | 0.9848 | 2.07 | $2.84\times10^{-4}$ |
| 2.53 | 1023.8 | 1,013 | 0.9910 | 0.9806 | 0.9858 | 2.57 | $3.48\times10^{-4}$ |
| 2.94 | 1025.8 | 1,013 | 0.9930 | 0.9806 | 0.9868 | 2.98 | $4.14\times10^{-4}$ |
| 3.40 | 1027.7 | 1,013 | 0.9948 | 0.9806 | 0.9877 | 3.44 | $4.75\times10^{-4}$ |

27. The data of column 7 (Table II) are then plotted as ordinates against column 8 (Table II) as abscissae. The points will be found to lie on a straight line through the origin, hence the flows are in the viscous region. (The same data plotted on log-log paper give a straight line having a 45° slope.) From the curve, which represents an average of the data, a specific value of $\overline{Q/A}$ and the corresponding $\frac{P_1-P_2}{L}$ are selected, as for example, 2.07 ml/sec/cm² at $2.84\times10^{-4}$ atmos/cm which is exactly on the curve. The permeability is then given by:

$$k = \frac{2.07 \times 0.0183}{2.84 \times 10^{-4}} = 133.3 \text{ darcys}$$

28. Similarly, data secured for a consolidated sand over a range of pressures for both air and water were plotted and averaged and yielded the values shown in Table III.

TABLE III

Sample, Wilcox sandstone, diam. 1.905 cm, area 2.85 cm², length, 2.54 cm.

| Fluid | Av. rate of flow ml/sec/cm² | Av. Pressure Gradient atmos./cm. | Viscosity,† Centipoises |
|---|---|---|---|
| Water | 0.702 | 1.11 | 0.884 |
| Air | 12.3* | 0.400 | 0.0182 |

* At mean pressure.

† At temperature of test.

Water data:

$$k = \frac{(0.702)(0.884)}{1.11} = 0.555 \text{ darcys (555 millidarcys)}$$

Air data:

$$K = \frac{(12.3)(.0182)}{0.400} = 0.559 \text{ darcys (559 millidarcys)}$$

29. For convenience in applying the proper values of viscosity at various temperatures, Tables IV and V are presented from data given in the International Critical Tables (Vol. 5). It is recommended that a chart of viscosity versus temperature be prepared from these data.

TABLE IV

VISCOSITY OF WATER

| Temp. °C | Viscosity (centipoises) | Temp. °C | Viscosity (centipoises) |
|---|---|---|---|
| 15 | 1.145 | 23 | 0.938 |
| 16 | 1.116 | 24 | 0.916 |
| 17 | 1.088 | 25 | 0.895 |
| 18 | 1.060 | 26 | 0.875 |
| 19 | 1.034 | 27 | 0.855 |
| 20 | 1.009 | 28 | 0.836 |
| 21 | 0.984 | 29 | 0.818 |
| 22 | 0.960 | 30 | 0.800 |

TABLE V

VISCOSITY OF AIR

| Temp. °C | Viscosity (centipoises) | Temp. °C | Viscosity (centipoises) |
|---|---|---|---|
| 0 | 0.01709 | 30 | 0.01856 |
| 10 | 0.01759 | 40 | 0.01904 |
| 20 | 0.01808 | 50 | 0.01951 |

Apparatus for determining permeability as outlined above, maintaining a constant inflow pressure, is rather expensive to construct because of the necessity for an air compressor, pressure reducing gauge, and pressure indicators. There have been developed, in modern foundry practice, methods for the determination of permeability to air of molding sands. These methods utilize the variable head of a descending column of water to propel air through the sample. The time is recorded for a given diminution of head, and the water displacement represents the volume of air drawn through the sample under a mean head which may be adduced from the data. An inexpensive and portable instrument of this type was designed and described by the writer[27] which seems amenable to further refinement and improvement.

[27] Tickell, F. G., "Permeability of Unconsolidated Rocks," *Bull. Amer. Assoc. Petr. Geol.*, **19** : 1233–38. (1935.)

# IV

# PREPARATION OF SPECIMENS

## Procedures

The preparation of specimens for microscopic examination and identification usually involves a certain amount of preliminary treatment, depending upon the state of aggregation of the sample. In general, it may be said that material suitable for study should be in grains not thicker than 1 mm., and preferably about 0.05 mm. thick. The grains should be separate and not aggregates of smaller grains, and they should be free from coatings of other material that would render them opaque.

One or more of the following procedures are required for the preparation of a specimen:

1. Crushing
2. Disaggregation
3. Sizing
4. Cleaning
5. Separation
6. Mounting

### *Crushing*

The material may be crushed in an iron or porcelain mortar, depending on the hardness. In any event, it should be pounded with the pestle and not ground with a rotary motion.

For crushing small quantities, a convenient equipment consists of a small assayer's anvil (3″ × 3″ × 1″ thick), a hammer, and a 1½″ ring cut from a 1½-inch or 2-inch pipe. The ring prevents the fragments from flying when struck with the hammer.

### *Disaggregation*

The procedure will depend upon the materials to be examined and the binding medium. Shales and fine grained sediments may sometimes be disaggregated by prolonged soaking in water. In some cases, it may be permissible or necessary to use acids or alkalies to promote the process.

Alternate freezing and boiling is sometimes efficaceous. Hanna[1] suggests the use of sodium acetate or sodium thiosulphate (photo "hypo"), the salt and a small quantity of water being added to the sample, which is heated until the sample absorbs the saturated solution. Cooling and adding a small crystal of the salt to act as a nucleus will cause the salt to crystallize within the sample, thus promoting disaggregation.

### *Sizing*

Sizing for sample preparation usually consists in passing the material through two or more screens in order to secure grains of uniform size for mounting and examination. Grains that are −100 +150 mesh are of about the right size.

The standard 8-inch diameter screen is not suitable for this purpose, as it is too difficult to clean. A piece of wire mesh soldered into the bottom of a hollow sheet-iron cylinder about 2½ inches in diameter and two inches high makes a good screen. It should be brushed thoroughly and pounded on the bench top in order to dislodge grains from other samples. If, then, the sample is sifted gently through it, avoiding severe jarring, there is little danger of contamination from grains that might be wedged in the meshes.

### *Cleaning*

If the grains are coated with ferruginous or other material, they must be cleaned by soaking or boiling in some substance that will remove the coatings but will not destroy the grains. Heavy residues of mineral grains can usually be boiled with 50% HCl without dissolving the grains. The lighter constituents, such as the carbonate minerals, would be destroyed by this treatment. It may, in some cases, be necessary to effect a separation of the acid soluble grains before such treatment.

If the coating of iron oxide is very heavy, the addition of a little stannous chloride to the acid will promote solution. If the grains are coated with pyrite, boiling in dilute nitric acid will dissolve the coating, although it is likely to dissolve some of the other minerals also.

Bituminous sands or oil sands may be cleaned with a mixture of petroleum ether and carbon disulphide, followed by a wash in alcohol.

### *Separation*

It is usually difficult, if not impossible, to make a complete separation of the constituents of a heterogeneous mineral assemblage. The study of

[1] Hanna, G. D., and Driver, H. L., "The Study of Sub-surface Formation in California Oil-Field Development," *Summary of Operations, California Oil Fields*, Vol. 10, No. 3, September 1924.

such an assemblage, however, is greatly facilitated by a separation into two or more groups, each of which is comparatively free from representatives of the other groups. In particular is this procedure advantageous where some constituents are present in very small proportion and where their isolation will not only furnish a quantitative estimate of their occurrence but will permit their closer study and more accurate identification.

The physical properties of minerals that may be made a basis for their separation into groups are, in order of their relative usefulness, as follows:

1. Density
2. Magnetic susceptibility
3. Electric conductivity
4. Dialectric strength
5. Surface energy (flotation separation; not applicable on a very small scale)

**Concentration.**—The separation of groups of minerals on the basis of density is effected by some process of concentration. Concentration processes make use of the buoyancy or velocity of a fluid: air, water, or various liquids.

The methods of concentration of especial utility in mineral grain study are: (1) **panning,** and (2) **heavy liquid separation.**

**Panning.**—Panning is done either with a gold pan or with a *batea.* The gold pan is used for comparatively large samples (5–10 lb.). For example, the separation of heavy accessory minerals from clay or from glass-sand calls for a large sample. The sample is placed in the pan, covered with water, and worked with the hands until lumps are broken and the material is wet. The pan is then shaken rapidly from side to side, at the same time allowing some of the material to spill over the lip. More water is added and the process repeated until only a few ounces of material remain in the pan, the heavy material concentrated in the angle between the bottom and the side. It is then better to complete the concentration in a batea.

The batea is a wooden pan, preferably about 10 inches in diameter, the inner surface being turned to the shape of a flat, shallow cone. The depth from the level of the lip to the central apex should be about one inch. The batea is used in a manner similar to the gold pan, except that it is shaken with a slight rotatory movement. The dish is tipped from time to time, and the material near the lip is swept off by the hand. The heavy material concentrates in the apex of the cone. This process should not be carried to a complete separation, but should be stopped when about 5 grams remain, the separation being completed with heavy liquids. The material should be washed (with a wash-bottle) from the batea into a filter paper and dried on a hot plate or radiator.

*Heavy liquid concentration.*—Heavy liquids may be used for mineral concentration by the sink and float method up to specific gravities of 5.3. Sullivan[2] has investigated most of the substances that have been proposed as heavy liquids and his recommendations appear in Table 10.

TABLE 10

HEAVY LIQUIDS FOR MINERAL SEPARATIONS

| Density Range Desired | Heavy liquid Recommended | Reagent to Clean Particles from Heavy Liquid | Remarks |
|---|---|---|---|
| 1.58 to 2.6 | Bromoform + carbon tetrachloride. | Carbon tetrachloride. | Liquid at ordinary room temperatures; reagents recovered by fractional distillation. |
| 2.6 to 2.9 | Acetylene tetrabromide + carbon tetrachloride. | Carbon tetrachloride, benzene. | Liquid at ordinary room temperatures; reagents recovered by fractional distillation. |
| 2.9 to 3.3 | Stannic bromide + carbon tetrachloride. | Carbon tetrachloride. | Molten at 30° when pure $SnBr_4$ is used, but with small addition of $CCl_4$ is molten at room temperatures; mineral particles must be dry to prevent decomposition of melt; reagents recovered by fractional distillation. |
| 3.3 to 3.65 | Antimony tribromide + stannic bromide. | Carbon bisulphide, absolute alcohol, bromoform, or absolute acetone. | Molten on steam or water bath; mineral particles must be dry; recovered by fractional distillation. |
| 3.65 to 4.95 | Thallium formate + $H_2O$* | Water | Water or steam bath will keep mass molten over entire range; reagent recovered by evaporation. |
| 4.95 to 5.2 | Eutectic of $HgCl_2$ and $HgI_2$ + antimony trichloride. | Aniline followed by alcohol or ether. | Molten on oil bath; cannot be used when sulphides are present. |

* The Clerici thallous formate malonate can be substituted for the formate except at the highest range of density. The prime difference between the two is that the mixture melts at a lower temperature for the same density. The malonate is more expensive than the formate.

For the purpose of many investigations, it is necessary only to carry

[2] Sullivan, John D., "Heavy Liquids for Mineralogical Analyses," *U.S. Bureau of Mines Tech. Paper No. 381,* 1927.

to completion the concentration begun by panning and to effect a separation of the heavier and more rarely occurring minerals from the preponderant quartz and feldspar. In this case, a single heavy liquid will often suffice.

From a number of liquids that will float quartz, feldspar, and the so-called *light minerals,* two have been chosen as being more suitable than the others; these are *bromoform* (tribrom-methane) and *acetylene tetrabromide* (tetrabromethane). The properties of these liquids at 20° C. are as listed below:

| | Bromoform | Acetylene Tetrabromide |
|---|---|---|
| Formula | $CHBr_3$ | $C_2H_2Br_4$ |
| Boiling point | 150.4°C. at 1 atmos. | 151°C. at 0.07 atmos. |
| Specific gravity | 2.89 | 2.964 |
| Viscosity | .068 poise | .098 poise |
| Surface tension | 41.53 dynes/cm. | 49.67 dynes/cm. |
| Diluent | Alcohol or carbon tetrachloride | Alcohol or carbon tetrachloride |
| Approximate price | $2.60 per lb. | $4.20 per lb. |

The choice between the two is more or less a matter of personal preference. They are both chemically inert, non-poisonous, of tolerable odor, and obtainable from chemical supply houses. The author prefers bromoform for the following reasons:

1. There are few minerals that sink in bromoform and will float in acetylene tetrabromide.
2. It is less viscous and will pass much more rapidly through a filter paper.
3. It is cheaper and can be obtained more easily.
4. While it is more volatile, this is not a serious disadvantage, since it need not be exposed to the air for long periods.
5. It will not darken badly, as will acetylene tetrabromide, upon heating to drive off the diluent.

Bromoform, as procurable commercially, is usually diluted with 4% alcohol. This is most easily removed by agitating with water in a separatory funnel, allowing the mixture to stand until the bromoform separates and drawing it off at the bottom of the funnel.

Bromoform that has been diluted with benzene or carbon tetrachloride can be recovered by boiling, either in an open dish or in a distilling flask, until it has a temperature of 300° F. or until white fumes are given off.

Purified bromoform will float dolomite, calcite, quartz, the feldspars, etc. The minerals that have specific gravities greater than 2.9, and sink in bromoform, are called *heavy minerals.*

The separation is most conveniently made in a porcelain evaporating

dish about 5 inches in diameter. The grains are added to about 50 cc. of bromoform and stirred with a glass rod until the heavy minerals have sunk. With the aid of the glass rod, the light minerals are transferred to a filter paper, the bromoform being allowed to drain back into the stock bottle.

The heavy crop is then transferred to another filter paper by means of a small wash-bottle filled with alcohol, care being taken to avoid the light minerals, many of which will adhere to the sides of the dish. Those that are near the lip of the dish may be wiped off with the finger.

The two crops are washed in the filter cones with alcohol and dried on a hot plate. It is well to save the filtrate from the alcohol washing, as considerable bromoform can be recovered from it by washing. This is somewhat of an item in view of the fact that bromoform costs about $2.60 a pound.

Glass *separatory funnels* of special design for carrying out heavy liquid concentration are advocated by some workers,[3] and there are great advantages in the use of these where a number of concentrations are being carried out at the same time.

For very finely divided sediments such as silts, heavy mineral concentration fails unless a procedure is followed similar to the ones described by Brown[4] and Berg[4a]. According to this method, the material is first separated, by means of settling and decantation (see page 12), into sand, silt, and clay grades. The silt grade is then dried very thoroughly at 150° C., and one or two gram samples are placed in 15-cc. centrifuge tubes, which are one-half filled with bromoform. The samples are centrifuged for five minutes, after which the tubes are shaken gently so as to dislodge any grains adhering to sides of tubes without disturbing the material in the bottoms. The samples are again centrifuged for five minutes, and the heavy minerals are removed from the bottoms of the tubes by means of a bulb-pipette.

A method of panning in a heavy liquid is advocated by Rogers[5] for the separation of a heavy mineral concentrated into several fractions.

**Magnetic separation.**—This method is based on the fact that minerals differ in their magnetic susceptibilities, some being attracted by a weak magnetic field, others by a stronger field, and still others not attracted by very strong fields. Close separations cannot, in general, be made by this method because the grains may have adherent or included particles of other

[3] Ross, C. S., "Methods of Preparation of Sedimentary Material for Study," *Econ. Geol.*, 21 (No. 5): 458. (1926.)

[4] Brown, S. C., "A Method for the Separation of Heavy Minerals of Fine Soil," *Jour. Paleont.*, 3 (No. 4): 412–14. (1929.)

[4a] Berg, Ernest, "A Method for the Mineralogical Fractionation of Sediments by Means of Heavy Liquids and the Centrifuge," *Jour. Sed. Petr.*, 7 (No. 2) : 51–54. (1937.)

[5] Rogers, A. F., personal communication.

minerals, or they may be ferriferous to a more or less degree. It is usually possible, however, to make a magnetic separation[6] that consists of four crops, as follows:

1. *Highly magnetic;* may contain:
   magnetite, pyrrhotite, magnetitic ilmenite, magnetitic hematite.
2. *Moderately magnetic;* may contain:
   ilmenite, chromite, hematite, garnet, glauconite, siderite, ferriferous amphiboles and pyroxenes.
3. *Weakly magnetic;* may contain:
   amphiboles, pyroxenes, tourmaline, epidote, olivine, staurolite, garnet, spinel, monazite, ferriferous rutile.
4. *Non-magnetic;* may contain:
   quartz, feldspars, zircon, kyanite, corundum, fluorite, brookite, anatase, calcite, andalusite, and many others.

The highly magnetic minerals may be removed by means of a permanent horseshoe magnet, over the pole pieces of which is held a piece of filter paper. The other magnetic crops require the use of an electro-magnet. An instrument of this kind is shown in Fig. 17 on page 60. The one-inch core of this magnet is of "*Armco*" iron, the pole pieces being of this material also. Over each limb of the core is slipped a brass spool upon which is wound 300 turns of No. 14 gauge insulated wire, the winding being clockwise on one spool and counter-clockwise on the other, the two being connected in series or parallel, according to the current supply. The pole pieces are wedge-shaped and adjustable for distance apart. The source of current is 110-volt, D.C., with an external variable resistance of 500 ohms maximum.

The lifting power of a magnet of a given design depends upon (1) the current, (2) the distance between pole pieces, and (3) the distance between the mineral grains and the pole pieces. In the magnet described, all of these may be varied, but it was found more convenient to keep each distance constant at about 0.1 inch and to vary the current by means of the rheostat.

A magnet which is an improvement on the one described above is described by Ksanda.[7] The pole pieces are adjusted by a micrometer screw, and the distance from minerals to pole pieces is adjusted by rack and pinion with attached scale. It operates directly on a 110-volt, D.C., circuit.

[6] Data after Holmes, *Petrographic Methods and Calculations*, 1921.

[7] Ksanda, C. J., "An Electro-magnetic Separator for Laboratory Use," *Jour. Opt. Soc. Amer.*, Vol. 13, No. 6 (December 1926).

Alternating current may be used with an electro-magnet if precaution is taken to avoid undue heating by not operating it for more than about five seconds at a time. Dry cells or storage batteries may also be used by making the design of the magnet conform with the available voltage, the intensity of the magnetic field depending upon the number of ampere-turns in the coils.

Magnetic separation is carried out with the magnet shown in Fig. 17 as follows:

1. A flat card (about 4″ × 6″) is placed on the glass table and the mineral grains are sprinkled thinly thereon.
2. The current is turned on and adjusted to the desired strength.
3. The glass table is made to slide around on its glass base until the pole pieces have picked up a moderate crop of grains.
4. The table is removed, another card is held beneath the pole pieces, and the current switched off. A small camel's hair brush is used to clean the pole pieces.
5. The process is repeated until no more grains are picked up at that amperage.
6. The current is increased to another definite amount and another crop separated. About four amperes, with this magnet, is sufficient to attract monazite and other weakly magnetic grains.

Experiments must be made to determine the proper amperage for the various crops of minerals.

**Electrostatic separation.**—Highly conducting minerals may be separated from poorly conducting ones by the application of an electrostatically charged body, and this method is effective in some cases where magnetic separation fails. Thus, pyrite, galena, and many non-magnetic sulphide minerals may be separated from quartz or other non-conducting minerals.

A laboratory type of electrostatic separator has been described by Holmes,[8] but the more simple method, using an ebonite rod excited by rubbing with fur, is preferable. The grains should be sized by screening and sprinkled lightly and evenly on a clean copper or metallic surface in a dry atmosphere. It is desirable to use a polished ebonite rod about eighteen inches long and three-quarters of an inch in diameter. This is rubbed vigorously with a piece of fur (or flannel) and then held horizontally above the grains and lowered gradually until grains are seen to be attaching themselves to it. The rod is then moved laterally over the grains, at the same time that it is rotated slowly. It is then raised and the adherent grains are removed.

[8] Holmes, Arthur, *Petrographic Methods and Calculations*, 1921, p. 96.

The principle is that the negatively charged rod induces positive charges on the upper surfaces of the grains and negative charges on the lower sides. In the case of conducting grains, these negative charges are removed to the metal plate, the grains have unsatisfied positive charges and are, therefore, attracted to the negatively charged rod. The negative charges of the non-conducting grains are, on the other hand, conducted away more slowly by the metal plate and they are not attracted by the rod to the same degree as are the conducting grains. The presence of moisture will cause the non-conducting grains to become conducting, and separation cannot be effected under these conditions.

TABLE 11

APPROXIMATE CONDUCTIVITIES OF MINERALS[9]

| Mineral | Conductivity (c.g.s. units) |
|---|---|
| Pyrrhotite | $2.36 \times 10^{3}$ |
| Galena | $3.78 \times 10^{2}$ |
| Pyrite | 4.16 |
| Hematite | 2.85 |
| Marcasite | .10 |
| Calcite | $1.82 \times 10^{-15}$ |
| Fluorite | $1.27 \times 10^{-18}$ |
| Quartz | $1.0 \times 10^{-20}$ |

**Dielectric separation.**—The dielectric strength of a substance is that property by virtue of which it resists the passage of a spark between two charged poles. Its numerical expression is the dielectric constant, which is the ratio of the attraction of two oppositely charged poles in a vacuum to their attraction in the substance.

Dielectric mineral separation is based on the work of Hatfield[10] and Holman[11] who showed that a mineral immersed in a liquid is attracted toward an electric field between two poles within the liquid if its dielectric constant is greater than that of the liquid. If the liquid has the greater dielectric constant, the mineral is repelled from the field.

The separation is best carried out in a watch-glass placed in the field of a binocular microscope. The sample should be sized to —100-mesh and the highly conducting minerals, such as magnetite and ilmenite, removed

[9] Adapted from *International Critical Tables*, 6: 154.

[10] Hatfield, H. S., "Dielectric Separation: A New Method for the Treatment of Ores," *Bull. Inst. Min. and Met.*, Nos. 233 and 234. (1924.)

[11] Holman, B. W., "Dielectric Mineral Separation: Notes on Laboratory Work," *ibid.*

by magnetic or electrostatic methods. A few milligrams of the grains are placed in the watch-glass and covered with *nitrobenzene* (dielectric constant = 36). The electric field is introduced with a pair of needles mounted on an insulating handle, the points being about 1 mm. apart.

Hatfield (*op. cit.*) recommends an electric supply of 250 volts, 100 cycles, alternating current, but this entails the use of a specially constructed commutator and a supply of direct current. The ordinary 60-cycle current has proved satisfactory, and this is transformed up to 300 or 400 volts for use. Inasmuch as no current is used, a large resistance (about 2,000 ohms) may be placed in the induced circuit, and this will prevent destructive arcing at the needle points in case they are shorted by a conducting grain.

After the needles are immersed in the nitrobenzene, the circuit is closed by a switch. The grains having a dielectric constant greater than the nitrobenzene (= 36) are attracted to the electric field between the needle points (see Fig. 18). They may be transferred to a small glass spoon immersed in the liquid, the needles being held above the spoon and raised to the surface of the liquid, whereupon the grains fall into the spoon and may be transferred to another watch-glass for microscopic study.

When all grains whose dielectric constant is greater than 36 have been removed, grains of smaller dielectric constants may be removed in a similar manner by diluting the nitrobenzene with *kerosene* (dielectric constant = 2).

The method is unique in that it is applicable upon extremely finely comminuted mineral. The separations are extraordinarily devoid of mechanically enmeshed grains because the grains that are not attracted to the field are actually repelled from it, and do not become enmeshed.

The dielectric constants of minerals vary, as do refractive indices, according to the axial direction in the crystal. A mineral grain will, however, tend to be controlled in its attraction to the electric field by its maximum dielectric constant. Impurities and inclusions sometimes greatly affect the dielectric properties.

Table 12 gives the maximum values for various pure minerals.

Precaution should be taken in the handling of nitrobenzene, not allowing it to remain in contact with the skin over long periods of time, as it is somewhat toxic when absorbed by the skin or lungs. Preliminary experiments made with *furfural* diluted with benzene (dielectric constant = 2.3) make it seem likely that this substance (dielectric constant = 42) is to be preferred to nitrobenzene.

The dielectric method of separation is especially valuable with the light minerals that occur in fine sediments, residual clays, and the like.

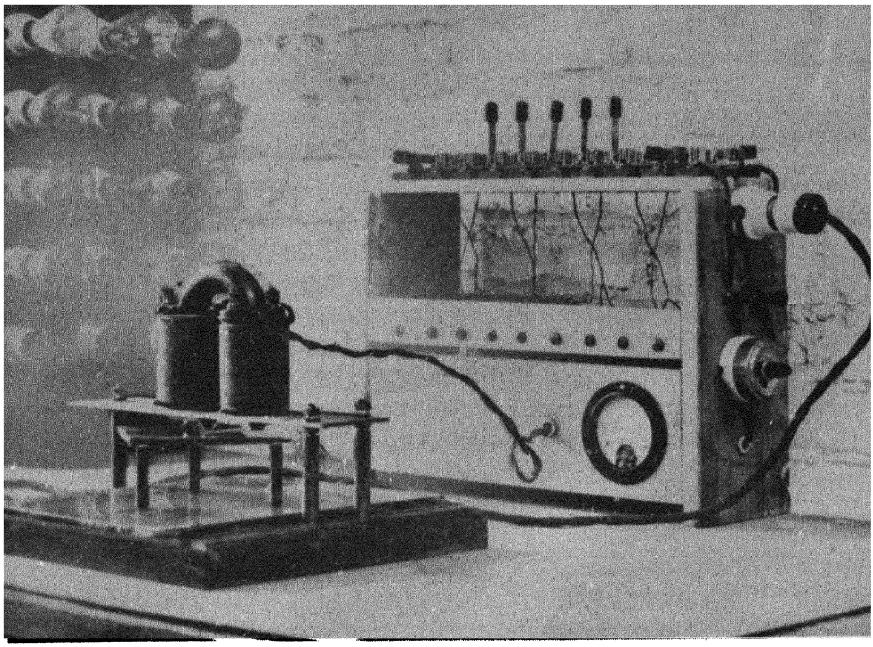


FIG. 17.—Electromagnet and rheostat for mineral grain separations

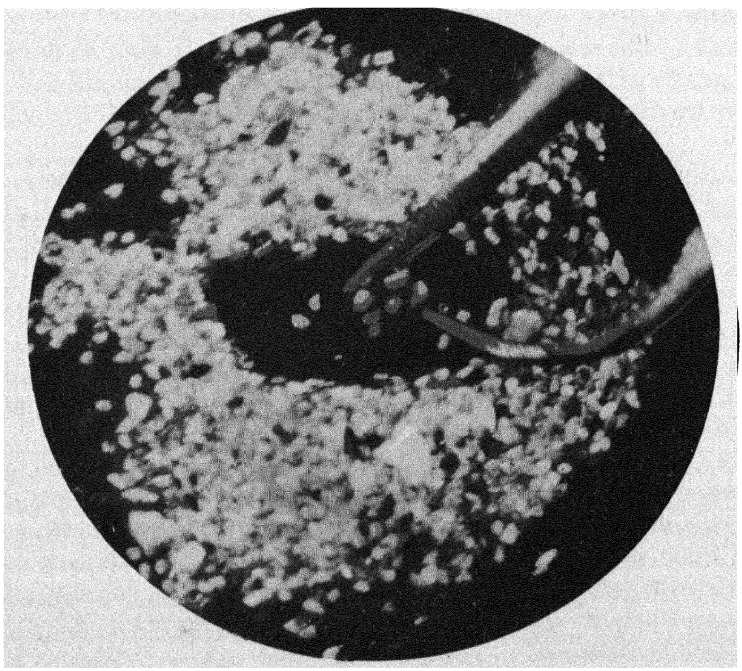


FIG. 18.—Dielectric separation. The grains attracted to the field between the needle points have dielectric constants greater than 36. The others have smaller dielectric constants and are repelled from the field.

