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4

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DEVELOPMENTS IN SEDIMENTOLOGY 4

THE TECHNIQUES OF SEDIMENTARY MINERALOGY

BY

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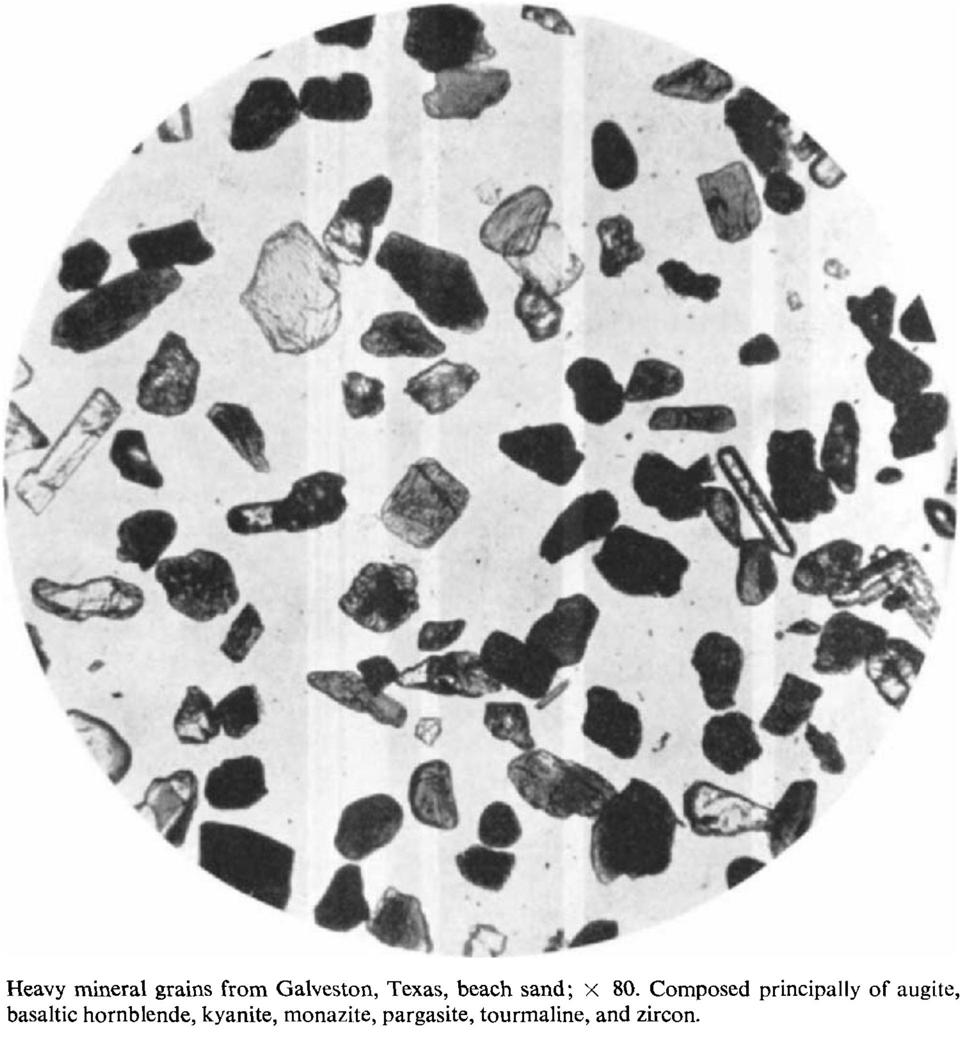

Heavy mineral grains from Galveston, Texas, beach sand; × 80. Composed principally of augite, basaltic hornblende, kyanite, monazite, pargasite, tourmaline, and zircon.

PREFACE

This book is concerned with the procedures that serve to describe or evaluate the various kinds of sedimentary material for those interested or engaged in a technical field requiring such information. It may be regarded as a handbook rather than a treatise on the subjects covered.

The exposition of the methods of optical mineralogy, however, is complete enough to permit one who is not acquainted with the techniques to gain facility with the method for the identification of minerals in fragments.

Some other techniques, such as the X-ray powder method for the identification of minerals and other crystallized substances, are discussed in considerable detail.

The description of minerals includes practically all that have been found in sediments, and the identification tables and crystal drawings include one hundred minerals.

For the crystal drawings the author wishes gratefully to acknowledge his debt to the late Dr. W. E. Tröger, Professor of Mineralogy and Sedimentary Petrology at the University of Freiberg, for his kind permission to reproduce many of the crystal drawings from his book, *Optische Bestimmung der gesteinsbildenden Minerale* (1959).