TABLE 12

MAXIMUM DIELECTRIC CONSTANTS OF MINERALS*

| Mineral | Dielectric Constant |
|---|---|
| Rutile | 170 |
| Brookite | 78 |
| Cassiterite | 24 |
| Sphalerite | 17 |
| Corundum | 13 |
| Zircon | 12 |
| Gypsum | 11 |
| Apatite | 10 |
| Augite | 10 |
| Barite | 10 |
| Aragonite | 10 |
| Vesuvianite | 9 |
| Calcite | 8.5 |
| Siderite | 8 |
| Dolomite | 8 |
| Beryl | 7 |
| Fluorite | 6.9 |
| Tourmaline | 6.7 |
| Topaz | 6.7 |
| Spodumene | 6.6 |
| Quartz | 5 |
| Chalcedony | 4.2 |
| Muscovite | 2.9 |

* From *International Critical Tables*, and Landolt-Bornstein, *Tabellen*.

Materials of such nature are very likely to flocculate strongly in nitrobenzene, and this tendency may be prevented by the addition of 1% of a mixture of equal parts of *aniline* and *oleic acid*.

### *Mounting*

Undoubtedly the simplest and quickest method of mounting fragmental material for microscopic study is to sprinkle the grains on a slide, and cover them with cedar or clove oil and a cover-glass.

The disadvantage of this temporary mount is that it cannot be filed for future reference. A very great advantage is that the grains may be moved about in order to reorient them. Larsen[12] recommends the use of a cover-glass only a few millimeters square in order to facilitate rolling the grains.

The best temporary mounting medium is probably *clove oil* with refractive index of 1.53+. Quartz and most of the plagioclase feldspars have

[12] Larsen, E. S., "The Microscopic Determination of the Non-Opaque Minerals," *U.S. Geol. Survey Bull. 848*, p. 21.

indices higher than that of clove oil, while the potash feldspars have lower indices.

It is often of advantage to have an immersion medium of higher index, in which case either *α-monobromnaphthalene* ($N_D = 1.655$) or *methylene iodide* ($N_D = 1.74$) may be used. In the study of interference figures, it is sometimes better to have the grain immersed in a liquid approximately equal to the intermediate refractive index, ($N_\beta$).

Permanent mounts are usually made in Canada balsam ($N_D = 1.53$–$1.54$), although *kollolith,* a German synthetic resin, has a more constant index ($N_D = 1.535$) and *hyrax,*[18] another synthetic resin ($N_D = 1.80\pm$) is excellent where a highly refringent medium is desired. "Aroclor" No. 4465 is another mountant. It has a refractive index of 1.655, and is made by the Monsanto Chemical Company, St. Louis, Missouri. See also footnote at bottom of page 23.

The permanent mounting of grains is effected in the following manner:

1. The slide is cleaned by dipping in cleaning solution (saturated potassium dichromate in concentrated sulphuric acid). It is then washed in water and dried with a clean, lintless cloth.

2. The slide is touched with the wet cork from a bottle of solution of *gum tragacanth,* and the grains are sprinkled evenly thereon.

3. The slide is placed on a hot plate, the solution evaporated off, and a piece of solid balsam or other resin placed on top of the grains. The resin is heated until all bubbles have disappeared from its surface, whereupon a clean cover-glass is placed over the grains and the slide is removed to a cold metallic plate. The cover-glass is pressed down lightly while the resin is cooling.

4. After the resin is cold, the part that has extruded from beneath the cover-glass may be cut off with a knife and the slide cleaned with xylene. It is well to number the slide with a diamond-pointed pencil.

In the mounting of very small grains, and where an oil immersion objective of small working distance is to be used, it is better to mount the grains on the cover-glass instead of on the slide. In this way, the grains are closer to the cover-glass than to the slide.

[18] Procurable from Spindler and Sauppé, San Francisco.

# V

# IDENTIFICATION OF MINERALS

## Crystallographic Systems

Every mineral crystal belongs to a crystal system which is characterized by a certain degree of ***symmetry.*** There are planes, axes, and centers of symmetry.

A ***plane of symmetry*** is one that divides the crystal in halves, such that each half is a mirror image of the other.

An ***axis of symmetry*** is a line about which the crystal might be made to revolve and during one complete revolution of which a similar face would present itself to the observer 2, 3, 4, or 6 times. The axis would be called an axis of twofold, threefold, etc., symmetry. Certain axes of reference are chosen for the various systems.

A ***center of symmetry*** exists when every face has a similar parallel face on the diametrically opposite side of the crystal.

*Isometric system.*—A crystal is isometric if it has more than one axis of threefold symmetry and one or more axes of fourfold or of twofold symmetry. Common isometric forms are:

| Form | Mineral Representative |
|---|---|
| Cube | Pyrite |
| Octahedron | Spinel |
| Dodecahedron | Garnet |

*Tetragonal system.*—A crystal is tetragonal if it has one, and only one, axis of fourfold symmetry. Common tetragonal forms are:

| Form | Mineral Representative |
|---|---|
| Tetragonal prism | Zircon |
| Tetragonal bipyramid | Anatase |

*Hexagonal system.*—A crystal is hexagonal (rhombohedral division) if it has one, and only one, axis of threefold symmetry. It is hexagonal (hexagonal division) if it has one, and only one, axis of sixfold symmetry. Common hexagonal forms are:

| Form | Mineral Representative |
|---|---|
| Hexagonal prism | Quartz |
| Hexagonal bipyramid | Corundum |
| Ditrigonal prism | Tourmaline |
| Rhombohedron | Calcite |

*Orthorhombic system.*—A crystal is orthorhombic if it has three (not all equal) axes of twofold symmetry. Common orthorhombic forms are:

| Form | Mineral Representative |
|---|---|
| Rhombic prism | Topaz |
| Rhombic bipyramid | Sulphur |

*Monoclinic system.*—Monoclinic crystals have one axis of twofold symmetry. The three reference axes are unequal, but one is at right angles to the other two, which are inclined to one another. Common monoclinic forms are:

| Form | Mineral Representative |
|---|---|
| Rhombic prism | Orthoclase, titanite |

*Triclinic system.*—Triclinic crystals have no axes of symmetry. They may have a center of symmetry. The three reference axes are unequal and are inclined to one another. Common minerals crystallizing in this system are kyanite and the plagioclases.

***Orientation of crystals.*** (See Fig. 19.)

Hand specimens of crystals are conventionally oriented as follows:

*Isometric,* one axis vertical and one pointing away from observer.

*Tetragonal,* axis of fourfold symmetry, (*c*) being vertical, and one of the other two pointing away from observer.

*Hexagonal,* axis of three- or sixfold symmetry, (*c*) being vertical.

*Orthorhombic,* any axis (*c*) vertical, and the shorter of the other two (*a*) pointing away from observer.

*Monoclinic,* the axis that is normal to the other two (*b*) is made to extend transversely; another axis (*c*) is made vertical, and the third (*a*) is made to point downward toward the observer.

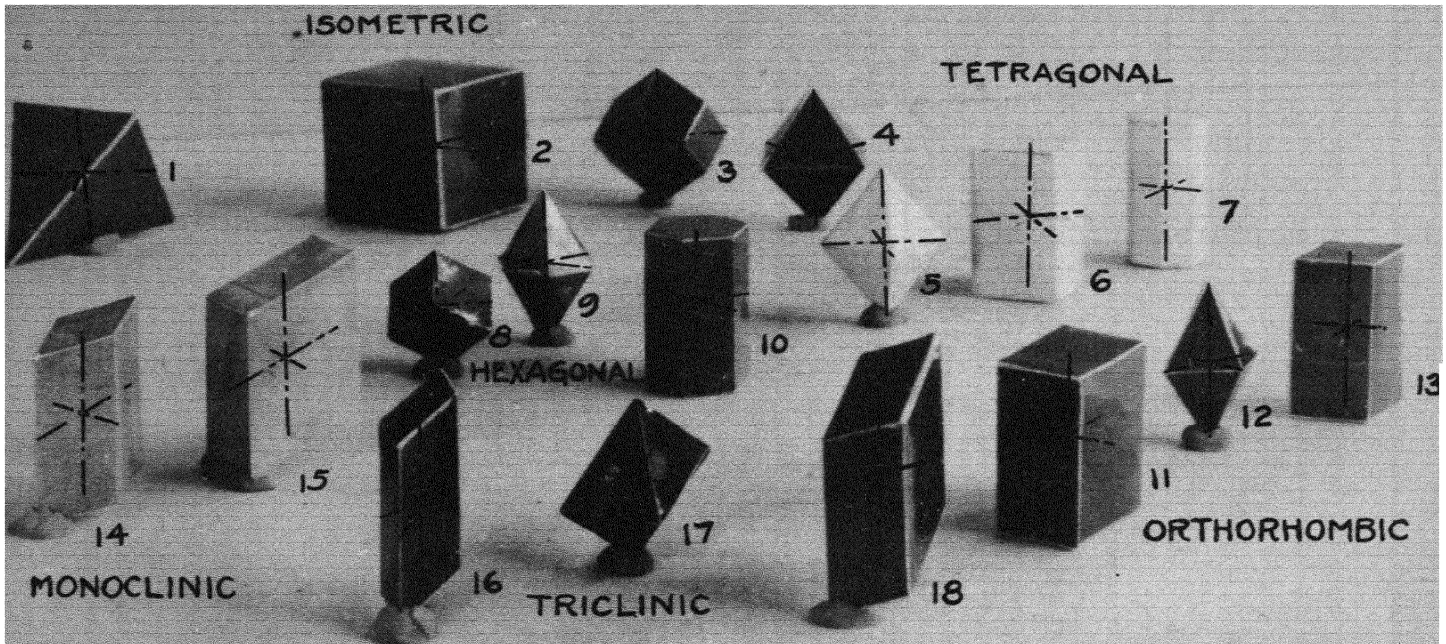



FIG. 19.—Crystal forms

| No. | System | Form |
|---|---|---|
| 1 | Isometric | Tetrahedron |
| 2 | Isometric | Cube |
| 3 | Isometric | Rhombic dodecahedron |
| 4 | Isometric | Octahedron |
| 5 | Tetragonal | Bipyramid |
| 6 | Tetragonal | Prism |
| 7 | Tetragonal | Ditetragonal prism |
| 8 | Hexagonal | Rhombohedron |
| 9 | Hexagonal | Bipyramid |
| 10 | Hexagonal | Prism |
| 11 | Orthorhombic | Prism |
| 12 | Orthorhombic | Bipyramid |
| 13 | Orthorhombic | Prism |
| 14 | Monoclinic | Prism |
| 15 | Monoclinic | Prism |
| 16 | Triclinic | Prism |
| 17 | Triclinic | Bipyramid |
| 18 | Triclinic | Prism |

*Triclinic,* any axis (*c*) is made vertical, and the shorter of the other two (*a*) is made to point downward toward the observer.

The crystallographic axes are labeled *a, b,* and *c*. The method of orientation is illustrated in Fig. 20.

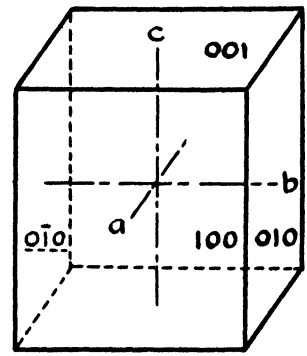



FIG. 20.—Orientation of an orthorhombic crystal

### *Miller Indices*

The axes of reference are chosen so that the distances from the origin to the intercepts of the various crystal faces make simple ratios with one another. In the Miller system, the three intercepts are given in the following order:

1. The intercept on the axis pointing toward observer;
2. The intercept on the axis extending to the right;
3. The intercept on the vertical axis.

The most common forms taken by the symbols are illustrated by the following examples:

| Crystal Face | Miller Symbol |
|---|---|
| 1. A front cube or prism face | **100** |
| 2. A side cube or prism face | **010** |
| 3. A diagonal (45°) prism face | **110** |
| 4. A base | **001** |
| 5. A pyramid or octahedron face | **111** |

For the hexagonal system four indices are used, the symbol for the base being **0001.**

In the orthorhombic and triclinic systems, the **010** faces are called the *brachypinacoid,* and the **100** faces are called the *macropinacoid.* In the monoclinic system, the **010** faces are called the *clinopinacoid,* and the **100** faces the *orthopinacoid.*

### *Cleavage*

Cleavage is of importance in the identification of mineral grains, either crushed or detrital, certain minerals (fluorite, calcite, etc.) being readily recognized by this property.

Cleavage in a crystal is always parallel to faces of forms characteristic of the system to which the crystal belongs. An isometric mineral, therefore, may crystallize in cubes and (like halite) have cubic cleavage, or (like fluorite) have octahedral cleavage.

| System | Cleavages | Parallel to |
|---|---|---|
| Isometric | Cubic | 001, 010, and 100 |
| | Octahedral | 111, etc. |
| | Dodecahedral | 101, 011, 110 |
| Tetragonal | Prismatic | 100, 010, 110 |
| | Basal | 001 |
| Hexagonal | Rhombohedral | $10\bar{1}1$, etc. |
| | Basal | 0001 |
| Orthorhombic | Prismatic | 110, 100, 010 |
| | Basal | 001 |
| Monoclinic | Prismatic | 110, 100, 010 |
| | Basal | 001 |
| Triclinic | Prismatic | 110, 100, 010 |
| | Basal | 001 |

Prismatic cleavages in a mineral often make dihedral angles that are ıaracteristic of the mineral or group. Thus the amphiboles have a prisatic angle of 124°, while pyroxenes have a prismatic angle of 87°. Also, orthoclase there is cleavage parallel to **001** and to **010**, making an angle of )°, while in plagioclases the corresponding angle is about 86°.

### *winning*

Twinning of crystals is exhibited when two or more crystals are grown gether in partial parallelism. They may be in mere contact, or they may terpenetrate. The elements of most twins can be thought of as having )tated about a common axis called the **twinning axis.** The plane normal ) this axis, which is parallel to some crystal face, is called the **twinning lane.** The kind of twinning is usually described, with reference either to ıe twinning axis or to the twinning plane.

Mineral grains can sometimes be identified by the type of twinning exibited. Some of the notable ones are tabulated below:

| Mineral | Type of Twinning | Name of Twinning | Twinning Plane |
|---|---|---|---|
| Rutile | Penetration | Knee | **101** |
| Staurolite | Penetration | Cruciform | **032** |
| Orthoclase | Contact | Carlsbad | **010** |
| Plagioclase | Contact | Albite (polysynthetic) | **010** |

The *polysynthetic* (repeated) twinning nearly always exhibited by lagioclases is very useful in identifying the various prismatic faces.

Cleavage fragments of plagioclase will show either the **001** or the **010** ıce. Polysynthetic albite twinning can be seen (with the polarizing microcope) on the **001**, but not on the **010** face. It is always parallel to the **01–010** edge. Pericline twinning is also polysynthetic and is sometimes

shown on the **010** face. It is parallel to the cleavage only in the case of andesine. This is shown in Fig. 21 (p. 69). Albite twinning, then, identifies the **001** face and makes possible certain optical measurements on this face which serve to identify the species of plagioclase, as shown in Fig. 22 (p. 69).

Crossed polysynthetic twinning (*grating structure*) is characteristic of a certain orthoclase feldspar (*microcline*), and the mineral can be recognized by this feature.

**Parting** often takes place along twinning planes, as in the **100** parting of spodumene.

## The petrographic microscope

The petrographic microscope has the following essential parts, enumerated in the order of their interception in the path of incident light (see Fig. 23):

1. A *mirror,* which reflects the incident light into the lower nicol prism (polarizer).

2. The *lower nicol prism* (polarizer) which transmits only that part of the light vibrating in one direction. This nicol prism can be rotated; but most microscopes are built so that when it is set at its zero position, the transmitted light vibrates in a N.–S. direction, that is, to and from the observer. It should be noted that light always vibrates in a plane normal to the direction of propagation.

3. The *substage condenser,* which converges the light upon the object under examination. It is mounted in such a way that it can be moved up or down with a rack and pinion mechanism. This condenser consists of two elements: (*a*) the lower or low-power one, which is used for observation of the object at low or medium magnification, and (*b*) the upper or high-power condenser, which can be inserted into or removed from the path of light and is used for observation of the object at high (and sometimes medium) magnification and for the observation of interference figures.

4. The *stage* upon which the object slide rests. This stage rotates about an axis that must be coincident with the axial cone of light. The periphery of the stage is graduated in degrees so that the amount of its rotation may be determined.

5. The *objective lens,* which produces a real and magnified image within the tube of the microscope. The magnification produced by the objective (called *initial magnification*) depends upon its focal length and the length of the tube above it. The tube length is usually fixed, so that magnification

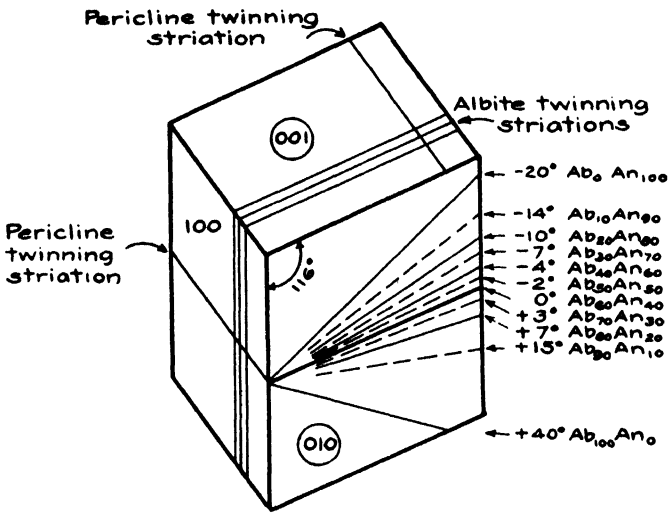



FIG. 21.—Plagioclase cleavage flake, showing relation of pericline twinning striations to cleavage faces. Faces with symbols encircled (or their opposites) are the ones seen in cleavage flakes. (Data after Schmidt.)

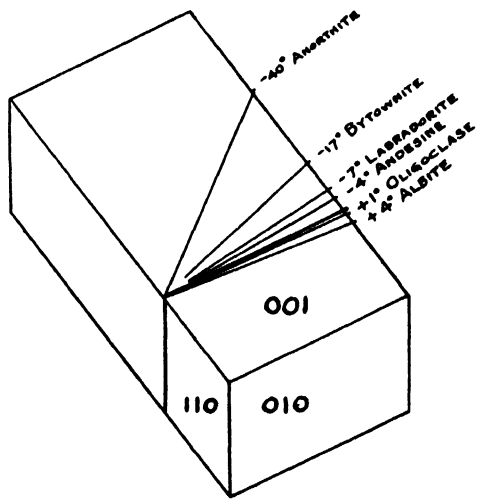



FIG. 22.—Plagioclase cleavage flake, showing angles between albite twinning striations (heavy line) and vibration direction of the fast ray.

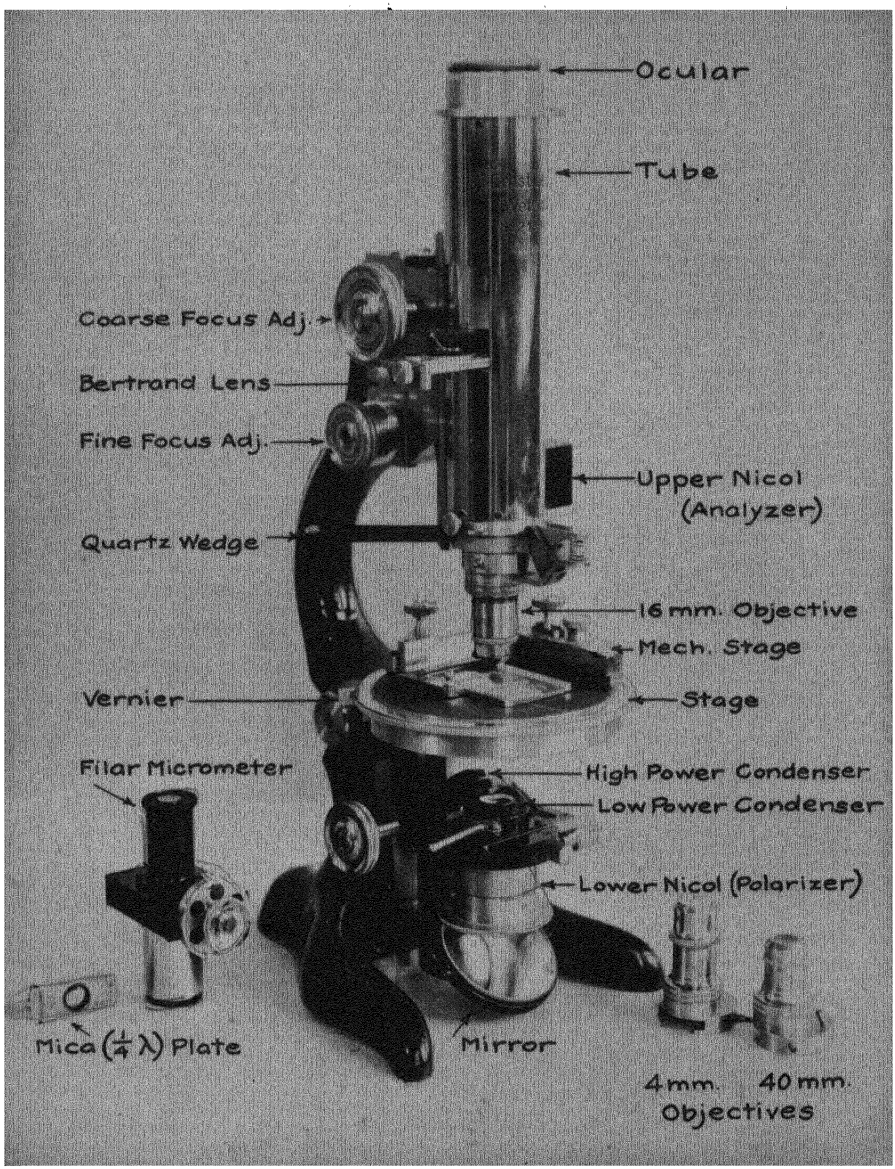



FIG 23.—Petrographic microscope (Leitz "GM" model)

is dependent upon the objective used. Objectives for petrographic purposes are often specially corrected for polarization. The most useful sizes are:

| Focal Length | Power |
|---|---|
| 40 mm. | Low |
| 16 mm. | Medium |
| 4 mm. | High |
| 2 mm. | Very high |

The *numerical aperture* (light-converging power) of the condenser should be as great as that of the objective. For very high-power work (with 2-mm. objective) it is necessary to use a special condenser with $NA = 1.4$ and homogeneous (oil) immersion. *Oil immersion* is attained by placing a film of cedar oil between condenser and object slide and another film between cover glass and objective. $NA = n \sin u$; where $u$ is the angle between the extreme rays of the cone of light, and $n$ is the refractive index of the immersion medium.

The high-power objectives have short *working distances* (distance between front lens and the object), so that thin objects and thin cover-glasses are necessary. High-power objectives also have short *tepths of focus* so that when one part of the object is brought to a focus other parts not in almost the same plane will be out of focus.

6. The *accessory* (*mica plate, gypsum plate, quartz wedge,* etc.) which is removable and used only for certain purposes. It is inserted through a slot which is usually located just above the objective mount. Where the vibration direction of the polarizer is N.–S., the accessory slot usually points NW.–SE.

7. The *upper nicol prism* (analyzer), which transmits only that part of the light vibrating in a direction (usually E.–W.) normal to the direction of vibration of the lower nicol. This nicol slides in and out of the tube. When it is inserted, the nicols are said to be *crossed* and, where no anisotropic object is interposed in the path of light, no light passes through the upper nicol.

8. The *Bertrand lens,* for the observation of interference figures. This lens slides in and out, and it is provided with an iris or other diaphragm. The Bertrand lens is not used for *orthoscopic* observations (observations of the object), but is used for *conoscopic* observations (observations of interference figures, sometimes called *"directions images"*).

9. The *ocular* (eyepiece), which magnifies the image produced by the objective and brings it to a focus just above the top of the tube, where the eye can observe it. Oculars are rated according to their magnifying power, 4×, 8×, 12×, etc. They are equipped with cross-wires, usually oriented N.–S. and E.–W., and these are brought to the same focus as the image.

The tube of the microscope moves up and down and is actuated by a coarse and a fine adjustment. The fine adjustment is graduated so that the vertical movement can be read accurately. This is convenient for measurements of thickness.

The petrographic microscope sometimes includes other features which are desirable for certain purposes, but not necessary. Some of these are as follows:

1. *Iris diaphragms* below the lower nicol and above the lower condenser. The latter diaphragm is useful for cutting down the illumination to increase depth of focus, but the same result can be accomplished by lowering the substage condenser. The first named diaphragm is of some use for the isolation of a small mineral grain when making conoscopic observations.

2. *Mechanical stage.*—This mechanism holds the object slide and permits movement in any direction. The two rack and pinion movements are provided with scales and verniers so that if the object slide is always placed in the stage in the same way, an object whose position is defined by the mechanical-stage readings can readily be found at some future time. The mechanical stage is indispensable in making counts of mineral grains. By its aid, the area of the slide can be traversed in straight and regularly spaced lines.

3. *Rotating upper nicol.*—This is useful for observations with parallel nicols, and obviates the necessity of rotating the lower nicol. It is easy to dispense with this feature.

4. *Synchronous rotation of nicols.*—This feature is provided on some microscopes and is useful for detailed petrographic studies, especially for measurement of optic axial angles. It is not recommended for general use.

5. *Ocular micrometer.*—This is a useful accessory for the measurement of grain size. It consists of an engraved scale in the focal plane of an ocular of special design. In some cases, a cross-wire may be made to move across the field of the ocular, the distance of its movement being read on a graduated drum. This is called a *filar micrometer.*

In order to calibrate the scale of the ocular micrometer for each objective used, it is necessary to have a *stage micrometer.* This is a glass slide upon which has been ruled a scale, usually 1 mm. divided into 100 parts.

The accessories advised for the study of mineral and other crystal grains are as follows:

1. Ocular and stage micrometers
2. Mica ($\frac{1}{4}\lambda$) plate
3. Johannsen (or Wright) quartz-gypsum wedge

## OPTICAL PROPERTIES

### Polarization

1. The mineral remains dark at all positions of the stage when nicols are crossed.

*a*) Conoscopic observation (see page 85) reveals no interference figure; the mineral is **isotropic** (and either isometric or amorphous).

*b*) Conoscopic observation reveals a uniaxial figure (usually well centered); the mineral is **uniaxial** and the section is normal to the optic axis (tetragonal or hexagonal).

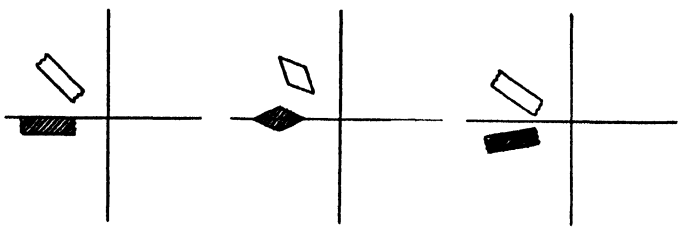
2. The mineral, when viewed between crossed nicols, is alternately light and dark four times during one revolution of the stage; the mineral is **anisotropic.**

3. The mineral, between crossed nicols, transmits some light but does not become alternately light and dark; the mineral is anisotropic and **biaxial,** and the section is normal to an **optic axis.**

4. The occurrence of complete extinction for white light indicates that the mineral is either tetragonal, hexagonal, or orthorhombic. In the other systems, the extinctions are not the same for all wave-lengths, and the extinction for white light is not quite complete. This phenomenon of incomplete extinction is due to dispersion and should not be confused with the undulatory extinction, commonly exhibited by quartz, nor to the incomplete extinction of sections of a biaxial mineral cut normal to an optic axis.

***Extinction*** (of anisotropic minerals)

1. The mineral, between crossed nicols, is dark when a prism face or a prismatic cleavage is parallel to cross-hairs; extinction is **parallel** (Fig. 24, *a*).



*a*) Parallel *b*) Symmetrical *c*) Inclined

FIG. 24.—Types of extinction

2. The cross-hairs bisect, at extinction, the angles of a rhombic cleavage plate; extinction is **symmetrical.** This is a special case of parallel extinction (Fig.24, *b*).

3. The cross-hairs, at extinction of mineral, are not parallel to prism faces nor do they bisect angles of a rhombic cleavage plate; extinction is **inclined** (Fig. 24, *c*).

| Crystal System | Extinction |
|---|---|
| Tetragonal | Parallel |
| Hexagonal | Parallel |
| Orthorhombic | Parallel |
| Monoclinic | Parallel only in sections parallel to *b* axis |
| Triclinic | Inclined |

## Refractive Index

The refractive index of a substance is inversely proportional to the velocity of light passing through it.

If a colorless, transparent grain is immersed in a liquid having the same index as the grain, the latter will be invisible, and to the degree that the two indices differ will the grain boundaries become distinct and the irregularities on its surface evident. This distinctness is called **relief**, and it is high when the index of mineral and immersion liquid vary greatly. Usually the mineral has higher index than the liquid, and it always has in cases of high relief in Canada balsam (see Fig. 25, p. 81).

### *Tests for index*

1. If relief is high, mineral has index considerably higher or lower than that of liquid. If relief is low, index is slightly higher or lower.

2. If relief is low, focus on grain with high power and cut down illumination with diaphragm or by lowering sub-stage condenser. Raise tube with tangent motion and note edge of grain. A **bright line** (*Becke line*) will move toward the medium of **higher index.** Lower tube, and the reverse will take place.

If relief is high, the Becke line may not appear, but the whole grain will illuminate toward the center as tube is raised. At the same time there may be a bright line moving out into the liquid. This should not be confused with the Becke line.

3. Another method is to use **inclined illumination**, secured by partly shading the reflector with the finger, using low-power objective, the condenser being lowered somewhat. When the mineral has higher index than the liquid, it will be shaded on the same side as the finger. If liquid has high dispersion, an immersed mineral of nearly the same index will be colored blue on the one side and red on the other.

**Immersion media.**—By immersing a grain in liquids of successively higher index, the point is reached where the grain is found to have slightly

higher index than one liquid and slightly lower than the next liquid. In this way the index of the mineral may be estimated to the third decimal place.

With an Abbé refractometer and the liquids recommended by Larsen,[1] a set of liquids may be compounded that differ in index from one another by 0.005 up to 1.70. This set may also be purchased from Ward's Natural Science Establishment, Rochester, New York.

A set of immersion liquids recommended by Emmons[2] (Table 13, p. 75) consists of pure organic compounds which will not vary in their indices over a period of time because each substance is homogeneous or, in the case of a mixture of two substances, the boiling points are nearly alike and each evaporates at nearly the same rate. The series does not have quite a constant increment of index between the consecutive members, but, as Emmons points out, it does not compare unfavorably with other proposed series in this respect because the members of the latter change in index after a lapse of time and do not maintain their original constancy of increment.

**Procedure.**—Isolate the desired grain by pushing it to one side of the slide with a mounted needle. Transfer it to a clean slide and immerse it in a drop of an immersion liquid. Note which index is the higher, and then remove the drop of liquid with the edge of a filter paper. Apply a drop of another liquid and repeat procedure.

### *Refraction in Anisotropic Minerals*

Isotropic minerals have only one index, since light travels at the same velocity in all directions through the grain.

Anisotropic minerals have either two or three directions in which the light travels at different velocities, and have two or three indices.

**Uniaxial minerals.**—Light incident normal to a basal cleavage (parallel to the optic-crystallographic long axis) is transmitted unrefracted and undivided. If the light is incident normal to a prism face, it will be divided, one part (*the ordinary ray*) vibrating normal to the optic axis, and the other part (*extraordinary ray*) vibrating parallel to the optic axis.

If the ordinary ray is faster than the extraordinary ray, then the index of the extraordinary ray is greater than that of the ordinary ray ($\varepsilon > \omega$) and the mineral is said to be optically (+). If $\omega > \varepsilon$, the mineral is (−).

[1] Larsen, E. S., "The Microscopic Determination of the Non-opaque Minerals," *U.S. Geol. Survey Bull. 848*, p. 12.

[2] Emmons, R. C., "A Set of Thirty Immersion Media," *Amer. Mineralogist*, 14 (No. 12): 482–83. (December 1929.) The table is quoted by permission.

TABLE 13

REFRACTIVE INDEX LIQUIDS[3]

| Liquid | Boiling Point °C. | at | Pressure (mm.) | $N_D$ 24°C. | Temperature Coefficient | Dark Container |
|---|---|---|---|---|---|---|
| Trimethylene chloride | 119.5 | | 735 | 1.446 | .00045 | |
| Cineol | 53–54 | | 8 (Eastman) | 1.456 | .00041 | |
| Hexahydrophenol | 161 | | 740 | 1.466 | .00044 | |
| Decahydronaphthalene | 88.5–90.5 | | 38 | 1.477 | .00040 | |
| Isomylphthalate | (Tech.) | | Eastman | 1.486 | .00038 | |
| Tetrachlorethane | 143–144.4 | | 740 | 1.492 | .00051 | |
| Pentachlorethane | 158–160 | | 740 | 1.501 | .00048 | |
| Trimethylene bromide | 165–167 | | Eastman | 1.513 | .00048 | |
| Chlorobenzene | 130.5–130.8 | | 740 | 1.523 | .00053 | |
| Ethylene bromide + chlorobenzene | | | | 1.533 | .00054 | |
| O-Nitrotoluene | 220–220.4 | | 740 | 1.544 | .00053 | |
| Xylidine | 114–118 | | 27 | 1.557 | .00050 | V |
| O-Toluidene | 87–88.5 | | 17 | 1.570 | .00047 | V |
| Aniline | 66.8–67.2 | | 4.5 | 1.584 | .00045 | V |
| Bromoform | 147.5 | | 736 | 1.595 | .00056 | |
| Iodobenzene + bromobenzene | | | | 1.603 | .00054 | V |
| Iodobenzene + bromobenzene | | | | 1.613 | .00054 | V |
| Quinolin | 117–121 | | 16 | 1.622 | .00049 | V |
| α-Chloronaphthalene | 128–132 | | 20 | 1.633 | .00044 | |
| α-Bromonaphthalene + α-chloronaphthalene | | | | 1.640 | .00044 | |
| + α-chloronaphthalene | | | | 1.650 | .00044 | |
| α-Bromonaphthalene + α-iodonaphthalene | | | | 1.660 | .00045 | V |
| + α-iodonaphthalene | | | | 1.670 | .00044 | V |
| + α-iodonaphthalene | | | | 1.680 | .00044 | V |
| + α-iodonaphthalene | | | | 1.690 | .00044 | V |
| Methylene iodide + iodobenzene | | | | 1.700 | .00060 | V |
| Methylene iodide + iodobenzene | | | | 1.710 | .00063 | V |
| Methylene iodide + iodobenzene | | | | 1.720 | .00066 | V |
| Methylene iodide + iodobenzene | | | | 1.730 | .00068 | V |
| Methylene iodide | 80 | | 15 | 1.738 | .00070 | V |

The mean index ($N'$) signifies $\frac{\varepsilon + 2\omega}{3}$.

**Biaxial minerals.**—Biaxial minerals have two optic axes, neither of which is parallel with $c$. There are three directions in which light travels

[3] All obtainable from Eastman Kodak Company, Rochester, New York, or in sets from Dr. C. E. Muehlberger, Service Memorial Institute, Madison, Wisconsin.

TABLE 14

REFRACTIVE INDICES ($N_D$) OF SOME COMMON LIQUIDS

| | |
|---|---|
| Water | 1.33 |
| Alcohol | 1.36 |
| Kerosene | 1.45 |
| Glycerine | 1.47 |
| Xylene | 1.49 |
| Cedar oil | 1.51 |
| Clove oil | 1.53 |
| Canada balsam | 1.54 |
| Bromoform | 1.58 |
| Cinnamon oil | 1.62 |
| α-Monobromnaphthalene | 1.65 |
| Methylene iodide | 1.74 |
| Methylene iodide and sulphur | 1.79 |

at different velocities, and hence three indices. $N_\alpha$, $N_\beta$, and $N_\gamma$ are the three indices in order of decreasing magnitude, $N_\beta$ being intermediate but not necessarily having a mean value. $N_\alpha$ is the index of the **fast ray** and $N_\gamma$ the index of the **slow ray.**

When the slow ray ($\gamma$) is parallel to the line bisecting the acute angle between the optic axes (acute bisectrix = $Bxa$) the mineral is optically (+). If the fast ray ($\alpha$) is parallel to $Bxa$, the mineral is (−). If the optic axes intersect at 90°, the mineral is optically neutral.

The mean index ($N'$) signifies $\frac{N_\alpha + N_\beta + N_\gamma}{3}$.

### *Indices of Anisotropic Minerals*

**Uniaxial minerals.**—If the mineral is uniaxial and lies on a prism face or cleavage, the index for the extraordinary ray ($\varepsilon$) may be determined in immersion media by placing ($c$) parallel to the vibration direction of the polarizer during the test. Rotating the prismatic grain 90° and determining the index again will give ($\omega$). For a random section of the mineral, and a determination of the indices parallel to each vibration direction of the nicols, one of these values will be for the ordinary ray ($\omega$). The other index ($\varepsilon$) can be obtained only by taking for a number of grains the maximum or minimum index, according as the optical character is (+) or (−).

**Biaxial minerals.**—If a grain can be found that gives an acute bisectrix interference figure (see page 88), and this orientation can be preserved while testing the index in various immersion media, the value obtained when the grain is placed with its axial plane parallel to the vibration direction of the polarizer will be $N_\gamma$ or $N_\alpha$, according as the

mineral is optically (+) or (−). The index for a vibration direction normal to the axial plane will be $N_\beta$.

A method for ascertaining the value of $N_\beta$ has been given by Tsuboi.[4] If an immersion liquid has an index greater than that of the grain for any orientation in plane polarized light, and another liquid has an index less than that of the grain for any orientation, then $N_\beta$ lies between the indices of the two liquids.

If a grain showing emergence of *Bxa* cannot be found, about the only method remaining is to obtain the maximum and minimum indices of a number of grains, the greatest and the least one so found being assumed to be $N_\gamma$ and $N_\alpha$ respectively.

Winchell and Emmons[5] describe a method which requires the variation and control of the temperature of the immersion medium and the variation and control of the wave-length of the incident light. The index of the mineral is matched with that of the liquid for two temperatures and two wave-lengths. The index is then read from a specially constructed chart. Wave-length control of the incident light is secured by means of a small-prism monochromator, and temperature control is secured by mounting the grains in a glass water-circulation cell. The index of the immersion liquid is determined, for the temperatures of observation, with an Abbé refractometer.

One of the most valuable methods for the identification of plagioclase feldspars[6] depends upon the determination of the lesser and/or greater indices of cleavage flakes, which are parallel either to **001** or to **010**, as shown in Fig. 21 (page 69). It happens, however, that the lesser index of a given plagioclase is almost the same for both **001** and **010** cleavage flakes, thus making it less necessary to recognize which face is presented. Thus a determination of the lesser index, by the immersion method (with sodium light), serves to identify the plagioclase.

These indices are substantially correct for either **001** or **010** cleavage flakes.

## Birefringence

**Birefringence (B)** is a measure of the ability of a mineral to separate two refracted rays. It is given by the difference $\varepsilon - \omega$ or $\omega - \varepsilon$ for uniaxial minerals and $N_\gamma - N_\alpha$ for biaxial minerals.

The light transmitted through an anisotropic mineral in any direction

[4] Tsuboi, S., *Jour. Geol. Soc. Tokyo,* **25**: 38. (1918.)

[5] Winchell, A. N., and Emmons, R. C., "Some Methods for Determining Refractive Indices," *Amer. Mineralogist,* **11**: 115. (1926.)

[6] Tsuboi, S., *Mineral. Mag.,* **20**: 108–122. (1923.)

TABLE 15

THE LESSER INDEX OF PLAGIOCLASE CLEAVAGE FLAKES
(AFTER TSUBOI)

| Mineral | Formula | Index ($N_D$) |
|---|---|---|
| Albite | $Ab_{100}An_0$ | 1.529 |
| Albiclase | $Ab_{90}An_{10}$ | 1.532 |
| Oligoclase | $Ab_{80}An_{20}$ | 1.539 |
| Andeclase | $Ab_{70}An_{30}$ | 1.543 |
| Andesine | $Ab_{60}An_{40}$ | 1.548 |
| Labradorite | $Ab_{50}An_{50}$ | 1.555 |
| Labratownite | $Ab_{40}An_{60}$ | 1.560 |
| Bytownite | $Ab_{30}An_{70}$ | 1.565 |
| Bytownorthite | $Ab_{20}An_{80}$ | 1.570 |
| Anorthite | $Ab_{10}An_{90}$ | 1.575 |
| | $Ab_0An_{100}$ | 1.580 |

other than parallel to an optic axis is divided so that one part travels faster than the other part, which latter is said to be *retarded*. These two rays then "interfere," and their phase difference determines the color of the resultant light from this interference.

The phase difference, or **retardation (R)**, and hence the interference color, is dependent upon the birefringence ($\pm \varepsilon \mp \omega$ or $N_\gamma - N_\alpha$), the optical orientation, and the thickness (t) of the mineral. That is:

$$R = Bt$$

Where the specimen is in thin section and one of the component minerals (such as quartz) can be recognized, then the maximum interference color given by grains of this mineral will determine its thickness:

$$t = \frac{R}{B}$$

Since the section is assumed to be uniform in thickness, the thickness of all the minerals is known and, by observing the interference colors, their birefringences may be calculated:

$$B = \frac{R}{t}$$

TABLE 16

TABLE OF INTERFERENCE COLORS

| Order | Color | Retardation ($m\mu$) |
|---|---|---|
| 1 | gray | 50 |
| | white | 100 |
| | white | 200 |
| | yellow | 300 |
| | orange | 400 |
| | red | 500 |
| 2 | blue-violet | 600 |
| | greenish blue | 700 |
| | greenish yellow | 800 |
| | yellow | 900 |
| | pink | 1,000 |
| | pink | 1,100 |
| 3 | pale blue | 1,200 |
| | pale green | 1,300 |
| | pale yellow | 1,400 |
| | pinkish yellow | 1,500 |
| | pale pink | 1,600 |

The usual thickness of a thin section is .03 mm., and quartz at this thickness gives a maximum interference color of white (first order). Colors of quartz higher than this, yellow, red, blue, etc., indicate a section thicker than 0.03 mm.

The numerical value of the retardation can be determined by means of a graduated quartz wedge or **compensator**, but for mineral grains this procedure is not practicable in the estimation of birefringence, because the thickness cannot be measured with sufficient accuracy.

**Birefringence** of mineral grains can be estimated roughly by noting the order of the interference colors and allowing for the apparent grain thickness. Practice brings good judgment in this respect (see Fig. 26).

Both low first-order and very high-order interference colors are white. In order to distinguish between them, the mica plate ($\frac{1}{4}\lambda$) may be inserted. If the color is first-order white, the plate will run the color up to yellow or down to gray, according as the mineral is in an additive or a subtractive position (see page 82). If the color is of high order, the plate will cause no perceptible change.

Low first-order colors may be differentiated more clearly with parallel nicols than with crossed nicols. For example:

| Crossed Nicols | Parallel Nicols |
|---|---|
| Gray | Yellow to brownish |
| White | Reddish brown to light red |

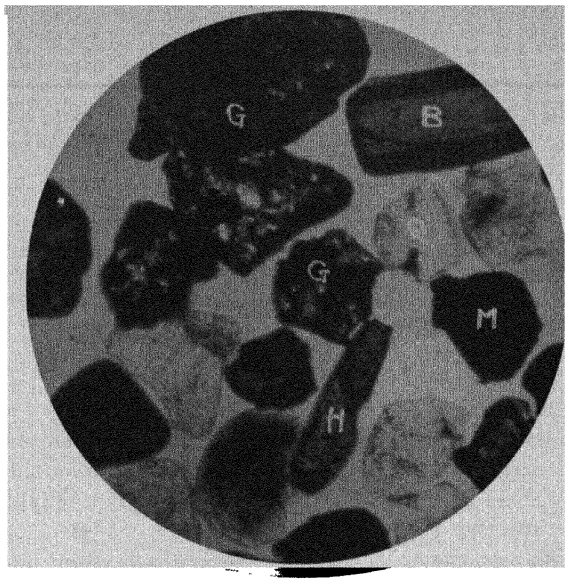



FIG. 25.—Mineral grains, showing degrees of relief (× 45)

| | RELIEF |
|---|---|
| B—Basaltic hornblende | High |
| G—Garnet | Very high |
| H—Hypersthene | High |
| M—Magnetite | Opaque |
| Q—Quartz | Low |

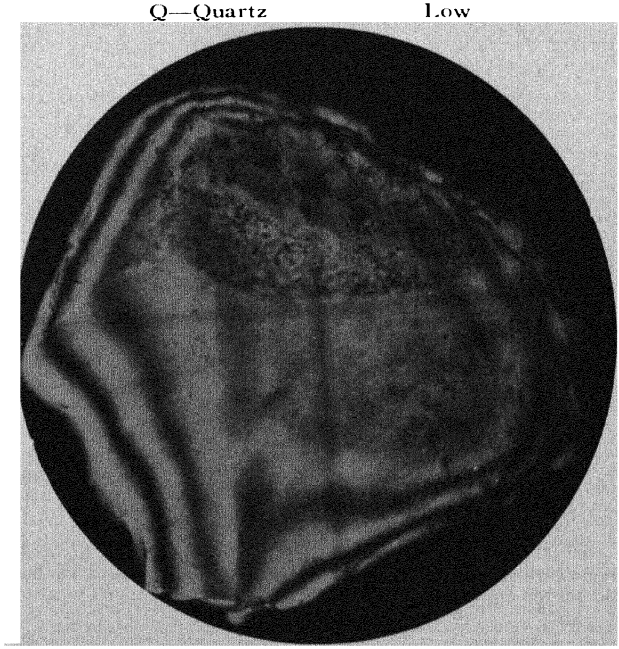


FIG. 26.—Quartz grain between crossed nicols, showing interference color bands. Four orders of red are shown. (× 150)

## Elongation Character

By definition:

When the vibration direction of the **slow ray** ($\gamma$) is parallel (or nearly parallel) to the crystallographic long axis ($c$), the elongation is (+); otherwise, it is (−).

## Test

1. Place mineral grain at 45° to extinction.
2. A. If the grain is flat and only one interference color is visible, insert *mica* ($\frac{1}{4}\lambda$) *plate*. If interference color goes up, the effect of the plate has been **additive**; if it does down, **subtractive** (see Fig. 27, *A–B*).

   B. If the grain is lens- or wedge-shaped and several interference colors are visible, insert *quartz wedge* (thin edge first). If colors in mineral seem to travel **toward** the thin edges of the grain, the effect of the wedge has been **additive**; otherwise, **subtractive** (see Fig. 27, *C–D*).

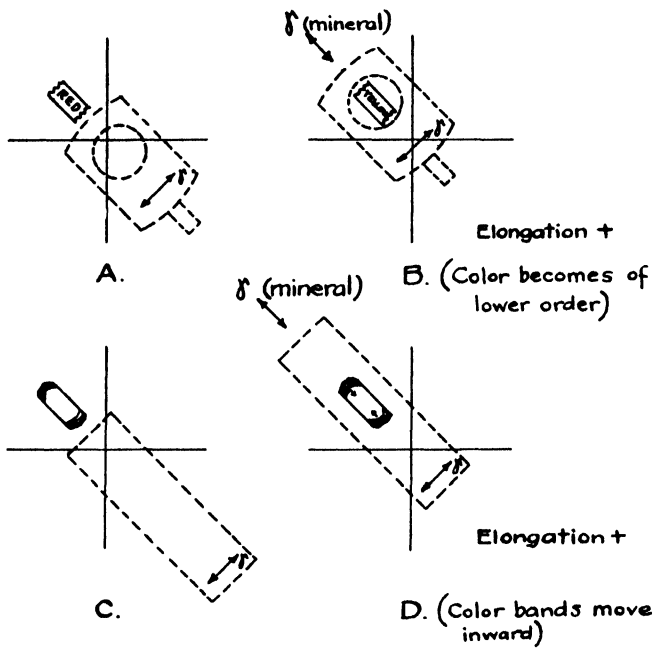



FIG. 27.—Method of determining elongation character with mica ($\frac{1}{4}\lambda$) plate (A and B) or with quartz wedge (C and D). The first method is useful for flat cleavage flakes, and the second for wedge- or lens-shaped fragments.

3. Rotate grain so that it is in **subtractive** position; i.e., so that the effect of the mica plate or the quartz wedge is subtractive. This means that the slow ray ($\gamma$) in the mineral and $\gamma$ in the plate or wedge are at right angles.

4. Knowing the direction of $\gamma$ in the plate or wedge, we then know the direction of $\gamma$ in the grain. If it coincides with the crystallographic long axis ($c$), the elongation is +.

This test cannot be applied to grains in which the crystallographic long axis cannot be determined by inspection. That is to say, a grain must be definitely elongated, as recognized by crystal boundaries or prismatic cleavage.

## Angular Measurements

A. Between cleavage directions, as amphiboles, angle between prismatic cleavages = 124°; pyroxenes, angle between prismatic cleavages = 87°.

B. Extinction angles, usually measured between an optical direction and a crystallographic direction; e.g., for spodumene, $\gamma \wedge c = +24°$.

The angle measured will be the apparent angle $\gamma \wedge c$ or $\alpha \wedge c$, according as the long axis of the grain is slow or fast (elongation + or −); but it will not necessarily be the maximum of that angle for the mineral. The latter will be given only when the grain is lying on a cleavage face parallel to the optic plane, and for monoclinic minerals with $\beta = b$.

In Fig. 51, the maximum extinction angle ($\gamma \wedge c = +24$) is a plus angle because, by definition, it is clockwise when viewed from the **010** side. It is always impossible, when working with mineral fragments, to tell whether a face is the **010** or the $0\bar{1}0$ face, so that the distinction of sign is not practicable.

The rotation apparatus shown in Fig. 28 is sometimes useful in determining the maximum extinction angle.

## Pleochroism

The color of a substance, when viewed by transmitted white light, depends upon the transmissibility of the substance for the various wave-lengths. If it transmits only those wave-lengths in the yellow band of the spectrum, the substance is said to be yellow in color.

Anisotropic minerals, in some cases, exhibit selective transmissibility for light vibrating in different directions, so that a mineral, viewed from a certain position, may be yellow when the incident light is vibrating in one direction, and green when the light is vibrating in some other direction. Since light coming through the lower nicol is vibrating in one direction only, it is possible to observe this selective transmissibility, or **pleochroism.**

When the mineral is rotated 45° from the position for the extremes of color, it will have about the same color as it would in ordinary light (without

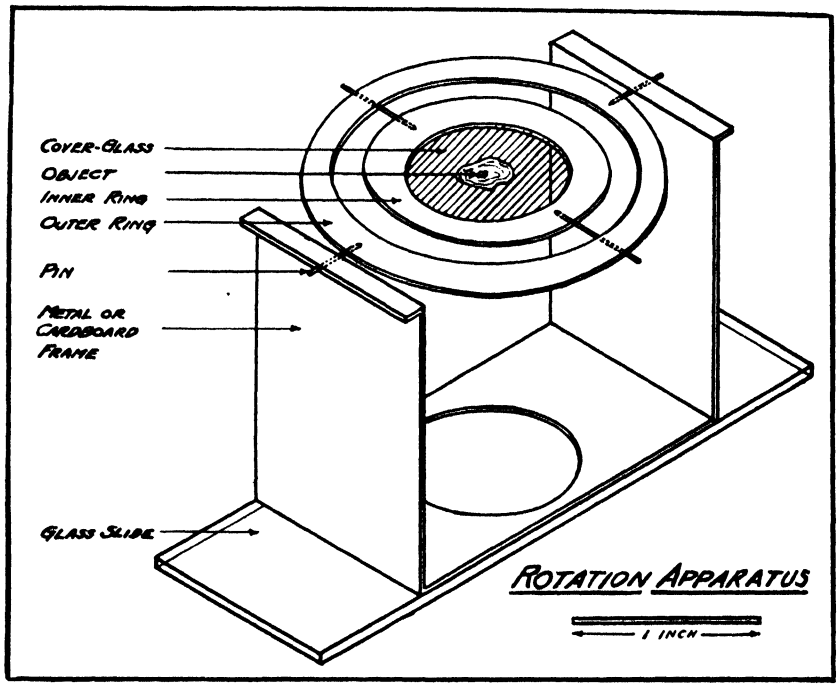



FIG. 28.—Improvised rotation apparatus

the polarizer). The pleochroism formula describes the color of a mineral for light vibrating parallel to the various optical directions in the mineral. Thus, for one variety of hypersthene:

$\alpha$ = red
$\beta$ = brown
$\gamma$ = green

When the selective transmissibility results not so much in a change of color as in a change of luminosity, the term **absorption** is used. Thus, the absorption formula for tourmaline, $O > E$, means that the ordinary ray is absorbed more than the extraordinary ray. This is tested by placing the grain with its long axis parallel to the direction of vibration of the polarizer (analyzer removed), noting appearance, revolving grain 90°, and noting again. Tourmaline, being uniaxial, will have $E$ parallel to $c$, so that when

it appears dark when $c$ $(= \boldsymbol{E})$ is normal to the vibration direction of the polarizer, the formula is stated $\boldsymbol{O} > \boldsymbol{E}$. The pleochroism formula for the same mineral might be:

$$\alpha = \text{yellow}$$
$$\gamma = \text{brown}$$

For biaxial minerals, the pleochroism formula may be worked out if the vibration directions can be identified by means of interference figures.

## Interference Figures

To obtain an interference figure, proceed as follows:

1. Focus on grain with high-power (3- or 4-mm.) objective. Sometimes a 2-mm. oil-immersion objective is useful.
2. Center objective (or stage) so that mineral remains beneath center of cross-wires when stage is revolved.
3. Use strongly **convergent** light, with iris diaphragm **open.**
4. Cross nicols.
5. Either remove ocular and look down the tube, or insert Bertrand lens and look into ocular.
6. Revolve stage and observe figure, while rotating stage, adjusting focus slightly and stopping down Bertrand diaphragm until figure is brought out as clearly as possible.

For very small grains, or in special cases, it may be necessary to use a 2-mm. oil-immersion objective. This necessitates the use of a condenser having a high numerical aperture ($NA = 1.45$).

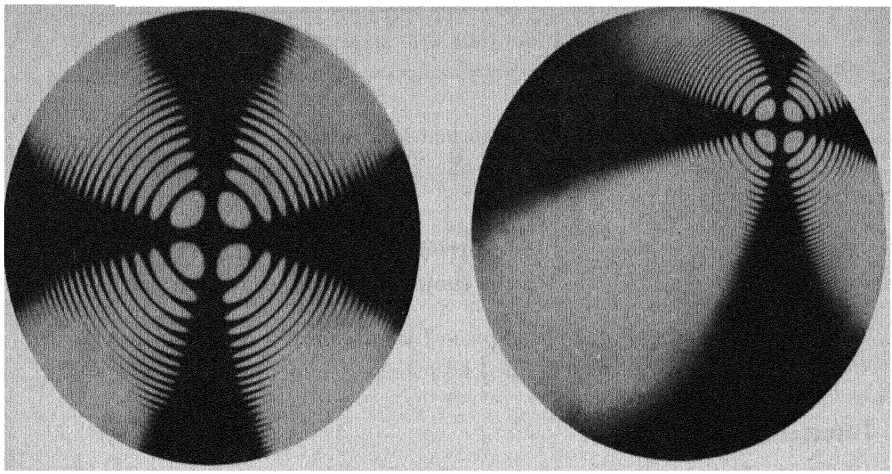
## Uniaxial figures

1. *Section normal to optic axis* (Fig. 29, *a*).

A dark **cross** in center of field, which remains stationary as stage is revolved.

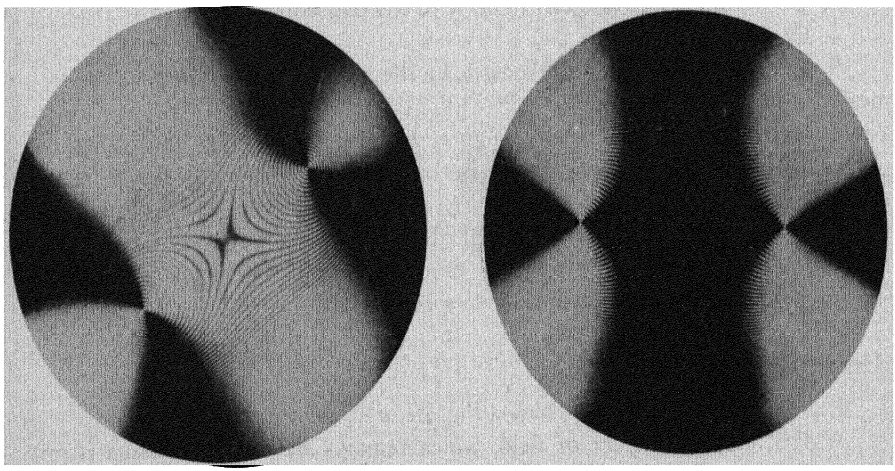
Concentric **rings,** showing various interference colors, may be observed if the grain is thick or the birefringence high. More often, however, the rings are not visible or are represented in the field of view by a single color.

2. Where the *section is at some angle to the optic axis,* the latter is not in the center of the field and may be altogether outside of the field. If, however, the section is not inclined at too great an angle from the optic axis, the arms of the dark cross will move across the field as the stage is rotated, the center rotating in the same direction as the stage is rotated, the arms (or bars) being parallel with the cross-wires at the position of transit and curving somewhat as they leave the field (Fig. 29, *b*).



*a*) Uniaxial; section cut normal to optic axis.

*b*) Uniaxial; section cut at an angle to optic axis; crystal at 45° to extinction.



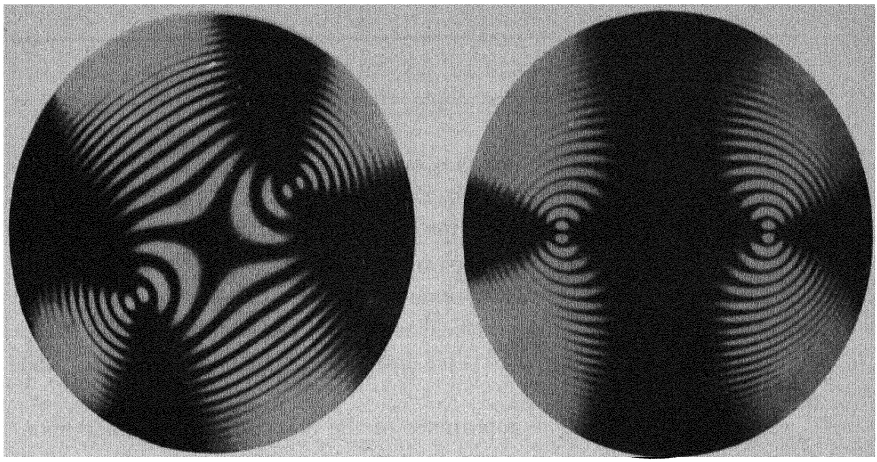
*c*) Biaxial; section cut normal to acute bisectrix; crystal at 45° to extinction.

*d*) Same as (*c*) Crystal at extinction.

FIG. 29.—INTERFERENCE FIGURES FROM ORIENTED SECTIONS (after Hauswaldt)

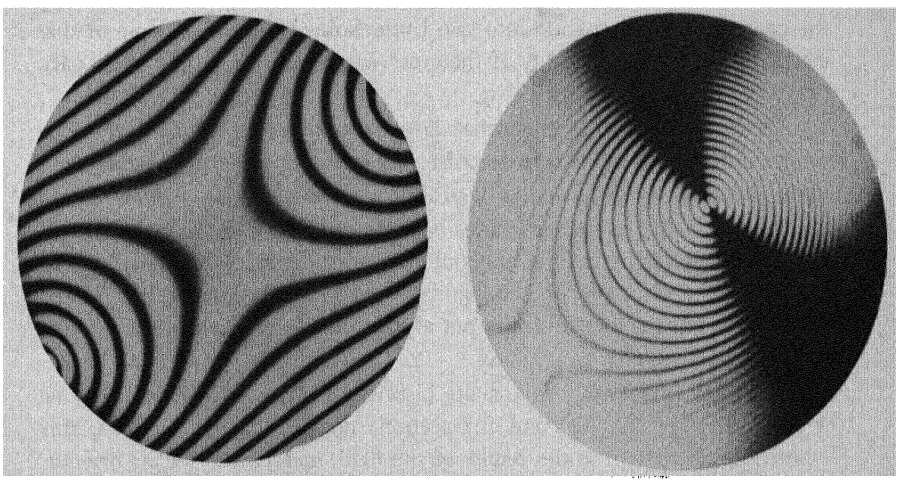
Figures similar to these, with respect to spacing of rings and bars, when obtained with grains equal in size to those of Fig. 25, would be suggestive of the following properties:

| | Birefringence | Axial Angle |
|---|---|---|
| *a*) | High | 0 |
| *b*) | Very high | 0 |
| *c*) and *d*) | Very high | Medium |



*a*) Biaxial; section cut normal to acute bisectrix; crystal at 45° to extinction.

*b*) Same as (*a*) Crystal at extinction.



*c*) Biaxial; section cut normal to acute bisectrix; crystal at 45° to extinction.

*d*) Biaxial; section cut at 80° to an optic axis; crystal at 45° position.

FIG. 30.—INTERFERENCE FIGURES FROM ORIENTED SECTIONS (after Hauswaldt)

Figures similar to these, with respect to spacing of rings and bars, when obtained with grains equal in size to those of Fig. 25, would be suggestive of the following properties:

| | Birefringence | Axial Angle |
|---|---|---|
| *a*) and *b*) | Medium | Small |
| *c*) | Medium | Large |
| *d*) | High | Large |

Where the center of the cross is outside of the field, the observer must visualize the cross, according to the description given above, and be able to identify the various arms and the quadrants between them.

In sections parallel, or nearly parallel, to the optic axis, the bars are dim and are only visible at exact position of transit of the cross-wires, after which they pass rapidly from the field as hyperbolas. This is called a "flash" figure because the bars are not visible during the greater part of the rotation of the stage.

**Biaxial figures.**—The appearance of the biaxial figure depends upon the orientation of the section and the angle between the optic axes (axial angle). If the axial angle is very small, the centered acute bisectrix figure is difficult to tell from a uniaxial figure. For example, a cleavage flake of biotite shows a centered acute bisectrix figure with axial angle almost zero. It looks like a centered uniaxial cross, except that when the stage is rotated, the cross is seen to separate into two **hyperbolas,** first in one pair of diametrically opposite quadrants of the cross-wires and then in the other pair. (Figs. 29, *c* and 30, *a*.)

For minerals having somewhat larger axial angle, the appearance is similar except that the two hyperbolas, after closing together to simulate a cross, separate to a distance that is proportional to the axial angle.

The emergence of the optic axes is at the point of greatest convexity of the hyperbolas. Whereas the uniaxial cross is encircled with colored rings, the pair of optic axes of the biaxial figure is surrounded by colored **lemniscate curves,** but these are not always plainly seen, except where the birefringence is high.

For sections inclined to the acute bisectrix, only one hyperbola may be in the field (Fig. 30, *d*); and for sections normal to an optic axis, this hyperbola will remain in the center of the field, merely altering its orientation as the stage is revolved. Where the axial angle is 90°, this centered optic axis figure becomes a straight bar, which rotates in a direction counter to that of the stage.

Sections cut normal to the obtuse bisectrix are sometimes similar to those for the acute bisectrix, but more often they are indefinite and difficult to identify.

Sections cut parallel to the plane of the optic axes give what are known as optic normal figures. The figures are similar to those exhibited by uniaxial minerals cut parallel to the optic axis. They are of little value in the study of mineral grains.

Interference figures from mineral grains are not often as perfect as those shown in Figs. 29 and 30. They are usually distorted by the uneven

or lenticular shape of the grain, and are more like the ones shown in Fig. 31.

Interference figures are useful principally for the following purposes:

1. To determine the sign of the mineral
2. To measure the axial angle
3. To determine the dispersion

### *Determining the Sign*

Some of the tests described are very delicate. They call for delicate manipulation of the wedges, etc., and careful scrutiny of the phenomena. Where the birefringence is high, the test is usually apparent and easily made; otherwise, it may require good discriminative ability.

### Uniaxial

A. *Optic axis figure* (centered cross)

1. Test with mica ($\frac{1}{4}\lambda$) plate. Insert plate. Cross is obliterated and two *dark dots* or blurs take its place, the line joining which, for negative minerals, is parallel to the slow direction of the plate, and for positive minerals is normal thereto.
2. Test with gypsum (first-order) plate. Insert plate. Quadrants between arms of cross are *colored* alternately yellow and blue, the yellow color corresponding to the dots of the preceding test.
3. Test with quartz wedge. Insert wedge, thin edge foremost. If there are colored rings, they will, for (+) minerals, move away from the optic axis in the NW. and SE. quadrants, and toward the optic axis in the other quadrants (Fig. 32).

B. *Uncentered cross in field.* The same tests apply.

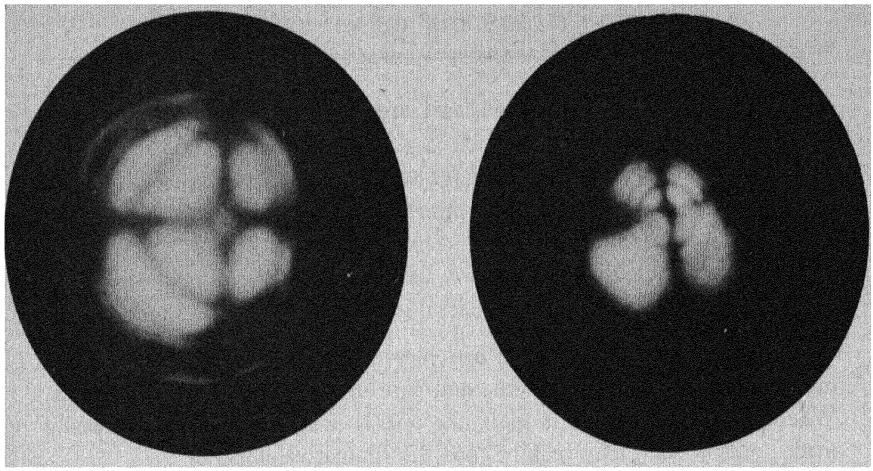
C. *Uncentered cross with center out of field.* Test No. 1 will not apply. Test No. 2 may apply if region near optic axis can be seen. Test No. 3 will apply if colored rings can be seen.

D. The *optic normal section* gives a *flash* figure and, in mineral grains, it is rarely possible to determine the sign from it. If it is possible to determine the quadrants in which the hyperbolas leave the field, these quadrants will contain the optic axis. Examination of the mineral itself will then determine whether this direction is *"slow"* or *"fast."* If slow, the mineral is positive.

### Biaxial

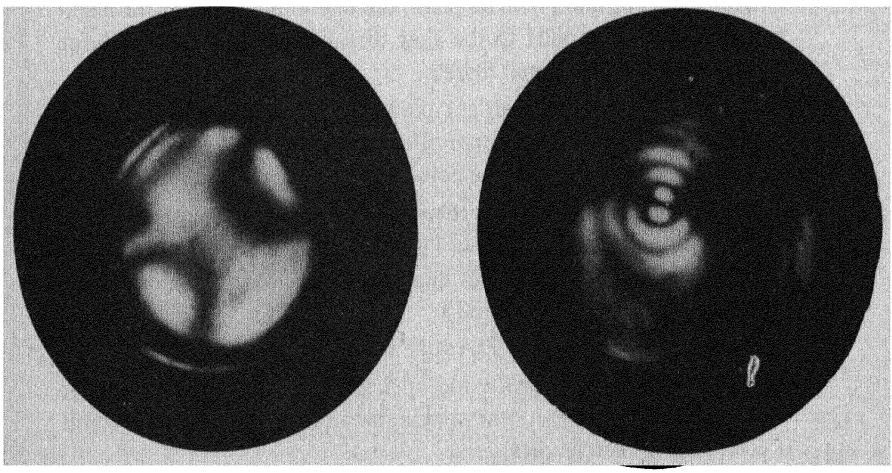
A. *Centered acute bisectrix figure*

1. *Mica plate.* If axial angle is small and dark cross can be obtained, test is similar to corresponding one for uniaxial minerals, except that the



*a*) Uniaxial; Similar to Fig. 29, *a*.

*b*) Uniaxial (distorted); Similar to Fig. 29, *b*.



*c*) Biaxial; Similar to Fig. 30, *a*.

*d*) Biaxial; Similar to Fig. 30, *d*.

FIG. 31.—INTERFERENCE FIGURES PHOTOGRAPHED WITH AN ORDINARY PETROGRAPHIC MICROSCOPE

The visual figures are somewhat better than the photographs portray.

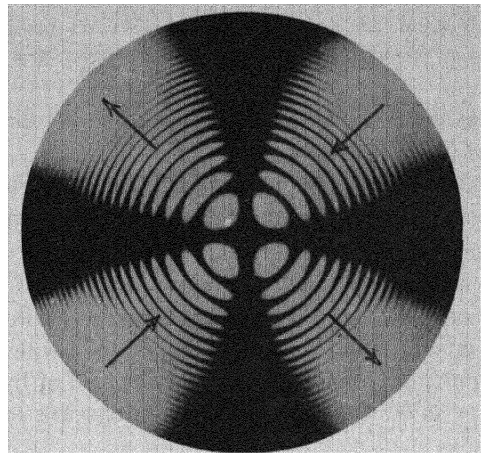


FIG. 32.—Uniaxial *positive* interference figure, showing direction of movement of colored rings when a length-fast quartz wedge is inserted from the SE. quadrant, thin edge foremost. Directions are reversed for (1) a negative crystal, or (2) a length-slow wedge.

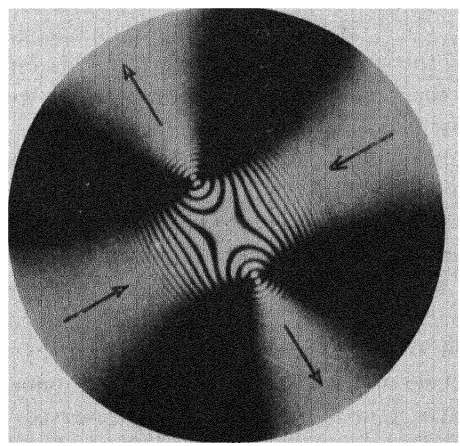


FIG. 33.—Biaxial *positive* interference figure, showing direction of movement of the colored bands when a length-fast quartz wedge is inserted from the SE. quadrant, thin edge foremost. Directions are reversed for (1) a negative crystal, (2) a length-slow wedge, or (3) orientation of the figure at 90° to the position shown.

line joining the dots will not be either quite parallel or quite normal to the slow direction of the plate.

2. *Gypsum plate.* Same phenomenon as for uniaxial minerals.

3. *Quartz wedge.* Same phenomenon as for uniaxial minerals (Fig. 33).

B. *Inclined acute bisectrix figure.* Test No. 1 will not apply. Test No. 2: when a hyperbola is in SE. quadrant (slow direction of plate being NE.–SW.); the color on the concave side of the hyperbola will be yellow or blue according as the mineral is (+) or (−). Test No. 3 will, for (+) mineral, show the colors moving from convex to concave side of hyperbola when the latter is in SE. or NW. quadrants, and from concave to convex in other quadrants.

If none of the above tests are decisive, the optical sign may be determined by noting that the acute bisectrix lies in the direction of the convexity of the hyperbola, and that this is also the trace of the axial plane. The normal to this plane will contain $\beta$, and the plane itself will contain either $\gamma$ or $\alpha$, according as the mineral is (+) or (−). As soon as the direction of the axial plane is determined, the mineral itself may be examined to see if this direction is "slow" or "fast." If slow, the bisectrix must be fast, and the mineral is negative.

C. *Optic axis figure.* If bar has no curvature, the axial angle is 90° and the sign is neutral ($\pm$). If the bar is straight on one side and slightly concave on the other, the straight side is toward the bisectrix, so that if there are colored rings their movement beneath the quartz wedge will determine the sign, as in Test No. 3.

If the curvature of the bar is apparent, Test No. 2 or No. 3 may determine the sign, as in Fig. 30, *d*.

In using the wedge, it is important to note the changes that occur when about 0.1″ of the wedge is inserted. It is also important not to mistake the colors of the wedge itself for those from the interference figure.

D. *Obtuse bisectrix figure.* This figure is difficult to use. It is, in general, distinguished from the acute bisectrix figure by disappearing more rapidly from the field as the stage is rotated. The same tests may be used as for acute bisectrix figures, the results being reversed.

E. *Optic normal figure.* This is a "flash" figure and difficult to use. The hyperbolas leave the field in those quadrants in which lies the acute bisectrix. Examination of the mineral itself will show whether this direction coincides with the slow or the fast ray.

## Axial Angle

There are two methods commonly used for the measurement of the acute angle between the optic axes.

1. In the acute bisectrix figure, measure, with a micrometer ocular, the distance between hyperbolas. Then

$$\sin E = cd$$

where $E = \frac{1}{2}$ apparent axial angle, measured in air.

$c$ = a constant for the optical system, determined by observation on a mineral of known axial angle.

$d$ = distance between hyperbolas (arbitrary units of the micrometer ocular).

The real axial angle ($2V$) may be computed from the relation

$$\sin E = \beta \sin V$$

2. The centered optic axis figure gives means for a good estimation of the axial angle ($2V$) according to the degree of curvature of the bar. The following figures (Fig. 34) are self-explanatory.

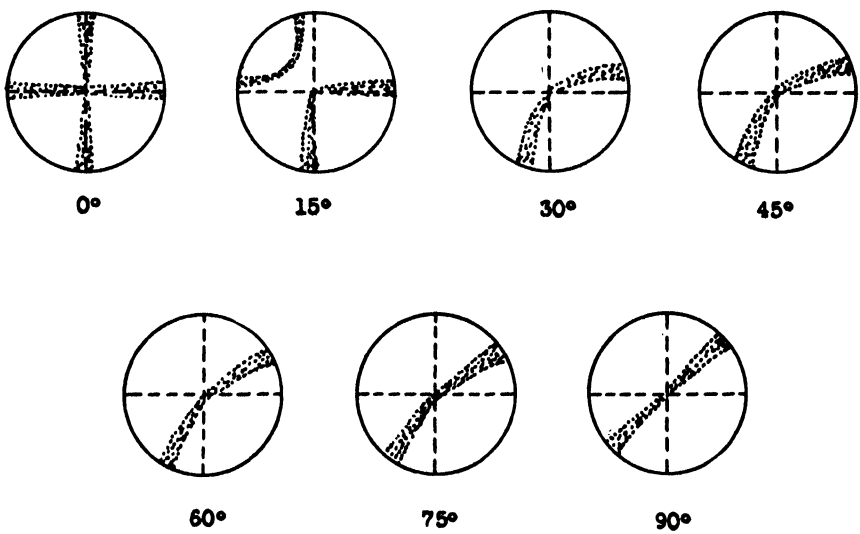



FIG. 34.—Curvature of the bar in optic axis interference figures. The amount of curvature serves for an estimate of the axial angle.

### *Triaxial Ellipsoid*

The "triaxial ellipsoid" is a convenient figure for representing the optical relationships of the biaxial minerals. It is constructed by drawing three

axes (representing directions of vibration α, β, and γ) at right angles to one another and of lengths proportional to the three indices $N_\alpha$, $N_\beta$, and $N_\gamma$, as shown in Fig. 35. The ellipsoid is then considered to envelop these three

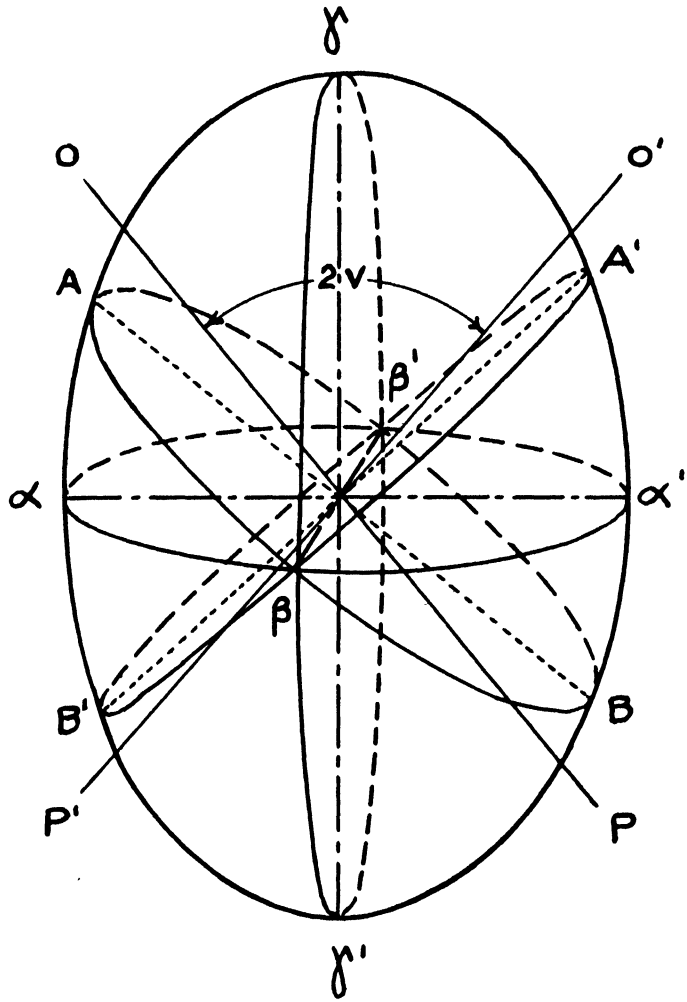



FIG. 35.—The triaxial ellipsoid

axes. The three mid-sections are ellipses; the horizontal one having α, α′ (= $N_\alpha$) as major axis and β, β′ (= $N_\beta$) as minor axis. Now this latter ellipse may be imagined to rotate on β, β′, but maintaining the extremities of its major axis on the surface of the ellipsoid. This major axis

($\alpha$, $\alpha'$) will then elongate until it is equal to $N_\gamma$. but at some intermediate position, it will be equal to $N_\beta$ and, hence, the section will be a circle (A–B). Rotation of the ellipse the same angular amount in the opposite direction will produce another circle (A′–B′).

Lines passing through the common center of these circular sections and normal to their plane are the optic axes (OP and O′P′), and the acute angle between these lines is the axial angle. The line ($\alpha - \alpha'$ or $\gamma - \gamma'$) bisecting this angle is the acute bisectrix, and the mineral is optically (+) or (−) according as this is $\gamma - \gamma'$ or $\alpha - \alpha'$. It should be noted also that when $N_\beta$ is more nearly equal to $N_\alpha$ than it is to $N_\gamma$, the mineral is optically (+); otherwise, it is (−). The optic axes may intersect at 90°, and in this case the mineral is optically neutral. The axial angle may also become 0°, and in this case the mineral is uniaxial.

### *Dispersion*

The refractive index of a substance varies according to the kind of monochromatic light used. It usually is reported for sodium light, or the D line of the spectrum ($N_D$). The difference between the refractive indices for the extremes of visible wave-lengths (violet to red) is termed the dispersion of the index. This is the kind of dispersion exhibited by liquids and other isotropic media.

Uniaxial crystals have two indices, and each has its dispersion.

Biaxial crystals have dispersion of all three indices, and this is often exhibited in dispersion of the optic axes, or of the bisectrices.

Each crystallographic system has its peculiar kind of dispersion; thus,

| System | Dispersion |
|---|---|
| Orthorhombic | Rhombic |
| Monoclinic | Inclined, horizontal, or crossed |
| Triclinic | Asymmetrical |

The kind of dispersion may sometimes be recognized in acute bisectrix interference figures. In such figures, the criteria are as follows:

1. *Rhombic dispersion* is indicated when the colors are (*a*) symmetrical to the trace of the axial plane, (*b*) symmetrical to the line normal to the trace of the axial plane and passing through the point of emergence of the *Bxa*, and (*c*) symmetrical to the point of emergence of the *Bxa*.

2. *Inclined dispersion* is indicated when the colors are symmetrical to the trace of the axial plane only.

3. *Horizontal dispersion* is indicated when the colors are symmetrical only to the line normal to the trace of the axial plane and passing through the point of emergence of the *Bxa*.

4. *Crossed dispersion* is indicated when the colors are symmetrical only to the point of emergence of the *Bxa*.

In the interference figures obtained from most mineral grains, however, the type of dispersion is difficult to recognize and about all that can be done is to note the strength of the dispersion and to determine whether the axial angle is greater for red or for violet light.

The strength of the dispersion may be estimated by observing, between crossed nicols, the mineral when it is near extinction. If the dispersion is weak, and providing that the section is not normal to an optic axis, the extinction will be sharp. If the dispersion is strong, the extinction will not be sharp, but abnormal interference colors will appear, and will persist during an amount of rotation of the stage that will depend on the strength of the dispersion.

Where a good acute bisectrix figure can be obtained, and the birefringence is high, the dispersion formula may be determined by measuring the apparent axial angle (distance between the hyperbolas). Where the dispersion is the same for each optic axis, as is the case with orthorhombic minerals or with monoclinic minerals for which crystallographic *b* lies in the axial plane, the colors that border the hyperbolas are indicative as to whether the axial angle is greater for red or for violet light. In this case the hyperbolas will show a color on their convex side that is the one for which dispersion is greater. For example, if both hyperbolas are fringed on their convex sides with red and on their concave sides with blue, the dispersion formula may be stated $\rho > \nu$. Where the blue color appears on the convex side and red on the concave, the formula is $\rho < \nu$.

## Orientation-Cleavage Diagrams

The study of the optical properties of biaxial minerals is greatly facilitated by the construction of orientation-cleavage diagrams. These diagrams show the relation of the optic to the crystallographic axes and the relation of both of these to the directions of cleavage. From such a diagram (see Figures 37 to 54, pp. 103–104) one may decide what kind of interference figure may be expected from cleavage fragments of a certain mineral or, conversely, what the chances are of a mineral, in cleavage fragments, exhibiting an interference figure indicative of a certain optical orientation.

Observation of the orientation-cleavage diagram for **barite** (Fig. 39) reveals the following properties of the mineral:

1. The system is orthorhombic, since the angle between *a* and *c* is 90°.

2. Cleavages parallel to **001** and **110** are perfect (symbols underscored with three solid lines), and parallel to **010** imperfect (symbol underscored with one solid line). The **110**, **1$\bar{1}$0**, etc., cleavage directions intersect at

angles of which the acute angle is 78° 22′. The cleavage fragments will, therefore, often be diamond-shaped.

3. Fragments cleaved parallel to **001** will give symmetrical extinction. Fragments lying on **110** or **010** will give parallel extinction. ($\gamma \wedge c = 0°$.)

4. Elongation is negative ($c = \alpha$).

5. Optical character is positive, since the slow ray ($\gamma$) is the acute bisectrix ($Bxa$).

6. The axial angle ($2V$) is 37°5.

7. Cleavage fragments will not show an acute bisectrix nor an optic axis figure, but fragments cleaved parallel to **001** will give an obtuse bisectrix figure and **110** fragments will show an uncentered acute bisectrix figure.

8. The axial plane contains $\alpha$ and $\gamma$, and fragments parallel to the imperfect **010** cleavage will give both $N_\alpha$ and $N_\gamma$.

The diagram for **spodumene** (Fig. 51) gives the following information:

1. The system is monoclinic since the angle between $a$ and $c$ is not 90° (is 69° 40′), and the directions of vibration are not coincident with the crystallographic axes.

2. Cleavages parallel to **110**, $1\bar{1}0$, etc., are perfect and the acute angle of intersection is 87°. There is an imperfect cleavage parallel to **010** and a good parting parallel to **100** (symbol underscored with two lines of dashes). Fragments formed by this parting are likely to have beveled **110** edges or show **110** cleavage striations.

3. The maximum extinction angle, $\gamma \wedge c = 24°$, will be given only by fragments lying on **010**. Fragments lying on the **100** parting will give parallel extinction ($\gamma \wedge c = 0°$).

4. Elongation is positive ($\gamma$ is more nearly parallel to $c$ than to $a$).

5. Optical character is positive, since the slow ray ($\gamma$) is the acute bisectrix ($Bxa$).

6. The axial angle ($2V$) is 60°.

7. Since $\gamma \wedge c = +24°$ and $a \wedge c = 69°\ 40'$, the emergence of the acute bisectrix ($\gamma$) is at an angle of 93° 40′ with **001**. Sections cut parallel to **001**, therefore, will give a slightly uncentered acute bisectrix figure, rather than an optic axis figure. Unfortunately, the **001** cleavage is not developed.

8. The axial plane contains $\alpha$ and $\gamma$, and fragments parallel to the imperfcet **010** cleavage will give both $N_\alpha$ and $N_\gamma$.

## SPECTROGRAPHIC EXAMINATION

The spectrograph as an analytical instrument of accuracy and convenience is only within recent years gaining general recognition by chemists,

mineralogists, and metallurgists. This is due, in large part, to the great improvements made in spectrographic instruments.

The emission spectrum of an element, as produced by flame, arc, condensed spark, or vacuum-tube discharge, is unique, and is entirely distinctive of that element. When the spectrum is photographed it is found to consist of a number of bright lines, each with a very definite and constant wave-length. The dispersion of the spectrographic instrument is its ability to spread these lines out so that they may be examined and their wave-lengths measured. The unit of measurement is the International Ångström (I.A.) or Ångström Unit (A.U.), which is $10^{-10}$ meter. The familiar "$D_1$" line of sodium has a wave-length of 5,895.9 ångströms.

In Table 17 it is shown that the ordinary photographic plate is sensitive to wave-lengths between 2,150 A.U. (in the ultra-violet) and 5,600 A.U. (in the visible), while the limits of human vision lie between 3,900 A.U.

TABLE 17

RANGE AND POWER OF SPECTROGRAPHS

Ultra-violet | Limits of human vision | Infra-red

Lengths of Spectra (cm.) on Photographic Plate Given by Various Types and Sizes of Instruments in Different Regions of the Spectrum.

Sensitivity of panchromatic plate

Sensitivity of Ordinary Photographic Plate

| | 2000 | 3000 | 4000 | 5000 | 6000 | 7000 | 8000 | Wave-Length (A.U.) |
|---|---|---|---|---|---|---|---|---|
| Quartz prism (small) | 3. | 1.5 | 1. | .5 | .7 | .8 | | |
| Quartz prism (medium) | 10. | 5. | 2.5 | 2. | 2. | 2.5 | | |
| Quartz prism (large) | 28. | 14. | 9. | 5. | 5. | 5.6 | | |
| Concave grating (Rad. = 3 ft.) | 3. | 3. | 3. | 3. | 6. | 18. | | |
| Concave grating (Rad. = 21 ft.) | 19. | 19. | 19. | 19. | 38. | 114. | | |

(violet) and 7,600 A.U. (red). It will be noted that the diffraction grating has a uniform scale of dispersion, while the prism has a varying scale. The modern quartz-prism spectrograph of medium size will photograph the whole ultra-violet spectrum on an 8-inch plate, and this amount of dispersion makes it possible, for qualitative analysis, to identify the lines of the various elements.

The quartz spectrograph has its greatest dispersion in the ultra-violet

region, and it is in this same region that are found lines that are the most persistent and distinctive for the various elements. It is for this reason that analytical spectroscopy is usually done in the ultra-violet region, especially for compounds or mixtures containing a number of elements.

Most of the elements, when volatilized in either the arc or the condensed spark, reveal certain lines that are persistent down to extremely low concentrations of the element in the substance studied. These lines are usually called *"raies ultimes* (R.U.)."[7] These residuary lines (see Table 18) often show a variation in intensity proportional to the concentration of the element in the substance, and may thus be used as a basis for quantitative analysis.

The procedure of spectrographic analysis has been described by Twyman[8] and Meggers.[9] For qualitative determinations, such as the identification of elements in minerals, a very convenient and rapid method is as follows:

1. A few milligrams of "R.U." powder is placed in the hollowed crater of the lower (positive) carbon electrode of a D.C. arc. This powder[10] is composed of salts of about fifty elements, so proportioned that very little more than the *raies ultimes* of the various elements will be present in the spectrum. A photograph of the ultra-violet region is taken.
2. A few milligrams of the powdered mineral are placed likewise in the arc and another photograph taken which can be made to register exactly underneath the first one.
3. The plate is developed, and it is then a simple matter to compare the lines in the mineral with the known lines of the R.U. powder and to pick out the elements that are present.

For quantitative work it is usual to use as a standard the arc that is struck between pure iron electrodes. It serves as a wave-length scale. This picture is taken at the top of the series, and is followed by pictures of the carbon arc spectrum for various known concentrations of the element under analysis. Finally, a photograph of the unknown substance is taken below

[7] Bardet, Jacques, *Atlas de Spectres d'Arc,* 1926.

[8] Twyman, F., *The Practice of Spectrum Analysis with Hilger Instruments,* Adam Hilger, Ltd., 1929.

Twyman, F., and Smith, D. M., "Quantitative Spectrum Analysis," *Proc. Amer. Inst. Min. & Met. Eng.* (Metals Div.), 1928, pp. 280–306.

[9] Meggers, W. F., Kiess, C. C., and Stimson, F. J., "Practical Spectrographic Analysis," *U.S. Bureau of Standards, Sci. Paper No. 444* (1922).

[10] Obtainable from Adam Hilger, Ltd., London.

all the others. A sensitive line is chosen from the series of known concentration, and these are examined to see which one matches most closely in strength with the same line in the unknown. In this way the concentration of the element in the unknown may be very rapidly estimated, even when it is present in only minute quantities. The duration of photographic exposure must, of course, be the same for all spectra, and the current supply to the arc must be constant.

TABLE 18

"RAIES ULTIMES" OF ELEMENTS*

| Element | Wave-Lengths of Principal *raies ultimes* |
|---|---|
| Aluminum | 3092.7; 3082.2 |
| Antimony | 2598.1; 2528.5 |
| Arsenic | 2780.2; 2349.8 |
| Barium | 2335.3; 4554.0; 4934.1 |
| Bismuth | 3067.7; 2898.0 |
| Boron | 2497.7; 2496.8 |
| Cadmium | 2288.0; 2265.0 |
| Caesium | 4593.2; 4555.3 |
| Calcium | 4226.7; 3968.5; 3933.7 |
| Carbon | 2478.6 |
| Cerium | 4040.8; 4012.4 |
| Chromium | 4254.3; 3605.3; 3593.5 |
| Cobalt | 3405.1; 2388.9; 2378.6 |
| Copper | 3274.0; 3247.5 |
| Gallium | 4172.1 |
| Germanium | 3269.5; 3039.1 |
| Gold | 2676.0; 2428.0 |
| Hydrogen | 6562.8 |
| Iridium | 3513.7; 3220.8 |
| Iron | 2755.7; 2395.6; 2382.0 |
| Lanthanum | 3949.1 |
| Lead | 4057.8; 3683.5; 2614.2 |
| Lithium | 6707.9; 4602.2 |
| Lutecium | 2911.4 |
| Magnesium | 2852.1; 2802.7; 2795.5 |
| Manganese | 4030.8; 2593.7; 2576.2 |
| Mercury | 5460.7; 4358.3; 2536.5 |
| Molybdenum | 3903.0; 3864.1; 3798.3 |
| Neodymium | 4303.6; 4177.3; 3951.2 |
| Nickel | 3414.8; 2416.2; 2316.1 |
| Palladium | 3634.7; 3609.6; 3404.6 |
| Phosphorus | 2553.3; 2535.6; 2534.0 |

* Twyman, F., *Wave-Length Tables for Spectrum Analysis* (1923); values from de Gramont's data given in pp. 81–84.

TABLE 18 -*Continued*

| Element | Wave-Lengths of Principal *raies ultimes* |
|---|---|
| Platinum | 3966.4; 2929.8; 2659.4 |
| Potassium | 4047.2; 4044.2; 3446.4 |
| Rhodium | 3434.9 |
| Rubidium | 4215.6; 4201.8 |
| Ruthenium | 3499.0 |
| Scandium | 3630.8; 3613.8 |
| Silicon | 2881.6; 2516.1 |
| Silver | 3383.0; 3280.2; 2437.7 |
| Sodium | 5895.9; 5890.0; 3303.0 |
| Strontium | 4215.5; 4077.7 |
| Tantalum | 3311.2 |
| Tellurium | 2385.8; 2383.3 |
| Thallium | 5350.5; 3775.7; 2767.9 |
| Thorium | 4019.1; 3601.1; 3539.6 |
| Tin | 3262.3; 2863.3 |
| Titanium | 3372.8; 3361.2; 3349.4 |
| Tungsten | 4302.4; 4294.7; 4008.8 |
| Vanadium | 4408.5; 3102.3; 3093.1 |
| Yttrium | 3710.3; 3600.7 |
| Zinc | 4810.5; 4722.2; 3345.0 |
| Zirconium | 3496.2; 3392.0 |

In Fig. 36, the spectrographic method, as applied to the identification of minerals, is illustrated. The spectra of three minerals (*beryl, cassiterite,* and *titaniferous magnetite*) are shown, each in juxtaposition with the iron spectrum as a scale of reference, and for a wave-length range of from 2860 A.U. to 3180 A.U. There are also shown, for comparison, the spectra of the three pure substances, Be, $SnCl_2$, and a titanium salt, each, also, with a juxtaposed iron spectrum.

It should be noted that, in the spectra both of the pure beryllium and of the beryl, the heavy line at about 3130 A.U. is, in reality, a doublet (3131 and 3132) and a *raie ultime* of beryllium. There should also be noted in the spectrum of beryl the two strong aluminum lines (3082 and 3093), both *raies ultimes,* and showing much stronger than they do in the beryllium spectrum, in which latter they are caused by impurity in the carbon electrodes. The *raie ultime* of silicon (2882) is also prominent in the beryl. Thus, all the metallic constituents (Be, Al, and Si) of the beryl are demonstrated by the one photographic exposure.

In the case of cassiterite, five distinctive lines of tin are marked (2863 [R.U.], 2914, 3009, 3034, and 3175 [R.U.]). These show more strongly in the spectrum of the mineral than they do in that of the pure salt

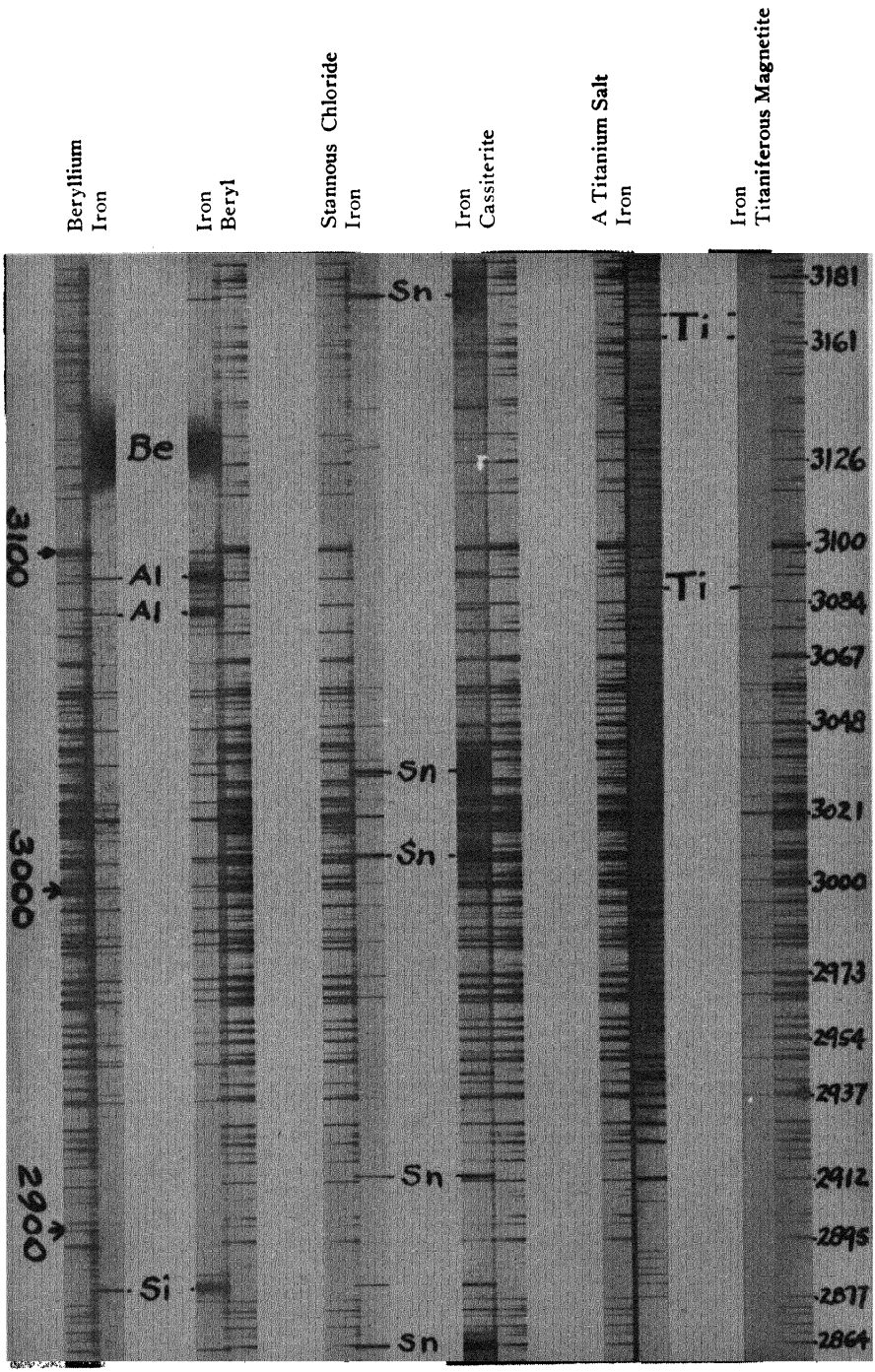



FIG. 36.—Arc spectra of minerals (same scale as original)

($SnCl_2$), and this is due, no doubt, to the greater volatility of the chloride than of the oxide and the consequent exhaustion of the element from the electrodes during the exposure. The duration of the exposures was one minute in all cases.

Only three titanium lines are marked (3088, 3163, and 3169), and they are rather weak, but strong enough, nevertheless, for purposes of identification. There are no *raies ultimes* of titanium in this spectral range. The comparison spectrum of titanium is poor because the salt used (titanium-potassium fluoride) gave a continuous spectrum, which obscures the titanium lines to some extent.

The spectrograph used was a concave grating, but a prism instrument would be as satisfactory and has the advantage of portability. The principal advantage of the grating lies in the uniform scale of dispersion.

As to the spectrographic sensitivities of the elements, as excited by the arc, Ryde and Jenkins[11] state that, in the range between 2288 A.U. and 6717 A.U., the elements fall in four groups, according to the concentrations in which they may be detected spectrographically, as follows:

GROUP I. Comprises Ag, Co, Cr, Cu, In, Li, Mg, Na, Ni, Os, Pd, Pt, Rh, and Ru. These elements may be detected in concentrations of from 1:100,000 (or more) to 1:1,000,000.

GROUP II. Comprises Al, Au, Ba, Be, Ca, Fe, Ge, Hg, Ir, Mn, Mo, Pb, Sc, Sn, Sr, Ti, and V. These elements may be detected in concentrations of from 1:10,000 (or more) to 1:100,000.

GROUP III. Comprises B, Bi, Cd, La, Sb, Si, Tl, Y, Zn, and Zr. These elements may be detected in concentrations of from 1:1,000 (or more) to 1:10,000.

GROUP IV. Comprises As, Cs, K, Nb, P, Rb, Ta, and W. These elements may be detected in concentrations of from 1:100 (or more) to 1:1,000.

[11] Ryde, J. W., and Jenkins, H. G., *Sensitive Arc Lines of Fifty Elements*, a booklet published by Adam Hilger, Ltd., 1930.

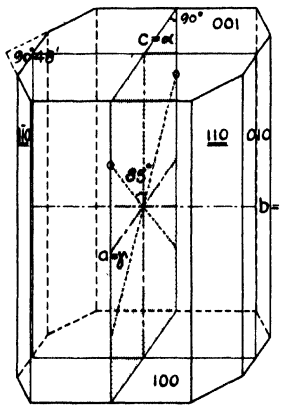



Fig. 37.—Andalusite

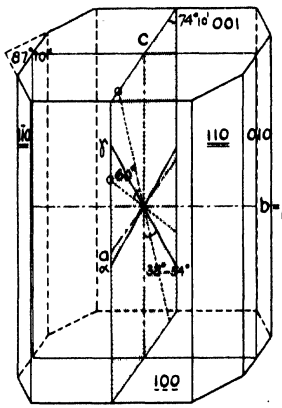



Fig. 38.—Augite

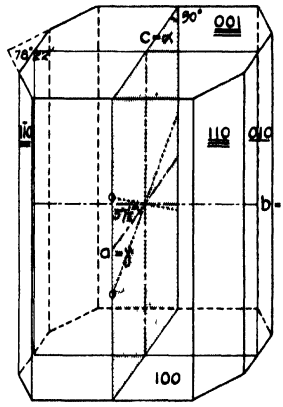



Fig. 39.—Barite

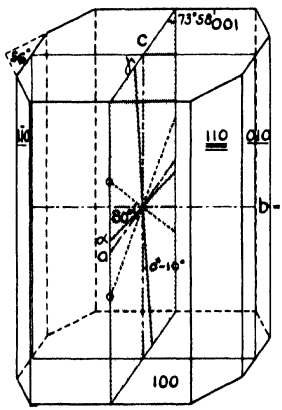



Fig. 40.—Basaltic Hornblende

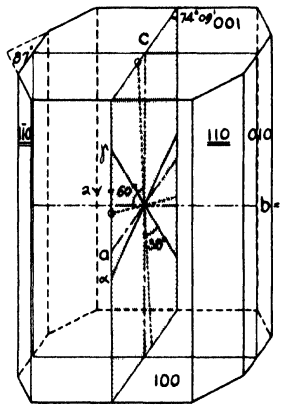



Fig. 41—Diopside

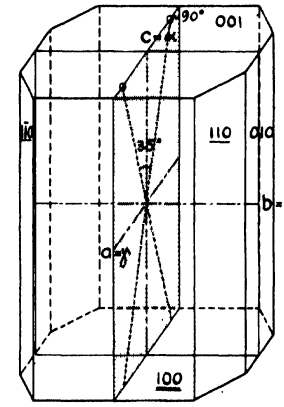



Fig. 42.—Dumortierite

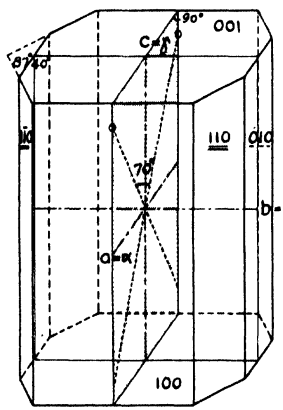



Fig. 43.—Enstatite

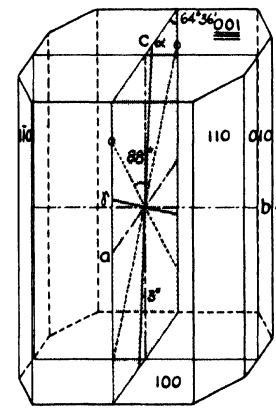



Fig. 44.—Epidote

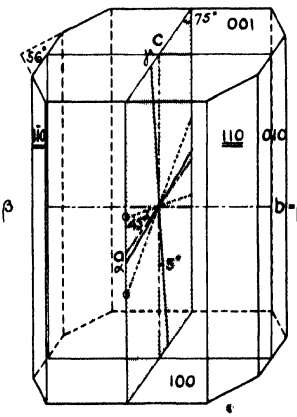



Fig. 45.—Glaucophane

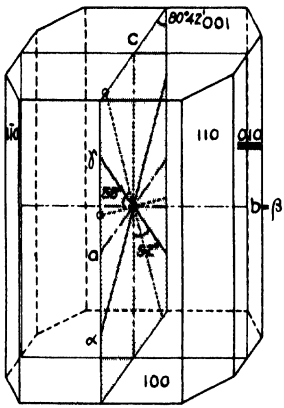



Fig. 46.—Gypsum

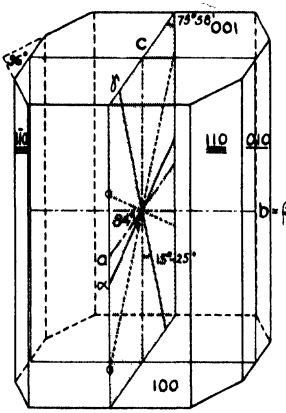



Fig. 47.—Hornblende

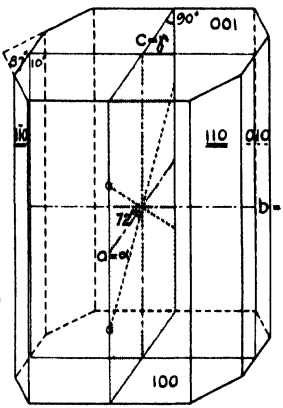



Fig. 48.—Hypersthene

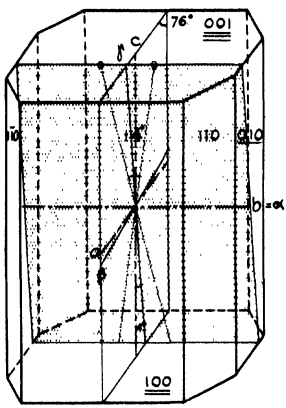



Fig. 49.—Monazite

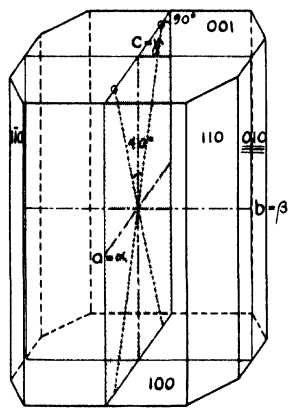



Fig. 50.—Sillimanite

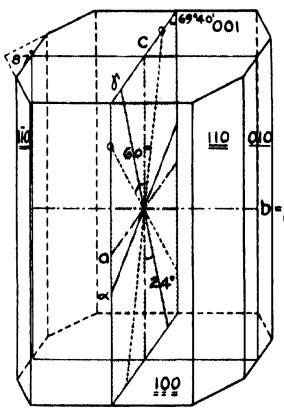



Fig. 51.—Spodumene

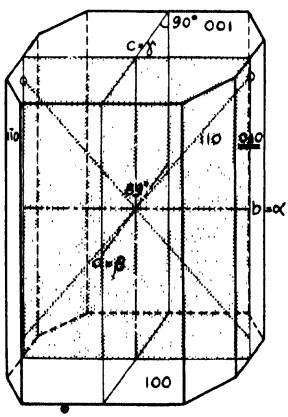



Fig. 52.—Staurolite

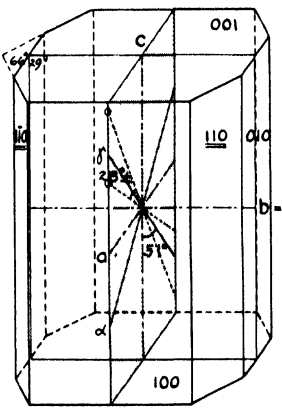



Fig. 53.—Titanite

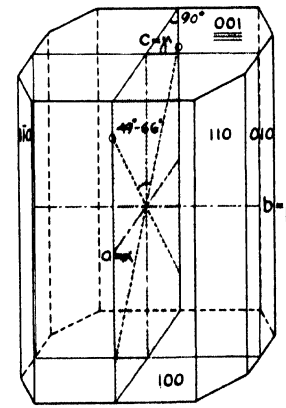



Fig. 54.—Topaz

# VI

# DESCRIPTION OF MINERALS FOUND IN SEDIMENTARY ROCKS

The minerals described in this chapter are those of widespread occurrence in sedimentary rocks. They are, for the most part, minerals that have considerable resistance to the common erosive agencies. Many others, not included in this chapter, may have local or very rare occurrence.

The minerals described may be classified, roughly, as to their frequency of occurrence as follows:

| Very Common | Common | Rare |
|---|---|---|
| Biotite | Actinolite | Anatase |
| Calcite | Andalusite | Apatite |
| Chalcedony | Augite | Aragonite |
| Chlorite | Cassiterite | Barite |
| Garnet | Chromite | Basaltic Hornblende |
| Hornblende | Corundum | Brookite |
| Ilmenite | Enstatite | Diopside |
| Kaolinite | Epidote | Dumortierite |
| Leucoxene | Glaucophane | Fluorite |
| Limonite | Gypsum | Galena |
| Magnetite | Hypersthene | Glauconite |
| Muscovite | Kyanite | Hematite |
| Orthoclase | Microcline | Sillimanite |
| Plagioclase | Monazite | Sphalerite |
| Pyrite | Pargasite | Spinel |
| Quartz | Rutile | Spodumene |
| Zircon | Staurolite | Vesuvianite |
| | Titanite | Xenotime |
| | Topaz | Zoisite |
| | Tourmaline | |

Their order below is entirely alphabetical.

## Actinolite

| | |
|---|---|
| Composition | Ca-Mg-Fe-Silicate |
| System | Monoclinic |
| Cleavage | *110* perfect; sometimes fibrous |
| Hardness | 5–6 |
| Spec. Gravity | 2.9–3.0 |
| Magnet | Slightly magnetic |
| Conductivity | Fair conductor |
| Optical Properties | $N_\alpha = 1.612$; $N_\beta = 1.627$; $N_\gamma = 1.639$; Biaxial (−); Birefringence = 0.027; Elongation (+); $2V = 81°$ |
| Color | Pale to dark green. |
| Pleochroism | Not strong; $\alpha$ = pale yellow; $\beta$ = greenish yellow; $\gamma$ = green. |
| Identification | With decrease of iron, actinolite grades into tremolite and color becomes paler. Usually acicular or fibrous with positive elongation. |
| Derivation | Metamorphic rocks, or as an alteration product in igneous rocks. |

## Anatase

| | |
|---|---|
| Composition | $TiO_2$ |
| System | Tetragonal |
| Cleavage | *001* and *111* perfect |
| Hardness | 5.5–6 |
| Spec. Gravity | 3.82–3.95 |
| Magnet | Non-magnetic |
| Conductivity | Fairly good conductor |
| Optical Properties | $\omega = 2.562$; $\varepsilon = 2.489$; Uniaxial (−); Birefringence = 0.073; Elongation (−) |
| Color | Brown, yellow, blue, black. |
| Pleochroism | Weak; $\alpha$ = yellow, light brown, or light blue; $\gamma$ = orange, dark brown, or dark blue. |
| Identification | Usually of secondary origin and occurs in sediments as uneroded tabular crystals of nearly square outline and with beveled edges. These crystals show high relief and appear isotropic, but give a uniaxial figure. |
| Derivation | Usually secondary; sometimes from igneous or metamorphic rocks. |

## Andalusite

(See Fig. 37)

| | |
|---|---|
| Composition | $Al_2SiO_5$ |
| System | Orthorhombic |
| Cleavage | *110* good; *100* poor |
| Hardness | 7.5 |
| Spec. Gravity | 3.2 |
| Magnet | Non-magnetic |
| Conductivity | Poor |
| Optical Properties | $N_\alpha = 1.632$;<br>$N_\beta = 1.638$;<br>$N_\gamma = 1.643$<br>Biaxial (−);<br>Birefringence = 0.011;<br>Elongation (−);<br>$2V = 85°$ |
| Color | Rose red, violet, or colorless. |
| Pleochroism | $\alpha$ = red; $\beta$ and $\gamma$ colorless. |
| Identification | Most easily identified by the pleochroism and negative elongation. Prismatic cleavage fragments do not give good interference figures. |
| Derivation | Igneous and metamorphic rocks. |

## Apatite

| | |
|---|---|
| Composition | $Ca_5(F, Cl)P_3O_{12}$ |
| System | Hexagonal |
| Cleavage | *0001* poor |
| Hardness | 5 |
| Spec. Gravity | 3.2 |
| Magnet | Non-magnetic |
| Conductivity | Poor |
| Optical Properties | $\omega = 1.634$;<br>$\varepsilon = 1.632$;<br>Uniaxial (−);<br>Birefringence = 0.002;<br>Elongation (−);<br>Sometimes pseudo-biaxial with $2E = 10°$ or more. |
| Color | Colorless to bluish and greenish. |
| Pleochroism | Very weak. |
| Identification | Usually in elongated crystals with rounded ends. Easily identified by low birefringence and negative elongation. |
| Derivation | Acidic igneous rocks. |

## Aragonite

| | |
|---|---|
| Composition | $CaCO_3$ |
| System | Orthorhombic |
| Cleavage | *010* good; *110* fair |
| Hardness | 3.5–4 |
| Spec. Gravity | 2.9 |
| Magnet | Non-magnetic |
| Conductivity | Non-conductor |
| Optical Properties | $N_\alpha = 1.530$;<br>$N_\beta = 1.682$;<br>$N_\gamma = 1.686$;<br>Biaxial (−);<br>Birefringence = 0.156;<br>Elongation (−);<br>$2E = 30°$;<br>Dispersion weak, $\rho < \nu$ |
| Color | Colorless. |
| Pleochroism | None. |
| Identification | Shows iridescent colors and "twinkling," like calcite, but is biaxial. |
| Derivation | Bedded deposits; various rocks. |

## Augite

(See Fig. 38)

| | |
|---|---|
| Composition | Ca, Mg, Al, Fe, silicate (a pyroxene) |
| System | Monoclinic |
| Cleavage | *110* good |
| Hardness | 5–6 |
| Spec. Gravity | 3.2–3.6 |
| Magnet | Somewhat magnetic |
| Conductivity | Moderate conductor |
| Optical Properties | $N_\alpha = 1.698$;<br>$N_\beta = 1.704$;<br>$N_\gamma = 1.723$;<br>Biaxial (+);<br>Birefringence = 0.025;<br>$2V = 60°$;<br>Dispersion weak, $\rho > \nu$ |
| Color | Greenish. |
| Pleochroism | Very weak. |
| Identification | Extinction angle usually greater than 45° and is less for red than for blue light. |
| Derivation | Basic igneous rocks. |

## Barite

(See Fig. 39)

| | |
|---|---|
| Composition | $BaSO_4$ |
| System | Orthorhombic |
| Cleavage | *001* and *110* perfect; *010* poor |
| Hardness | 2.5–3.5 |
| Spec. Gravity | 4.5 |
| Magnet | Non-magnetic |
| Conductivity | Poor |
| Optical Properties | $N_\alpha = 1.636$; $N_\beta = 1.637$; $N_\gamma = 1.648$; Biaxial (+); Birefringence = 0.012; Elongation (+); $2V = 37\frac{1}{2}°$; Dispersion weak, $\rho < \nu$ |
| Color | Colorless. |
| Pleochroism | None. |
| Identification | Easily confused with celestite, anhydrite, etc. It is best to make flame test for barium. |
| Derivation | Veins, sediments, and bedded deposits. |

## Basaltic Hornblende

(See Fig. 40)

| | |
|---|---|
| Composition | Same as hornblende with addition of titanium and alkalies |
| System | Monoclinic |
| Cleavage | *110* perfect; *010* good |
| Hardness | 5.5 |
| Spec. Gravity | 3.4 |
| Magnet | Moderately magnetic |
| Conductivity | Moderate |
| Optical Properties | $N_\alpha = 1.692$; $N_\beta = 1.730$; $N_\gamma = 1.760$; Biaxial (−); Birefringence = 0.068; $2V = 80°$; Dispersion, $\rho < \nu$ |
| Color | Reddish brown, brown. |
| Pleochroism | Rather strong, $\alpha < \beta < \gamma$. |
| Identification | Higher relief than hornblende, and stronger pleochroism; $\gamma \wedge C$ small (0°–15°). |
| Derivation | Diorites and other igneous rocks. |

## Biotite

| | |
|---|---|
| Composition | K, Mg, Al, Fe, silicate (a mica) |
| System | Monoclinic (pseudo-hexagonal) |
| Cleavage | *001* perfect |
| Hardness | 2.5–3 |
| Spec. Gravity | 2.8–3.4 |
| Magnet | Moderately magnetic |
| Conductivity | Moderate conductor |
| Optical Properties | $N_\alpha = 1.541$;<br>$N_\beta = 1.574$;<br>$N_\gamma = 1.574$;<br>Biaxial (−);<br>Birefringence = 0.033;<br>$2V$ usually less than 10°;<br>Dispersion weak, $\rho < \nu$ |
| Color | Colorless, yellow, green, brown. |
| Pleochroism | Pleochroic, but not noticeable in the usual orientation of cleavage flakes. |
| Identification | Cleavage flakes with ragged edges. Appears almost isotropic, but gives a centered biaxial figure with small axial angle. |
| Derivation | Igneous and metamorphic rocks. |

## Brookite

| | |
|---|---|
| Composition | $TiO_2$ |
| System | Orthorhombic |
| Cleavage | *110* poor |
| Hardness | 5.5–6 |
| Spec. Gravity | 3.8–4.1 |
| Magnet | Non-magnetic |
| Conductivity | Moderate conductor |
| Optical Properties | $N_\alpha = 2.583$;<br>$N_\beta = 2.586$;<br>$N_\gamma = 2.741$;<br>Biaxial (+);<br>Birefringence = 0.158;<br>$2E = 55°$ for red light and 0° for yellowish green;<br>Dispersion very strong |
| Color | Brown or yellow. |
| Pleochroism | Weak. |
| Identification | Usually as tabular fragments of irregular outline. Extreme dispersion makes the interference figure of unique appearance. |
| Derivation | Acidic igneous and metamorphic rocks. |

| | Calcite | | Carborundum (artificial) |
|---|---|---|---|
| Composition | $CaCO_3$ | Composition | SiC |
| System | Hexagonal | System | Hexagonal (rhombohedral) |
| Cleavage | *10$\bar{1}$1* perfect | Cleavage | *10$\bar{1}$1* rare; *0001* poor |
| Hardness | 3 | Hardness | 9.5 |
| Spec. Gravity | 2.7 | Spec. Gravity | 3.2 |
| Magnet | Non-magnetic | Magnet | Non-magnetic |
| Conductivity | Non-conductor | Conductivity | Non-conductor |
| Optical Properties | $\omega = 1.658$; $\varepsilon = 1.486$; Uniaxial (−); Birefringence = 0.172; $N_D$ on the cleavage face = 1.566; Symmetrical extinction | Optical Properties | $\omega = 2.654$; $\varepsilon = 2.697$; Uniaxial (+); Birefringence = 0.043; Dispersion very strong |
| Color | Pale tints or colorless. | Color | Usually bluish gray. |
| Pleochroism | None; exhibits "twinkling" in plane polarized light on rotation of the lower nicol. | Pleochroism | Apparent; $\alpha > \gamma$. |
| Identification | Cleavage striae parallel to long diagonals of rhombohedral cleavage flakes; "twinkling" characteristic. One index lower than balsam. | Identification | The Delf blue color and pleochroism usually distinguish this substance. |
| Derivation | Various sources. | Derivation | A product of the electric furnace. Included in this list because, as a grinding powder, it is found frequently in thin sections prepared by its aid. |

## Cassiterite

| | |
|---|---|
| Composition | $SnO_2$ |
| System | Tetragonal |
| Cleavage | *100, 111* poor |
| Hardness | 6–7 |
| Spec. Gravity | 6.8–7.1 |
| Magnet | Non-magnetic |
| Conductivity | Moderate conductor |
| Optical Properties | $\omega = 1.997$; $\varepsilon = 2.093$; Uniaxial (+); Birefringence = 0.096; Elongation (+); Sometimes anomalously biaxial |
| Color | Brown, black, reddish brown, or gray. |
| Pleochroism | Rare. |
| Identification | Usually in prismatic grains. Distinguished from rutile by the lower birefringence. |
| Derivation | Acidic igneous rocks or pegmatitic veins. |

## Chalcedony

| | |
|---|---|
| Composition | $SiO_2$ |
| System | Cryptocrystalline |
| Cleavage | None; conchoidal fracture |
| Hardness | 7 |
| Spec. Gravity | 2.55–2.64 |
| Magnet | Non-magnetic |
| Conductivity | Non-conductor |
| Optical Properties | $N_\alpha = 1.530$; $N_\gamma = 1.537$; Probably uniaxial (±); Birefringence = 0.007 |
| Color | Colorless or pale tints. |
| Pleochroism | None. |
| Identification | Usually exhibits fibrous structure, spherulites, or aggregate polarization (var. chert). |
| Derivation | A product of hydrothermal action in many kinds of rock. |

## Chlorite Group

| | |
|---|---|
| Composition | Mg, Al, Fe, silicate (a mica group) |
| System | Monoclinic |
| Cleavage | *001* perfect |
| Hardness | 2.0–2.5 |
| Spec. Gravity | 2.6–3.0 |
| Magnet | Weakly magnetic |
| Conductivity | Poor |
| Optical Properties | $N_{mean} = 1.560–1.600$; Biaxial (±); Birefringence = 0.004–0.015; Dispersion strong |
| Color | Usually green. |
| Pleochroism | Sometimes pleochroic; green to yellowish green. |
| Identification | Irregular flakes with pale green color, weak birefringence and strong dispersion. Sometimes deep blue, anomalous, interference colors. |
| Derivation | Metamorphic rocks. |

## Chromite

| | |
|---|---|
| Composition | $FeCr_2O_4$ |
| System | Isometric |
| Cleavage | None |
| Hardness | 5.5 |
| Spec. Gravity | 4.5 |
| Magnet | Moderately magnetic |
| Conductivity | Good |
| Optical Properties | Opaque except in very thin flakes; $N_D = 2.07$ |
| Color | Black, purplish or brownish black. |
| Pleochroism | None. |
| Identification | Use borax bead test for chromium. Bead is green in oxidizing and in reducing flames. |
| Derivation | Basic igneous rocks. |

## Corundum

| | |
|---|---|
| Composition | $Al_2O_3$ |
| System | Hexagonal (rhombohedral) |
| Cleavage | None; sometimes parting on *0001* |
| Hardness | 9 |
| Spec. Gravity | 3.95–4.10 |
| Magnet | Non-magnetic |
| Conductivity | Non-conductor |
| Optical Properties | $\omega = 1.768$: $\varepsilon = 1.760$; Uniaxial (−); Birefringence = 0.008; Anomalous $2E = 11°$ (sometimes larger); Elongation (−) |
| Color | Colorless, blue, red, yellow, brown. |
| Pleochroism | Colored varieties are pleochroic, as in sapphire ($\alpha$ = bluish green; $\gamma$ = blue). |
| Identification | Low birefringence and high relief. |
| Derivation | Volcanic and metamorphic rocks. |

## Diopside

(See Fig. 41)

| | |
|---|---|
| Composition | $CaMgSi_2O_6$ (a pyroxene) |
| System | Monoclinic |
| Cleavage | *110* good; parting on *100* |
| Hardness | 5–6 |
| Spec. Gravity | 3.3 |
| Magnet | Weakly magnetic |
| Conductivity | Moderate conductor |
| Optical Properties | $N_\alpha = 1.673$: $N_\beta = 1.680$; $N_\gamma = 1.702$; Biaxial (+); Birefringence = 0.029; $2E = 70°$–$112°$; Dispersion weak, $\rho > \nu$ |
| Color | Pale green or gray. |
| Pleochroism | Very weak or lacking. |
| Identification | Easily confused with augite, but birefringence is greater and dispersion less, and it gives more complete extinction in white light. |
| Derivation | Basic igneous and metamorphic rocks. |

## Dumortierite

(See Fig. 42)

| | |
|---|---|
| Composition | $HBAl_8Si_4O_{20}$ |
| System | Orthorhombic |
| Cleavage | *100* good; *110* poor; *001* parting |
| Hardness | 7 |
| Spec. Gravity | 3.3 |
| Magnet | Non-magnetic |
| Conductivity | Poor |
| Optical Properties | $N_\alpha = 1.670$; $N_\beta = 1.691$; $N_\gamma = 1.692$; Biaxial (−); Birefringence = 0.022; Elongation (−); Dispersion strong, $\rho < \nu$ or $\rho > \nu$ |
| Color | Blue, violet, etc. |
| Pleochroism | Strong; $\alpha$ = blue; $\beta$ = yellow or violet; $\gamma$ = colorless or green. |
| Identification | Strong pleochroism, $\alpha > \gamma$. Resembles tourmaline. |
| Derivation | Pegmatites and gneisses. |

## Enstatite

(See Fig. 43)

| | |
|---|---|
| Composition | $MgSiO_3$ (a pyroxene) |
| System | Orthorhombic |
| Cleavage | *110* good; parting on *010* |
| Hardness | 5.5 |
| Spec. Gravity | 3.2 |
| Magnet | Non-magnetic |
| Conductivity | Poor |
| Optical Properties | $N_\alpha = 1.650$; $N_\beta = 1.653$; $N_\gamma = 1.658$; Biaxial (+); Birefringence = 0.008; $2V = 30°$–$70°$; Elongation (+); Dispersion weak, $\rho > \nu$ |
| Color | Gray, yellow, green. |
| Pleochroism | Weak, $\alpha$ = yellow; $\gamma$ = green. |
| Identification | Distinguished from hypersthene by weak pleochroism. Grains usually lie on *110* face and have ragged terminations. |
| Derivation | Metamorphic rocks. |

## Epidote (Pistacite)

(See Fig. 44)

| | |
|---|---|
| Composition | $HCa_2(Al, Fe)_3 Si_3O_{13}$ |
| System | Monoclinic |
| Cleavage | *001* perfect; *100* poor |
| Hardness | 6–7 |
| Spec. Gravity | 3.4–3.5 |
| Magnet | Weakly magnetic |
| Conductivity | Poor |
| Optical Properties | $N_\alpha = 1.729$;<br>$N_\beta = 1.754$;<br>$N_\gamma = 1.768$;<br>Biaxial (−);<br>Birefringence = 0.039;<br>$2V = 90° \pm$;<br>Dispersion strong,<br>$\rho > \nu$ |
| Color | Pale green or yellowish green. |
| Pleochroism | Weak, β = greenish yellow; α and γ colorless. |
| Identification | Grains are usually clear and transparent, and show a centered optic axis figure. Clinozoisite is similar, but is colorless. |
| Derivation | Metamorphic rocks. |

## Fluorite

| | |
|---|---|
| Composition | $CaF_2$ |
| System | Isometric |
| Cleavage | *111* perfect |
| Hardness | 4 |
| Spec. Gravity | 3.2 |
| Magnet | Non-magnetic |
| Conductivity | Non-conductor |
| Optical Properties | Isotropic $N_D = 1.434$ |
| Color | Colorless and various tints. |
| Pleochroism | None. |
| Identification | Often as triangular grains with beveled edges. Index is less than balsam. |
| Derivation | Acidic igneous rocks, metamorphic rocks, and veins. |

| Galena | | Garnet | |
|---|---|---|---|
| Composition | PbS | Composition | Silicate of Ca, Mg, Fe, etc. |
| System | Isometric | System | Isometric |
| Cleavage | *100* perfect | Cleavage | *110* poor |
| Hardness | 2.5 | Hardness | *7* |
| Spec. Gravity | 7.4–7.6 | Spec. Gravity | 3.8 |
| Magnet | Non-magnetic | Magnet | Moderately magnetic |
| Conductivity | Good | Conductivity | Poor |
| Optical Properties | Opaque; luster metallic | Optical Properties | Isotropic, $N_D$ = 1.71–1.89; Rarely anomalously biaxial (−) with strong dispersion |
| Color | Bluish gray or lead gray. | Color | Usually colorless or pink. |
| Pleochroism | None. | Pleochroism | None. |
| Identification | The cubical cleavage and bluish gray color are distinctive. | Identification | Irregular transparent and isotropic grains. Compare with spinel. |
| Derivation | Veins and ore deposits. | Derivation | Metamorphic rocks. |

## Glauconite

| | |
|---|---|
| Composition | K, Fe, Al silicate (hydrous) |
| System | Microcrystalline |
| Cleavage | Very fine *001* laminae |
| Hardness | 2 |
| Spec. Gravity | 2.2–2.8 |
| Magnet | Moderately magnetic |
| Conductivity | Poor |
| Optical Properties | $N_D = 1.61$; Sometimes shows low birefringence |
| Color | Green, altering to brown. |
| Pleochroism | Sometimes green to yellowish green. |
| Identification | Usually rounded grains with microcrystalline texture and green color. |
| Derivation | Marine sediments. |

## Glaucophane

(See Fig. 45)

| | |
|---|---|
| Composition | Na, Al, Fe, Mg, silicate (an amphibole) |
| System | Monoclinic |
| Cleavage | *110* perfect |
| Hardness | 6–6.5 |
| Spec. Gravity | 3–3.5 |
| Magnet | Moderately magnetic |
| Conductivity | Moderate |
| Optical Properties | $N_\alpha = 1.621$; $N_\beta = 1.638$; $N_\gamma = 1.639$; Biaxial (−); Birefringence = 0.018; $2V = 45°$; Dispersion strong, $\rho > \nu$; Elongation (+) |
| Color | Blue-violet to bluish black. |
| Pleochroism | Marked, $\alpha$ = colorless or yellowish; $\beta$ = blue-violet; $\gamma$ = dark blue. |
| Identification | Easily identified by pleochroism and positive elongation. |
| Derivation | Metamorphic rocks. |

## Gypsum

(See Fig. 46)

| | |
|---|---|
| Composition | $CaSO_4 \cdot 2H_2O$ |
| System | Monoclinic |
| Cleavage | *010* perfect; *100* and $\bar{1}11$ poor |
| Hardness | 2 |
| Spec. Gravity | 2.32 |
| Magnet | Non-magnetic |
| Conductivity | Non-conductor |
| Optical Properties | $N_\alpha = 1.521$;<br>$N_\beta = 1.523$;<br>$N_\gamma = 1.530$;<br>Biaxial (+);<br>Birefringence = 0.009;<br>$2E = 95°$;<br>Inclined dispersion strong, $\rho > \nu$ |
| Color | Colorless. |
| Pleochroism | None. |
| Identification | Low refringence and birefringence, with strong dispersion |
| Derivation | Sedimentary rocks and bedded deposits. |

## Hematite

| | |
|---|---|
| Composition | $Fe_2O_3$ |
| System | Hexagonal (rhombohedral) |
| Cleavage | None |
| Hardness | 5 |
| Spec. Gravity | 5.2 |
| Magnet | Moderately magnetic |
| Conductivity | Good |
| Optical Properties | $\omega = 3.22$;<br>$\varepsilon = 2.94$;<br>Opaque except in thin flakes;<br>Uniaxial (−);<br>Birefringence = 0.28 |
| Color | Steel gray to iron black; earthy varieties red. |
| Pleochroism | In very thin scales<br>$\gamma$ = brownish red;<br>$\alpha$ = yellowish red. |
| Identification | Red in streak or powder. |
| Derivation | Many sources. |

## Hornblende

(See Fig. 47)

| | |
|---|---|
| Composition | Na, Al, Ca, Mg, Fe silicate (an amphibole) |
| System | Monoclinic |
| Cleavage | *110* perfect; *010* good |
| Hardness | 5.5 |
| Spec. Gravity | 3–3.47 |
| Magnet | Moderately magnetic |
| Conductivity | Moderate |
| Optical Properties | Indices variable with amount of iron; average about 1.67 with Birefringence = about 0.02; Biaxial (−); $\gamma \wedge c = 15°$–$25°$; Dispersion, $\rho < \nu$ |
| Color | Green, brown, black. |
| Pleochroism | Variable; usually green to brown. |
| Identification | Prismatic fragments, with rather strong birefringence and moderate pleochroism. |
| Derivation | Igneous and metamorphic rocks. |

## Hypersthene

(See Fig. 48)

| | |
|---|---|
| Composition | (Mg, Fe) $SiO_3$ |
| System | Orthorhombic |
| Cleavage | *110* good |
| Hardness | 5–6 |
| Spec. Gravity | 3.3–3.5 |
| Magnet | Somewhat magnetic |
| Conductivity | Moderate |
| Optical Properties | $N_\alpha = 1.692$; $N_\beta = 1.702$; $N_\gamma = 1.705$; Biaxial (−); Birefringence = 0.013; $2V$ = about 75°; Elongation (+); Dispersion weak, $\rho > \nu$ |
| Color | Yellowish brown, brown, brownish green. |
| Pleochroism | Strong; $\alpha$ = pink, $\beta$ = yellow, $\gamma$ = green. |
| Identification | Prismatic grains usually have ragged terminations and strong pleochroism. Enstatite is similar. |
| Derivation | Basic igneous rocks. |

| Ilmenite | | Kaolinite | |
|---|---|---|---|
| Composition | $FeTiO_3$ | Composition | $H_4Al_2Si_2O_9$ |
| System | Hexagonal (rhombohedral) | System | Monoclinic |
| Cleavage | *0001* parting | Cleavage | *001* perfect |
| Hardness | 5.5 | Hardness | 2–2.5 |
| Spec. Gravity | 4.6–4.9 | Spec. Gravity | 2.6–2.63 |
| Magnet | Moderately magnetic | Magnet | Non-magnetic |
| Conductivity | Good | Conductivity | Non-conductor |
| Optical Properties | Opaque, sub-metallic luster | Optical Properties | $N_\alpha = 1.561$; $N_\beta = 1.565$; $N_\gamma = 1.567$; Biaxial (−); Birefringence = 0.006; $2V = 60°$; Dispersion weak, $\rho > \nu$ $\alpha \wedge c = 4°$ |
| Color | Black, purplish black. | Color | Colorless or tinted. |
| Pleochroism | None. | Pleochroism | None. |
| Identification | Crush a grain and dissolve in HCl; add one drop to a $H_2SO_4$ solution of phenol; brick red color proves titanium. Ilmenite often has white borders of leucoxene. | Identification | Usually very finely comminuted; sometimes pseudo-hexagonal plates are seen. Distinguished from serecite and talc by low birefringence. |
| Derivation | Basic igneous rocks. | Derivation | Clay; alteration products. |

## Kyanite (Cyanite)

| | |
|---|---|
| Composition | $Al_2SiO_5$ |
| System | Triclinic |
| Cleavage | *100* perfect; *010* good; *001* parting |
| Hardness | 4–5 on *100;* 7 on *010* |
| Spec. Gravity | 3.6 |
| Magnet | Non-magnetic |
| Conductivity | Poor |
| Optical Properties | $N_\alpha = 1.712$; $N_\beta = 1.720$; $N_\gamma = 1.728$; Biaxial (−); Birefringence = 0.016; $2V = 82°$; *Bxa* (= α) is nearly normal to *100;* Dispersion weak, $\rho > \nu$ |
| Color | Blue to colorless. |
| Pleochroism | Faint; α = colorless; β = violet; γ = blue. |
| Identification | Has many cleavage lines. Elongated *100* grains are common with extinction of 30°. Pleochroism not often seen. High relief; moderate birefringence. |
| Derivation | Metamorphic rocks. |

## Leucoxene

| | |
|---|---|
| Composition | A form of titanite occurring as an alteration product of ilmenite or titaniferous magnetite. |
| System | Amorphous |
| Cleavage | None |
| Hardness | Unknown |
| Spec. Gravity | 3.5–4.5 |
| Magnet | Non-magnetic |
| Conductivity | Moderate |
| Optical Properties | Opaque, dull luster |
| Color | White, yellow. |
| Pleochroism | None. |
| Identification | Rounded grains with dull luster and pitted surface. |
| Derivation | Alteration product. |

## Limonite

| | |
|---|---|
| Composition | $Fe_2O_3 \cdot nH_2O$ |
| System | Amorphous |
| Cleavage | None; earthy |
| Hardness | 5 |
| Spec. Gravity | 3.8 |
| Magnet | Non-magnetic |
| Conductivity | Moderate conductor |
| Optical Properties | Opaque, or translucent and isotropic in very thin fragments. $N_D = 2.0\pm$ |
| Color | Yellow, brown. |
| Pleochroism | None. |
| Identification | Yellow or brown stains or coatings on other minerals. Soluble in hot dilute HCl. |
| Derivation | Secondary; very common in the oxidized zone. Also a product of hydrothermal alteration. |

## Magnetite

| | |
|---|---|
| Composition | $Fe_3O_4$ |
| System | Isometric |
| Cleavage | None; *111* parting |
| Hardness | 6 |
| Spec. Gravity | 5.17 |
| Magnet | Strongly magnetic |
| Conductivity | Good |
| Optical Properties | Opaque; luster metallic to dull |
| Color | Black, bluish black. |
| Pleochroism | None. |
| Identification | Octahedra and irregular grains. Readily lifted by bar magnet. |
| Derivation | Basic igneous and metamorphic rocks. |

## Microcline

| | |
|---|---|
| Composition | $KAlSi_3O_8$ (an orthoclase feldspar) |
| System | Triclinic |
| Cleavage | *001* perfect; *010* good, intersecting at 90° |
| Hardness | 6–6.5 |
| Spec. Gravity | 2.55 |
| Magnet | Non-magnetic |
| Conductivity | Non-conducting |
| Optical Properties | $N_\alpha = 1.522$; $N_\beta = 1.526$; $N_\gamma = 1.530$; Biaxial (−); Birefringence = 0.007; $2E = 180°$; Dispersion weak, $\rho > \nu$ |
| Color | Colorless, pale tints. |
| Pleochroism | None. |
| Identification | *001* flakes show grating structure due to crossed polysynthetic twinning. |
| Derivation | Acidic igneous rocks. |

## Monazite

(See Fig. 49)

| | |
|---|---|
| Composition | $CePO_4$ |
| System | Monoclinic |
| Cleavage | *001* perfect; *100* good |
| Hardness | 5 |
| Spec. Gravity | 5.1 |
| Magnet | Weakly magnetic |
| Conductivity | Poor |
| Optical Properties | $N_\alpha = 1.786$; $N_\beta = 1.788$; $N_\gamma = 1.837$; Biaxial (+); Birefringence = 0.051; $2E = 6°–19°$; Dispersion weak, $\rho < \nu$ or $\rho > \nu$ |
| Color | Yellow, reddish brown. |
| Pleochroism | Very weak; $\alpha$ = yellow, $\gamma$ = greenish yellow. |
| Identification | Commonly in honey-yellow, rounded grains or crystals; with weak dispersion and small axial angle. |
| Derivation | Acidic igneous rocks. |

## Muscovite

| | |
|---|---|
| Composition | $H_2(K, Na)Al_3(SiO_4)_3$ (a mica) |
| System | Monoclinic (pseudo-hexagonal) |
| Cleavage | *001* perfect |
| Hardness | 2.5–3 |
| Spec. Gravity | 2.76–3 |
| Magnet | Non-magnetic |
| Conductivity | Non-conductor |
| Optical Properties | $N_\alpha = 1.552$; $N_\beta = 1.582$; $N_\gamma = 1.588$; Biaxial (−); Birefringence = 0.036; $2V = 45°$; Dispersion moderate, $\rho < \nu$ |
| Color | Colorless. |
| Pleochroism | None. |
| Identification | Colorless plates with strong birefringence that give good biaxial figure. |
| Derivation | Acidic igneous and metamorphic rocks. |

## Orthoclase

| | |
|---|---|
| Composition | $KAlSi_3O_8$ (a feldspar) |
| System | Monoclinic |
| Cleavage | *001* perfect; *010* good |
| Hardness | 6–6.5 |
| Spec. Gravity | 2.55 |
| Magnet | Non-magnetic |
| Conductivity | Non-conductor |
| Optical Properties | $N_\alpha = 1.518$; $N_\beta = 1.524$; $N_\gamma = 1.526$; Biaxial (−); Birefringence = 0.007; $2E = 120°$; Dispersion moderate, $\rho > \nu$ |
| Color | Colorless. |
| Pleochroism | None. |
| Identification | Distinguished from quartz by the cleavage, somewhat lower index and negative sign. |
| Derivation | Acidic igneous rocks. |

## Pargasite

| | |
|---|---|
| Composition | Ca, Mg, Fe, silicate (an amphibole) |
| System | Monoclinic |
| Cleavage | *110* perfect; *010* good |
| Hardness | 5.5 |
| Spec. Gravity | 3–3.47 |
| Magnet | Moderately magnetic |
| Conductivity | Moderate |
| Optical Properties | $N_\alpha = 1.613$; $N_\beta = 1.618$; $N_\gamma = 1.633$; Biaxial (+); Birefringence = 0.020; $2V = 56°$; Dispersion, $\rho > \nu$; $\gamma \wedge c = 30°$ |
| Color | Green. |
| Pleochroism | Not strong; $\alpha$ = greenish yellow, $\beta$ = green, $\gamma$ = greenish blue. |
| Identification | Prismatic fragments with rather strong birefringence and positive sign. |
| Derivation | Igneous and metamorphic rocks. |

## Plagioclase

| | |
|---|---|
| Composition | A feldspar containing albite ($Ab = NaAlSi_3O_8$) and anorthite ($An = CaAl_2Si_2O_8$) in various proportions |
| System | Triclinic |
| Cleavage | *001* perfect; *010* good, at angles of about 94° |
| Hardness | 6–6.5 |
| Spec. Gravity | 2.6–2.8 |
| Magnet | Non-magnetic |
| Conductivity | Non-conductor |
| Optical Properties | $N_\alpha = 1.525$–$1.576$; $N_\beta = 1.529$–$1.583$; $N_\gamma = 1.536$–$1.589$; Biaxial (±); Birefringence = 0.011–0.013; $2E = 125°$–$160°$; Dispersion weak, $\rho > \nu$ or $\rho < \nu$ |
| Color | Colorless, gray. |
| Pleochroism | None. |
| Identification | Grains often turbid and show polysynthetic twinning. Distinction between the various members of the series is best made on the basis of Tsuboi's method, which see. |
| Derivation | Igneous rocks. |

| | Pyrite | | Quartz |
|---|---|---|---|
| Composition | $FeS_2$ | Composition | $SiO_2$ |
| System | Isometric | System | Hexagonal |
| Cleavage | Poor | Cleavage | None |
| Hardness | 6–6.5 | Hardness | 7 |
| Spec. Gravity | 5 | Spec. Gravity | 2.65 |
| Magnet | Non-magnetic | Magnet | Non-magnetic |
| Conductivity | Good | Conductivity | None |
| Optical Properties | Opaque, luster metallic | Optical Properties | $\omega = 1.544$; $\varepsilon = 1.553$; Uniaxial (+); sometimes anomalously biaxial; Birefringence = 0.009; Elongation (+) |
| Color | Brass yellow. | Color | Colorless or tinted. |
| Pleochroism | None. | Pleochroism | None. |
| Identification | Often in octahedra or dodecahedra with striated faces; also aggregates and nodules which may appear greenish yellow. Soluble in $HNO_3$ but not in HCl. | Identification | Irregular grains with no cleavage and low index and birefringence. Most grains will give uniaxial figure. |
| Derivation | Igneous rocks, veins, and as a secondary mineral in sediments. | Derivation | Various; very resistant to decomposition. |

## Rutile

| | |
|---|---|
| Composition | $TiO_2$ |
| System | Tetragonal |
| Cleavage | *110* and *100* good |
| Hardness | 6–6.5 |
| Spec. Gravity | 4.18–4.25 |
| Magnet | Non-magnetic |
| Conductivity | Moderate |
| Optical Properties | $\omega = 2.61$;<br>$\varepsilon = 2.90$;<br>Uniaxial (+);<br>Birefringence = 0.286;<br>Elongation (+) |
| Color | Reddish brown to black. |
| Pleochroism | Weak, brown to yellow. |
| Identification | Rounded prismatic grains, sometimes knee-twinned with prismatic cleavages. Parallel extinction. |
| Derivation | Acidic igneous and metamorphic rocks. |

## Sillimanite

(See Fig. 50)

| | |
|---|---|
| Composition | $Al_2SiO_5$ |
| System | Orthorhombic |
| Cleavage | *010* perfect |
| Hardness | 6.5 |
| Spec. Gravity | 3.25 |
| Magnet | Non-magnetic |
| Conductivity | Non-conductor |
| Optical Properties | $N_\alpha = 1.660$;<br>$N_\beta = 1.661$;<br>$N_\gamma = 1.681$;<br>Biaxial (+);<br>Birefringence = 0.021;<br>$2E = 42°$;<br>Elongation (+);<br>Dispersion strong, $\rho > \nu$ |
| Color | Colorless or tinted. |
| Pleochroism | Weak, $\gamma > \beta > \alpha$. |
| Identification | Slender prisms or fibers with strong birefringence. |
| Derivation | Metamorphic rocks. |

## Sphalerite

| | |
|---|---|
| Composition | ZnS |
| System | Isometric |
| Cleavage | Dodecahedral, perfect |
| Hardness | 3.5–4 |
| Spec. Gravity | 4.1 |
| Magnet | Moderately magnetic |
| Conductivity | Good |
| Optical Properties | Translucent to opaque; luster resinous; $N_D = 2.4$ |
| Color | Yellow, brown, black. |
| Pleochroism | None. |
| Identification | Best made with blowpipe; gives sublimate on charcoal that is yellow when hot and white when cold. |
| Derivation | Veins and ore bodies. |

## Spinel

| | |
|---|---|
| Composition | $MgAl_2O_4$ |
| System | Isometric |
| Cleavage | *111* poor |
| Hardness | 8 |
| Spec. Gravity | 3.6 |
| Magnet | Non-magnetic |
| Conductivity | Non-conductor |
| Optical Properties | Isotropic; $N_D = 1.72$–$2.05$ |
| Color | Red, blue, green, brown. |
| Pleochroism | None. |
| Identification | Rounded octahedra. Infusible before the blowpipe. |
| Derivation | Metamorphic rocks. |

## Spodumene

(See Fig. 51)

| | |
|---|---|
| Composition | $LiAlSi_2O_6$ (a pyroxene) |
| System | Monoclinic |
| Cleavage | *110* good at 87°; parting on *010* |
| Hardness | 6–7 |
| Spec. Gravity | 3.1–3.2 |
| Magnet | Non-magnetic |
| Conductivity | Non-conductor |
| Optical Properties | $N_\alpha = 1.651$; $N_\beta = 1.669$; $N_\gamma = 1.677$; Biaxial (+); Birefringence = 0.026; $2V = 54°–60°$; Dispersion weak, $\rho < \nu$ |
| Color | Yellow, green, pink. |
| Pleochroism | Weak. |
| Identification | Fragments on *010* parting, showing traces of *110* cleavage; will have extinction angle of $\gamma \wedge C = 24°$. |
| Derivation | Acidic plutonic rocks and metamorphics. |

## Staurolite

(See Fig. 52)

| | |
|---|---|
| Composition | Fe, Mg, Al, silicate |
| System | Orthorhombic |
| Cleavage | *010* good |
| Hardness | 7–7.5 |
| Spec. Gravity | 3.65–3.77 |
| Magnet | Weakly magnetic |
| Conductivity | Poor |
| Optical Properties | $N_\alpha = 1.74$; $N_\beta = 1.74$; $N_\gamma = 1.75$; Biaxial (+); Birefringence = 0.012; $2V = 88°$; Elongation (+); Dispersion weak, $\rho > \nu$ |
| Color | Reddish brown to yellow. |
| Pleochroism | Moderate, $\alpha < \beta < \gamma$. |
| Identification | Flat, irregular grains with weak birefringence and pleochroic in yellow tints. |
| Derivation | Metamorphic rocks. |

## Titanite (Sphene)

(See Fig. 53)

| | |
|---|---|
| Composition | $CaTiSiO_5$ |
| System | Monoclinic |
| Cleavage | *110* good |
| Hardness | 5–5.5 |
| Spec. Gravity | 3.4–3.56 |
| Magnet | Non-magnetic |
| Conductivity | Moderate |
| Optical Properties | $N_\alpha = 1.899$;<br>$N_\beta = 1.905$;<br>$N_\gamma = 2.008$;<br>Biaxial (+);<br>Birefringence = 0.109;<br>$2E = 52°$;<br>Dispersion extreme,<br>$\rho > \nu$ |
| Color | Brown, orange, green. |
| Pleochroism | Weak, $\alpha < \beta < \gamma$. |
| Identification | Irregular grains with extreme index, birefringence, and dispersion. Some grains give good *Bxa* figure. |
| Derivation | Igneous and metamorphic rocks. |

## Topaz

(See Fig. 54)

| | |
|---|---|
| Composition | $Al_2(F, OH)_2SiO_4$ |
| System | Orthorhombic |
| Cleavage | *001* perfect |
| Hardness | 8 |
| Spec. Gravity | 3.52–3.57 |
| Magnet | Non-magnetic |
| Conductivity | Poor |
| Optical Properties | $N_\alpha = 1.619$;<br>$N_\beta = 1.620$;<br>$N_\gamma = 1.627$;<br>Biaxial (+);<br>Birefringence = 0.008;<br>$2E = 85°$–$125°$;<br>Dispersion, $\rho > \nu$;<br>Elongation (+) |
| Color | Colorless, yellow, blue, red, green. |
| Pleochroism | Very weak. |
| Identification | Irregular grains that usually give good *Bxa* figure. |
| Derivation | Acidic plutonics and metamorphics. |

## Tourmaline

| | |
|---|---|
| Composition | B, Al, silicate with other bases |
| System | Hexagonal |
| Cleavage | Poor |
| Hardness | 7–7.5 |
| Spec. Gravity | 2.9–3.2 |
| Magnet | Weakly magnetic |
| Conductivity | Moderate conductor |
| Optical Properties | $\omega = 1.642$; $\varepsilon = 1.622$; Uniaxial (−); Birefringence = 0.020; Elongation (−) |
| Color | Brown, bluish black, green, red, colorless. |
| Pleochroism | Strong; $\alpha < \gamma$. |
| Identification | Nearly always easily identified by the greater absorption when crystallographic axis is normal to vibration direction in lower nicol. |
| Derivation | Acidic plutonics and metamorphics. |

## Vesuvianite

| | |
|---|---|
| Composition | Hydrous Ca, Al, silicate |
| System | Tetragonal |
| Cleavage | *110* poor |
| Hardness | 6.5 |
| Spec. Gravity | 3.35–3.45 |
| Magnet | Non-magnetic |
| Conductivity | Poor |
| Optical Properties | $\omega = 1.705$–$1.736$; $\varepsilon = 1.701$–$1.732$; Uniaxial (−); Birefringence = 0.001–0.006; $2E = 30°$–$60°$; Elongation (−) |
| Color | Red, brown, yellowish green. |
| Pleochroism | Variable, $\gamma > \alpha$. |
| Identification | Prismatic grains with high index and low birefringence. |
| Derivation | Metamorphic rocks. |

## Xenotime

| | |
|---|---|
| Composition | $YPO_4$ |
| System | Tetragonal |
| Cleavage | *110* perfect |
| Hardness | 4–5 |
| Spec. Gravity | 4.59 |
| Magnet | Moderately magnetic |
| Conductivity | Poor |
| Optical Properties | $\omega = 1.720$; $\varepsilon = 1.815$; Uniaxial (+); Birefringence = 0.095; Elongation (+) |
| Color | Brown, reddish brown, yellow. |
| Pleochroism | Very weak; $\alpha < \gamma$. |
| Identification | Difficult to distinguish from colored zircon. Spectrographic examination is desirable. |
| Derivation | Plutonic rocks. |

## Zircon

| | |
|---|---|
| Composition | $ZrSiO_4$ |
| System | Tetragonal |
| Cleavage | *110* or *111* rare |
| Hardness | 7.5 |
| Spec. Gravity | 4.7 |
| Magnet | Non-magnetic |
| Conductivity | Non-conductor |
| Optical Properties | $\omega = 1.923$–$1.960$; $\varepsilon = 1.968$–$2.015$; Uniaxial (+); Birefringence = 0.045–0.058; Elongation (+) |
| Color | Colorless, yellow, brown, purple. |
| Pleochroism | None. |
| Identification | Usually as slightly rounded prismatic, colorless crystals with extreme index and moderate birefringence. (See Xenotime.) |
| Derivation | All kinds of rocks. |

## Zoisite

| | |
|---|---|
| Composition | $HCa_2Al_3Si_3O_{13}$ |
| System | Orthorhombic |
| Cleavage | *010* perfect |
| Hardness | 6 |
| Spec. Gravity | 3.25–3.36 |
| Magnet | Non-magnetic |
| Conductivity | Poor |
| Optical Properties | $N_\alpha = 1.696–1.700$;<br>$N_\beta = 1.696–1.702$;<br>$N_\gamma = 1.702–1.706$;<br>Biaxial (+);<br>Birefringence = 0.005–0.009;<br>$2V = 0°–60°$;<br>$\gamma = a$;<br>Dispersion variable |
| Color | Colorless, gray, green, brown. |
| Pleochroism | Weak; in Thulite, $\alpha$ = pink, $\beta$ = pink, $\gamma$ = yellow. |
| Identification | Usually colorless prismatic grains with high index and low birefringence. Parallel extinction. |
| Derivation | Basic igneous rocks and metamorphics. |

## TABLE 19

## DETRITAL MINERALS

TABLES FOR THE IDENTIFICATION OF THE "OPAQUE" MINERALS COMMONLY OCCURRING IN SEDIMENTARY ROCKS

| | |
|---|---|
| **LIGHT MINERALS** (Float in Bromoform) | |
| *Ferruginous chert;* | Brown to black. |
| *Glauconite;* | Green to brown; rounded grains and aggregates; soluble in HCl. |
| **HEAVY MINERALS** | |
| **Lifted by permanent magnet** | |
| *Magnetite;* | Bluish or grayish black; octahedral or rounded grains. |
| *Pyrrhotite;* | Bronze yellow; irregular grains. |
| **Lifted by electro-magnet** (with flux enough just to lift red garnet) | |
| *Ilmenite;* | Purplish to black; rounded or subangular grains; luster sub-metallic. |
| *Chromite;* (ferruginous) | Black; rounded or irregular grains; luster sub-metallic. |
| *Hematite;* | Brown or gray; rounded grains; sub-metallic to dull luster. |
| **Not magnetic as above** | |
| Color Black | |
| *Chromite;* | Black; rounded or irregular grains; luster sub-metallic. |
| *Sphalerite;* | Black to brown; grains often show dodecahedral cleavage; adamantine luster. |
| Color Brown | |
| *Limonite;* | Dull luster; often as coatings on other grains. Soluble in HCl. |
| Color Yellow | |
| *Gold;* | Characteristic golden yellow color. |
| *Pyrite;* | Brass yellow; pyritohedra, or cubes with striated faces. Often as coatings on other grains. Soluble in $HNO_3$. |
| Color White | |
| *Leucoxene;* | Rounded and pitted grains with dull luster; coatings on ilmenite. |

# DETRITAL MINERALS

## TABLES FOR THE MICROSCOPIC IDENTIFICATION OF NON-OPAQUE MINERALS OCCURRING IN SEDIMENTARY ROCKS

## KEY TO TABLES

**ISOTROPIC** — GROUP Nº

- INDEX < BALSAM
  - COLORLESS 1
  - COLORED 2
- INDEX > BALSAM
  - COLORLESS 3
  - COLORED 4

**ANISOTROPIC**

**EXTINCTION PARALLEL**

COLORLESS

- INDEX < BALSAM
  - UNIAXIAL
    - + 5
    - − 6
  - BIAXIAL
    - + 7
    - − 8
- INDEX > BALSAM
  - UNIAXIAL
    - + 9
    - − 10
  - BIAXIAL
    - + 11
    - − 12

COLORED

NON-PLEOCHROIC

- INDEX < BALSAM
  - UNIAXIAL
    - + 13
    - − 14
  - BIAXIAL
    - + 15
    - − 16
- INDEX > BALSAM
  - UNIAXIAL
    - + 17
    - − 18
  - BIAXIAL
    - + 19
    - − 20

PLEOCHROIC

- INDEX < BALSAM
  - UNIAXIAL
    - + 21
    - − 22
  - BIAXIAL
    - + 23
    - − 24
- INDEX > BALSAM
  - UNIAXIAL
    - + 25
    - − 26
  - BIAXIAL
    - + 27
    - − 28

**EXTINCTION INCLINED**

COLORLESS

- INDEX < BALSAM
  - + 29
  - − 30
- INDEX > BALSAM
  - + 31
  - − 32

COLORED

NON-PLEOCHROIC

- INDEX < BALSAM
  - + 33
  - − 34
- INDEX > BALSAM
  - + 35
  - − 36

PLEOCHROIC

- INDEX < BALSAM
  - + 37
  - − 38
- INDEX > BALSAM
  - + 39
  - − 40

## ABBREVIATIONS & SYMBOLS

**SYSTEM**

| | |
|---|---|
| A | Amorphous |
| I | Isometric |
| Te | Tetragonal |
| H | Hexagonal |
| O | Orthorhombic |
| M | Monoclinic |
| Tr | Triclinic |

**HABIT**

| | | | |
|---|---|---|---|
| Acic | Acicular | Ang | Angular |
| Gra | Grains | Xls | Crystals |
| Rd | Round or Rounded | ◊ | Diamond shaped |
| Par | Parallel | Oct | Octahedral |
| Tbl | Tables or Tabular | Frag | Fragments |

**CLEAVAGE**

Numerals are Miller indices

| | |
|---|---|
| P | Perfect |
| G | Good |
| I | Imperfect |
| Part. | Parting |

**COLOR**

| | | | |
|---|---|---|---|
| C | Colorless | Pk | Pink |
| Bl | Blue | R | Red |
| Br | Brown | V | Violet |
| Gr | Green | Y | Yellow |
| Gy | Gray | Or | Orange |
| Bk-Y | Brownish yellow etc | Bk | Black |

**ORIENTATION**

| | | | |
|---|---|---|---|
| α | Vibration direction of fast ray. Same as Wright's X or Geman a | | |
| β | " " " Intrmd ray | " " " Y " " | b |
| γ | " " " Slow " | " " " Z " " | c |
| a | Crystallographic axis a | | |
| b | " " b | | |
| c | " " c | | |
| ∧ | Makes angle with | | |
| ⊥ | Is normal to | | |
| Ext | Extinction | | |

**MAXIMUM BIREFRINGENCE**

| | | | |
|---|---|---|---|
| H | High | VH | Very High |
| L | Low | VL | Very Low |

**ELONGATION**

| | |
|---|---|
| + | Slow ray (γ) approximately ∥ direction of elongation of fragment |
| − | Fast ray (α) " " ∥ " " " " |
| ± | Usually +, sometimes − |

**PLEOCHROISM**

α=C Fast ray colorless
β=b Slow ray dark yellow etc

| | |
|---|---|
| Str | Strong |
| Wk | Weak |

**INTERFERENCE FIGURE**

This column indicates nature of figure usually seen in fragments

| | |
|---|---|
| C | Centred |
| I | Inclined |
| Ax | Optic Axis |
| Bxa | Acute Bisectrix |
| Bxo | Obtuse " |

**DISPERSION**

| | |
|---|---|
| Str | Strong |
| Wk | Weak |
| Dst | Distinct |
| r | Greater for red than for violet light |
| v | " " violet " " red " |

**SPECIAL CHARACTERS**

| | |
|---|---|
| Anom | Anomalous |
| Tw | Twinning |

## — INDEX —

| | GROUPS | | GROUPS |
|---|---|---|---|
| ACIDIC GLASS | 1 | GLAUCOPHANE | 28 |
| ACTINOLITE | 36 | GYPSUM | 7,29 |
| ANATASE | 18,26 | HORNBLENDE | 40 |
| ANDALUSITE | 12,28 | HYPERSTHENE | 28 |
| ANTHOPHYLLITE | 19,27 | KYANITE | 32,36,40 |
| APATITE | 10,16,26 | LABRADORITE | 31 |
| ARAGONITE | 12 | MICROCLINE | 8,30,36 |
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| GARNET | 3,6,9,17 | | |

TABLE 20—*Continued*

| GROUP | MINERAL | SYSTEM | HABIT | CLEAVAGE | COLOR | ORIENTATION | MEAN INDEX | MAX. BIREFR. | ELONGATION | PLEOCHROISM | INT. FIGURE | DISPERSION | 2V | SPECIAL CHARACTERS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ACIDIC GLASS | A | Irreg. frag. | None | | | 1.5 | | | | | | | Conch. fract. Gas inclus. |
| | FLUORITE | I | Trianq. or Oct. Plates | 111 P | May be blotchy | | 1.4 | | | | | | | Rounded grains rare. |
| | OPAL | A | | None | | | 1.4 | | | | | | | Conch. fract. Anom. Polariz. common. |
| 2 | FLUORITE | I | Trianq. or Oct. Plates | 111 P | C.M, Gr, Bl, Br, or Blotchy | | 1.4 | | | | | | | Rounded grains rare |
| | OPAL | A | | None | Var | | 1.4 | | | | | | | Conch fract. |
| 3 | BASIC GLASS | A | Irreg. frag. | None | | | | | | | | | | Rare |
| | GARNET | I | Fract. Grs. | 110 I | | | 1.7 | | | | | | | Inclus. common. Fract. Sub. conch. |
| | SPINEL | I | | 111 I | | | 1.7 | | | | | | | Usually well rounded grs.; pitted Conch fract. |
| | DIAMOND | I | | 111 P | | | 2.4 | | | | | | | Rounded faceted grs. |
| 4 | GARNET | I | Fract Grs | 110 I | Pk, R, Br, Gr, grc. | | 1.7 | | | | | | | Inclus common, Fract sub-conch |
| | SPINEL | I | | 111 I | R, Or, gr | | 1.7 | | | | | | | Usually well rounded grs.; pitted Conch fract |
| | DIAMOND | I | | 111 P | Y, NN, R, BC | | 2.4 | | | | | | | Rounded faceted grs. |
| 5 | CHALCEDONY | O | Grs | None | | | 1.5 | L | − | | | | 10 to 40 | Aggregate polarization Sometimes nearly uniaxial |
| | OPAL | A | | None. | | | 1.4 | VL | | | | | | Anom Polariz. |
| 6 | | | | | | | | | | | | | | |
| 7 | CHALCEDONY | O | Grs | None | | | 1.5 | L | − | | | | 10 to 40 | Aggregate polarization |
| | GYPSUM | M | Rdd Xls plates | 010 G 100 G | | β = b | 1.5 | L | | | I | V dbt | 58 | |
| 8 | ORTHOCLASE | M | Laths & Irreg. Grs. | 010 G 001 P | | β or γ = b | 1.5 | L | ± | | | p wk | 0 to 70 | Sometimes Carlsbad Tw. Often turbid; 001 plates give ⊥ Ext. |
| | MICROCLINE | Tr | Irreg. Grs. | 010 I 001 G | | | 1.5 | L | | | | p wk | 83 | 001 plates show grating struct. |
| | | | | | | | | | | | | | | |
| 9 | GARNET | I | Fract. grs. | 110 I | | | 1.7 | VL | | | | | | Anom. Polariz. Fract. sub-conch |
| | QUARTZ | H | Irreg or Rd. grs. | None | | | 1.5 | L | | | I | | | Extinction commonly undulatory Inclusions common, but never turbid Conch. fract. Anom. biax. |
| | ZIRCON | Te | Rd. grs. or Shaggy Xls | 001 I | | | 1.9 | H | + | | I | | | Inclusions common Sometimes anom. biax. |
| | CASSITERITE | Te | Rd. grs. | 100 I | | | 2.0 | H | + | | | | | Sometimes Polysyn Tw. or Knee Tw. " anom. biax |
| | | | | | | | | | | | | | | |
| 10 | CORUNDUM | H | Plates & Irreg Grs. | 0001 part | | | 1.8 | L | + | | | | | Sometimes pseudo-biax fig. |
| | APATITE | H | Rdd along prisms. | 0001 I | | | 1.6 | VL | − | | I | | | Sometimes with small inclusions ⊥ c |
| | CALCITE | H | Rhombs Grs | 1011 P 0112 part | | | 1.5 1.7 | HH | | | I | | | Usually has twin. strie ∥ major diag (1011) Thinkling. Acid soluble |
| | VESUVIANITE | Te | | 110 I | | | 1.7 | VL | F | | | | | |
| | BERYL | H | Laths | 0001 I | | | 1.6 | L | + | | | | | Often striated vertically |
| 11 | BROOKITE | O | Irreg grs. | 110 I | | γ = a | 2.7 | HH | F | | C | p str | 0 to 30 | Biaxial uniax. fig. for dark H. |
| | ENSTATITE | O | Laths & Grs | 110 G | | δ = c β = b | 1.7 | L | + | | | V wk | 30 | An ortho. pyroxene, may have jagged fract. |
| | TOPAZ | O | Irreg. grs. | 001 P | | α = a γ = c | 1.6 | L | + | | C | p dst | 49 to 66 | Prs. seen give ⊥ Ext. Inclus mostly fluid |
| | BARITE | O | Laths & O Plates | 001 P 110 P | | α = c γ = a | 1.6 | L | + | | I | V wk | 37 | O plates give Bx$_o$, Rarely found |
| 12 | ANDALUSITE | O | Irreg. or Prs. grs. | 110 G 100 P | | β = a α = c | 1.6 | L | − | | | | 85 | Often turbid or with elong. inclus. |
| | OLIGOCLASE | Tr | Laths & Irreg. grs. | 001 P 010 G | | α : 010 = 1° | 1.5 | L | | | | p wk | 86 | Often turbid Polysyn tw. |
| | EPIDOTE | M | Irreg. gr. | 001 G 100 I | | β = b α ^ c = 3° | 1.7 | H | ± | | Rc | p wk | 74 to 90 | Very transp. grs. |
| | ARAGONITE | O | Elong. or Acic. | 010 I. | | α = c γ = b | 1.5 1.7 | HH | | | | V wk | 18 | Acid soluble |
| | BERYL | H | Laths | 0001 I | | | 1.6 | L | | | | | | Often striated vertically |
| | | | | | | | | | | | | | | |

TABLE 20—*Continued*

| GROUP | MINERAL | SYSTEM | HABIT | CLEAVAGE | COLOR | ORIENTATION | MEAN INDEX | MAX. BIREFR. | ELONGATION | PLEOCHROISM | INT. FIGURE | DISPERSION | 2V | SPECIAL CHARACTERS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 13 | CHALCEDONY | O | Gel | None | Bl, R, Br, Var | | 1.5 | L | – | | | | 10 to 40 | Aggregate polarization. Sometimes nearly uniax. |
| | OPAL | A | Gel | None | Wh, Y, Br, Var | | 1.4 | VL | | | | | | Anom. Polariz. |
| | | | | | | | | | | | | | | |
| 14 | CALCITE | H | Rhombs, Grs | 1011 P 0112 part. | Wh, Y, R, or Br. | | 1.5 1.7 | VH | | | I | | | Usually has twin. striae if maj. diag (1011) Thinkling Acid soluble. |
| | | | | | | | | | | | | | | |
| 15 | QUARTZ | H | Irreg. or Rd grs. | None | Wh, Pr, Y, Br. | | 1.5 | L | | | | | | Extinction commonly undulatory Anom. Biax.; Conch. fract. Incluss common, but never turbid |
| | | | | | | | | | | | | | | |
| 16 | | | | | | | | | | | | | | |
| 17 | GARNET | I | Fract. grs | 110 I | Pk, R, Br, Gr, etc. | | 1.7 | VL | | | | | | Anom. Polariz. Fract sub-conch |
| | QUARTZ | H | Irreg or Rd grs. | None | Wh, Pr, Y, Br. | | 1.5 | L | | | | | | Extinction commonly undulatory Conchoidal fract. Inclus common, but never turbid. |
| | CASSITERITE | Te | Rd. grs. | 100 I | Br, Blk, Y, w Hand | | 2.0 | H | + | | | | | Often polysyn tw or knee tw. |
| | ZIRCON | Te | Rd grs. or shrimpy xls | 001 I | R-Br, Gr. | | 1.9 | H | + | | I | | | Inclusions common, conch fract |
| | RUTILE | Te | Prisms or Acy. grs. | 110 G 100 G | R, R-Br, Y | | 2.6 2.9 | VH | + | None, if it colored | | | | Knee twins common (63° angle) |
| | XENOTIME | Te | Pr. Rd grs. | 110 P | Br, Br-R, Y, Transl. | | 1.7 1.8 | H | + | | | | | |
| | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| 18 | ANATASE | Te | Bipr Tbls Bipyr | 001 P 111 P | Y, Br, Blk, Indigo | | 2.5 | H | | | C | | | Octahedrite. |
| | APATITE | H | Rdd Elong prisms | 0001 I | Wh, Gr, Br. | | 1.6 | VL | – | | I | | | Often with minute incls. if C |
| | CALCITE | H | Rhombs, Grs | 1011 P 0112 part. | Wh, Y, R, Br, | | 1.5 1.7 | VH | | | I | | | Usually has twin. striae if maj. diag (1011) Thinkling Acid soluble. |
| | BERYL | H | Laths | 0001 I | Bl, Gr, Y, | | 1.6 | L | | | | | | Often striated vertically. |
| | VESUVIANITE | Te | | 110 I | Var. | | 1.7 | VL | F | | | | | |
| | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| 19 | BRONZITE | O | Laths & Grs | 110 G | Y, R-Br | $\beta = c$ $\gamma = b$ | 1.7 | L | + | weak | | V wk | L | An orthorhombic pyroxene. |
| | SILLIMANITE | O | Thin prisms Fbrl grs | 010 G | Br, Gr, Gy | $\alpha = b$ $\beta = c$ | 1.6 | H | + | | | p. sh. | 20 to 30 | |
| | ANTHOPHYLLITE | O | Laths | 110 P 010 G | Gy, Br, Gr | $\alpha = a$ $\beta = c$ | 1.6 | H | + | | | V | 80 ± | An amphibole |
| | MONAZITE | M | Rd. grs. | 001 P 100 G | Y, Y-Br, R | $\alpha = b$ $\beta \wedge C = 2°$ | 1.8 | H | – | | | V wk | M. | Brown blotches common |
| | BROOKITE | O | Irreg. gr. & Flakes | 110 I | Br, Y | $\beta = a$ | 2.7 | VH | F | | C | p. sh | 0 to 30 | Pseud-uniax fig for Gr-Y lt |
| | BARITE | O | Laths & O flakes | 001 P 110 P | | $\alpha = c$ $\beta = a$ | 1.6 | L | + | | I | V wk | 37 | O flakes give Bxa; Rarely found |
| | TOPAZ | O | Irreg grs | 001 P | Y, Bl, R, Gr. | $\alpha = a$ $\beta = c$ | 1.6 | L | + | | C | p. distk | 49 to 66 | Inclus mostly fluid Never turbid Grs often have irregular edges |
| | | | | | | | | | | | | | | |
| 20 | BERYL | H | Laths | 0001 I | Bl, Gr, Y. | | 1.6 | L | | | | | | Often striated vertically |
| | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| 21 | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| 22 | | | | | | | | | | | | | | |
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| | | | | | | | | | | | | | | |

TABLE 20—*Continued*

| GROUP | MINERAL | SYSTEM | HABIT | CLEAVAGE | COLOR | ORIENTATION | MEAN INDEX | MAX BIREF. | ELONGATION | PLEOCHROISM | INT. FIGURE | DISPERSION | 2V | SPECIAL CHARACTERS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 23 | | | | | | | | | | | | | | |
| 24 | CORDIERITE | O | Gr | 010 G | Bl, P-Gl | $\alpha = c$ $\beta = b$ | 15 | L | − | $\alpha$ = Y Weak C $\beta$ - V, $\gamma$ = C | | V wk | 40 ± | Rare in sediments, alters to Pinite |
| 25 | RUTILE | Tc | Prisms or elong grs | 110 G 100 G | R, R-Br, | | 26 29 | VH | + | Weak, Lt Br | | | | Knee tw common (65° angle) |
| 26 | TOURMALINE | H | Laths, Anh & Rd grs | None | Br, Bl, Gr, Y | $\alpha = c$ | 16 | H | − | Very strong O > E | I | | | Never turbid, vertical striae common. |
| | CORUNDUM | H | Rd grs | 0001 part | Bl, R, Br Basally | | 18 | L | + | O > E | | | | Sometimes pseudo-biax. |
| | ANATASE | Tc | Rect Tab, Bipyr | 001 P 111 P | Y, Br, Bl, Indigo | | 25 | H | | Weak O = Bl, Y E = Dk Bl, Or | C | | | Octahedrite |
| | APATITE | H | Rdd, elong prisms | 0001 I | Bl, Gr | | 16 | VL | − | Weak | I | | | Sometimes with small inclus of C |
| 27 | SILLIMANITE | O | Thin pris Flat grs | 010 G | Bl, Gr | $\alpha = b$ $\beta = c$ | 16 | H | + | Weak Dk to lt | | p sh | 20 33 | Pleoc. only in darkly col var. |
| | STAUROLITE | O | Platy grs | 010 G | R-Br, Br | $\alpha = b$ $\beta = c$ | 17 | L | + | Weak Br to Y | | p wk | 88 ± | Cruciform tw common |
| | ENSTATITE | O | Laths & grs | 110 G | Gr | $\gamma = c$ $\beta = b$ | 17 | L | + | Weak $\alpha$=Y, $\beta$=Gr $\gamma$ = Bl | | V wk | 30 | An orthorhombic pyroxene |
| | BRONZITE | O | Laths & grs | 110 G | Y, R-Br | $\gamma = b$ $\alpha = c$ | 17 | L | + | Weak | | V wk | L | An orthorhombic pyroxene |
| | BROOKITE | O | Irreg grs | 110 I | Br, Y | $\gamma = a$ | 27 | VH | F | Very weak | C | p Str | 0 30 | Pseudo-uniax. f/g for Gr-Y Lt |
| | TITANITE | M | Rd & flat grs | 110 G | Br, Br-Y | $\beta = b$ | 19 20 | VH | | Weak, DK-Lt $\alpha$ = lt | I | p sh | 27 ± | |
| | ANTHOPHYLLITE | O | Laths | 110 P 010 G | Br, Gr | $\alpha = c$ $\gamma = c$ | 16 | H | + | Weak $\alpha$ = lt | | Y | 90 ± | An amphibole |
| 28 | ANDALUSITE | O | Irreg or pris grs | 110 G 100 I | Pk, Gr, Br, Y, | $\gamma = a$ $\alpha = c$ | 16 | L | − | Str to wk $\alpha$ = C $\beta$ & $\gamma$ = Gr or C | | | 85 | Often turbid or with dark inclus |
| | HYPERSTHENE | O | Laths or rd grs | 110 G 100 I | Br-Gr Gy, Gr | $\alpha = a$ $\gamma = c$ | 17 | L | + | Strong $\alpha$ = R, $\beta$ = Y $\gamma$ = Gr | | | | An orthorhom pyroxene; inclus common Grs often hdre, jagged ends |
| | GLAUCOPHANE | M | Rd or Irreg pris. gr | 110 G | Bl, Bl-Vl | $\beta = b$ | 16 | H | + | Strong $\alpha$ = Y to C $\beta$ = V; $\gamma$ = Bl | | V Str | 45 ± | An amphibole |
| | EPIDOTE | M | Irreg gr | 001 G 100 I | Gr-Y, Gr, Br | $\beta = b$ $\alpha \wedge C = 3°$ | 17 | H | L | Weak $\alpha$ = C, $\gamma$ = Gr-Y | Ax | p wk | 74 92 | Very transp grs |
| | BASALTIC HORNB | M | Laths or Irreg grs | 110 P at 124° | Br, R-Br | $\beta = b$ $\gamma \wedge C$ = 1-10° | 17 | H | + | Strong $\alpha$ = R-Br $\beta, \gamma$ = Br or Gr | | Y | 90 | An amphibole |
| 29 | PLAGIOCLASE | Tr | Laths or plates | 001 P 010 I | | | 15 & 16 | L | | | I | | 70 90 | Polysyn tw common |
| | GYPSUM | M | Rdd Xls Plates | 010 G 100 G | | $\beta = b$ $\gamma \wedge C$ = 52° | 15 | L | | | I | V dif | 58 | |
| 30 | MICROCLINE | Tr | Irreg grs | 010 I 001 G | | Ext on 001 13 Ext on 010 5° | 15 | L | | | I | p wk | 83 | 001 plates show grating struct |
| | PLAGIOCLASE | Tr | Laths or plates | 001 P 010 I | | | 15 16 | L | | | I | | 70 90 | Polysyn tw common |
| | ORTHOCLASE | M | Laths & Irreg grs | 010 G 001 P | | $\beta = b$ $\gamma \wedge a$ = 5° | 15 | L | | | I | | 0 70 | Sometimes Carlsbad tw Often turbid |
| | BIOTITE | M | Flakes, ragged edges | 001 P | | $\beta = b$ $\alpha \wedge C$ = 3°± | 15 | H | | | C | V wk | 0 90 | Hex flakes sometimes noted |
| 31 | LABRADORITE | Tr | Laths & grs | 001 P 010 P | | | 16 | L | | | I | V wk | 79 | Always polysyn tw |
| | AUGITE | M | Laths or Irreg grs | 110 P at 90° | | $\beta = b$ $\gamma \wedge C$ = 38°-58° | 17 | H | | | I | P dif | 60 | Laths commonly have jagged ends A pyroxene |
| | TITANITE | M | Rd & flat grs | 110 G | | $\beta = b$ $\gamma \wedge C$ = 31° | 19 20 | VH | | | C | p sh | 27 ± | |
| | MONAZITE | M | Rd grs | 001 P 100 G | | $\alpha = b$ $\gamma \wedge C$ = 2° | 18 | H | − | | C | V wk | 16 | |
| | SPODUMENE | M | Laths & grs | 110 P at 88° | | $\beta = b$ $\gamma \wedge C$ = 24° | 17 | L | | May show dissolution | | V | 58 ± | A pyroxene |

TABLE 20 – Concluded

| GROUP | MINERAL | SYSTEM | HABIT | CLEAVAGE | COLOR | ORIENTATION | MEAN INDEX | SIGN OF ELONGATION | ELONGATION | PLEOCHROISM | INT. FIGURE | DISPERSION | 2V | SPECIAL CHARACTERS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 | KYANITE | Tr | Elong grs | 110 P<br>010 G | | α ⊥ 110<br>Ext on 100<br>∧AC = 30° | 17 | L | + | | Bxa | p wk | 82 | |
| | MUSCOVITE | M | Thin flakes | 001 P | | b = b<br>αAC = 0°± | 16 | H | | | C | p wk | 40 ± | Undulatory Ext common<br>Inclusions common |
| | EPIDOTE | M | Irreg grs | 001 G<br>100 I | | B = b<br>αAC = 3° | 17 | H | ± | | Ax | p wk | 74<br>92 | Very transp grs |
| | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| 33 | | | | | | | | | | | | | | |
| 34 | BIOTITE | M | Flakes<br>zonal infl | 001 P | Br, Gr-Br | B = b<br>αAC = 3°± | 15 | H | | None ⊥ 001 | C | v wk | 0<br>50 | Hex flakes sometimes noted |
| | MICROCLINE | Tr | Platy grs | 010 I<br>001 G | Gr, Y, R | Ext on 001 15°<br>Ext on 010 3° | 15 | L | | | I | p wk | 83 | 001 plates show grating struct |
| | | | | | | | | | | | | | | |
| 35 | AUGITE | M | Laths or<br>irreg grs | 110 P<br>at 90° | Gr, Br-Gr | B = b<br>∧AC 38°-54° | 17 | H | | | I | p dif | 60 | Laths commonly have jagged ends<br>A pyroxene |
| | CHLORITE | M | Flakes | 001 P | Gr | αAC = 0°± | 16 | L | | | | p wk | 0°<br>± | May show abnor Bl int col without ext |
| | MONAZITE | M | Rd grs | 001 P<br>100 G | Y, Y-Br | α = b<br>∧AC = 2° | 18 | H | - | | C | v wk | 14 | |
| | TITANITE | M | Rd & flat grs | 110 G | Br, Br-Y | B = b<br>∧AC = 51° | 19<br>20 | VH | | | C | p Str | 27 ± | |
| | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| 36 | CHLORITE | M | Flakes | 001 P | Gr | αAC = 0°± | 16 | L | | | | p wk | 0°<br>± | May show abnor Bl int col without ext |
| | EPIDOTE | M | Irreg grs | 001 G<br>100 I | Gr, Y-Gr<br>Br-Y | B = b<br>αAC = 3° | 17 | H | ± | Weak | Ax | p wk | 74<br>92 | Very transp grs |
| | KYANITE | Tr | Elong grs | 110 P<br>010 G | Bl-Gr<br>Bl | α ⊥ 110<br>Ext on 100<br>∧AC = 30° | 17 | L | + | Weak | Bxa | p wk | 82 | |
| | MUSCOVITE | M | Thin flakes | 001 P | Y if thick | b = b<br>αAC = 0°± | 16 | H | | | C | p wk | 40 ± | Undulatory ext & inclus common |
| | ACTINOLITE | M | Laths &<br>grs | 110 P<br>at 124° | Gr | B = b<br>∧AC = 15° | 16 | H | + | Weak | | v wk | 78 | An amphibole much like Hornblende |
| | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| 37 | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| 38 | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| 39 | CHLORITE | M | Flakes | 001 P | Gr | αAC = 0°± | 16 | L | | In thick flakes<br>α = C<br>Bβ = Gr | | p wk | 0°<br>± | May show abnor Bl int col without ext |
| | MONAZITE | M | Rd grs | 001 P<br>100 G | Y, Y-Br<br>R | α = b<br>∧AC = 2° | 18 | H | - | Weak<br>α = b Y, Br-BRY<br>β = Gr-Y | C | v wk | 14 | |
| | TITANITE | M | Rd & flat grs | 110 G | Br, Br-Y | B = b<br>∧AC = 51° | 19<br>20 | VH | | Weak<br>α = C, β = Y-Gr<br>γ = Y, R or PK | C | p Str | 27 ± | |
| | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| 40 | CHLORITE | M | Flakes | 001 P | Gr | αAC = 0°± | 16 | L | | In thick flakes<br>α = C<br>Bβ = Gr | | p wk | 0°<br>± | May show abnor Bl int col without ext |
| | EPIDOTE | M | Irreg grs | 001 G<br>100 I | Gr, Y-Gr<br>Br-Y | B = b<br>αAC = 3° | 17 | H | ± | Weak<br>α = C, β = C<br>β = pale Br-Y | Ax | p wk | 74<br>92 | Very transp grs |
| | HORNBLENDE | M | Laths or<br>irreg grs | 110 P<br>at 124° | Gr, Br, Bl | B = b<br>∧AC = 15°-25° | 16 | L | + | α < β < γ | | v wk | 84<br>± | Ext angle usually 10° to 15°<br>An amphibole |
| | KYANITE | Tr | Elong grs | 110 P<br>010 G | Bl-Gr<br>Bl | α ⊥ 110<br>Ext on 100<br>∧AC = 30° | 17 | L | + | Weak<br>α = C, β = Li-Bl<br>γ = Bl | Bxa | p wk | 82 | |
| | | | | | | | | | | | | | | |
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