Grateful acknowledgment is also made to Dr. C. Osborne Hutton, Professor of Mineralogy at Stanford University, for his kind help and advice on the sections dealing with mineralogy.

Stanford University
October 1964

F. G. Tickell

CONTENTS

Chapter 1

INTRODUCTION

The 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; (*18*) clays.

The attributes of these materials that may, for one purpose or another, be examined are: (*a*) state of aggregation; (*b*) grain-size distribution; (*c*) grain shape; (*d*) density; (*e*) porosity; (*f*) permeability; (*g*) mineral content; (*h*) chemical composition.

Some sedimentary rocks are referred to as *fragmental* in that they consist of fragments of minerals or of previously existing rocks. The specific name of such a rock usually suggests the origin. Tuff, for example, is of igneous and volcanic origin, and it is composed of fragments of mineral matter that may be sedimented from the air onto land or water. Diatomite is sedimentary and of organic origin, being composed of the siliceous frustules of diatoms.

The commonest kinds of fragmental rocks are the aqueous sediments, such as sand, silt, and clay, the individual particles of which have been derived, perhaps from a specific source or, more likely, from various sources. As examples, there are aeolian deposits such as loess, which is fragmental and wind-transported. There are also glacially deposited fragmental rocks, such as till and varved clay. Fault-breccias, too, are composed of fragments made by crustal disturbances.

A fragmental rock may be examined with various purposes in view, as to: (*1*) origin; (*2*) composition, chemical or mineralogical; (*3*) extent, areal or in depth; (*4*) the occurrence of valuable minerals or ores; (*5*) stratigraphic correlation; (*6*) suitability for a specific application.

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

TABLE I

MEGASCOPIC DETERMINATION OF SEDIMENTARY ROCKS

(After HUANG, 1962)[1]

	Usual texture	*Constituents: rock particles and minerals*	*Sedimentary rock*	*Diagnostic feature*
Clastics: rocks determined by size and shape of particles	Rudites 2–> 256 mm	One or mixed constituents, especially chert, quartz, granite, quartzite, limestone, etc.	Conglomerate	Particles mostly subrounded to rounded
			Breccia	Particles most angular
			Fanglomerate	Lithified piedmont debris or alluvial fan
		Any rock particles mixed with mineral flour	Tillite	Rock particles striated, practically unsorted
	Arenites 1/16–2 mm	Chiefly quartz	Quartzose sandstone or arenite	Well-sorted, mature, and clean sands
		> 25 % feldspar Potassium feldspar or plagioclase	Arkose	Red to light gray, poorly sorted, immature
		10–25 % feldspar	Feldspathic sandstone	More mature than arkose
		Rock chips of basalt, slate, rhyolite, shale, etc., feldspar, micas, sericite, chlorite, iron ores	Graywacke	Strongly indurated, tough, dark to greenish gray, microbreccia
			Subgraywacke	Intermediate between quartzose sandstone and graywacke

	Lutites 1/16–1/256 mm	Chiefly clay minerals: aphanitic quartz, opal, chalcedony, carbonates, pyrite, chlorite, iron ores	Siltstone	Intermediate between sandstone and shale
			Shale	Characteristically fissile
			Mudstone	Nonplastic
			Claystone	Plastic when wet
Nonclastics: rocks determined by chemical or mineralogical composition	Dense, aphanitic coarse-grained, crystalline, porous, mosaic, oölitic	Chiefly calcite	Limestone	Readily react to cold HCl, limestones may be organic, bioclastic, cherty, argillaceous, chalky
		Chiefly dolomite	Dolomite	Not readily react to cold HCl, fossils rarely present, tend to be medium-grained
	Fine-grained	Finely crystalline calcite with tests of micro-organism	Chalk	White to light gray, very friable, fossiliferous
		Calcareous matter and clay minerals	Marl	Light gray, friable
	Dense, layered	Mixture of colloidal silica, opal, chalcedony, etc.	Chert	Variegated, hard, dull to semivitreous luster, conchoidal fracture
	Crystalline or massive	Chiefly gypsum Chiefly anhydrite Chiefly halite	Rock gypsum Rock anhydrite Rock sale	Evaporites are often associated in the field, crystal aggregates common
	Massive or bedded	Phosphate minerals and bone fragments	Phosphorite	Chemical test for P_2O_5 necessary
	Amorphous, layered, banded	Humus, Sapropel, Carbon, Moisture	Coals: Lignite	Brown color
			Bituminous	Prismatic fracture
			Anthracite	Conchoidal fracture

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[1] By permission of McGraw-Hill Book Co., Inc., New York, N.Y.

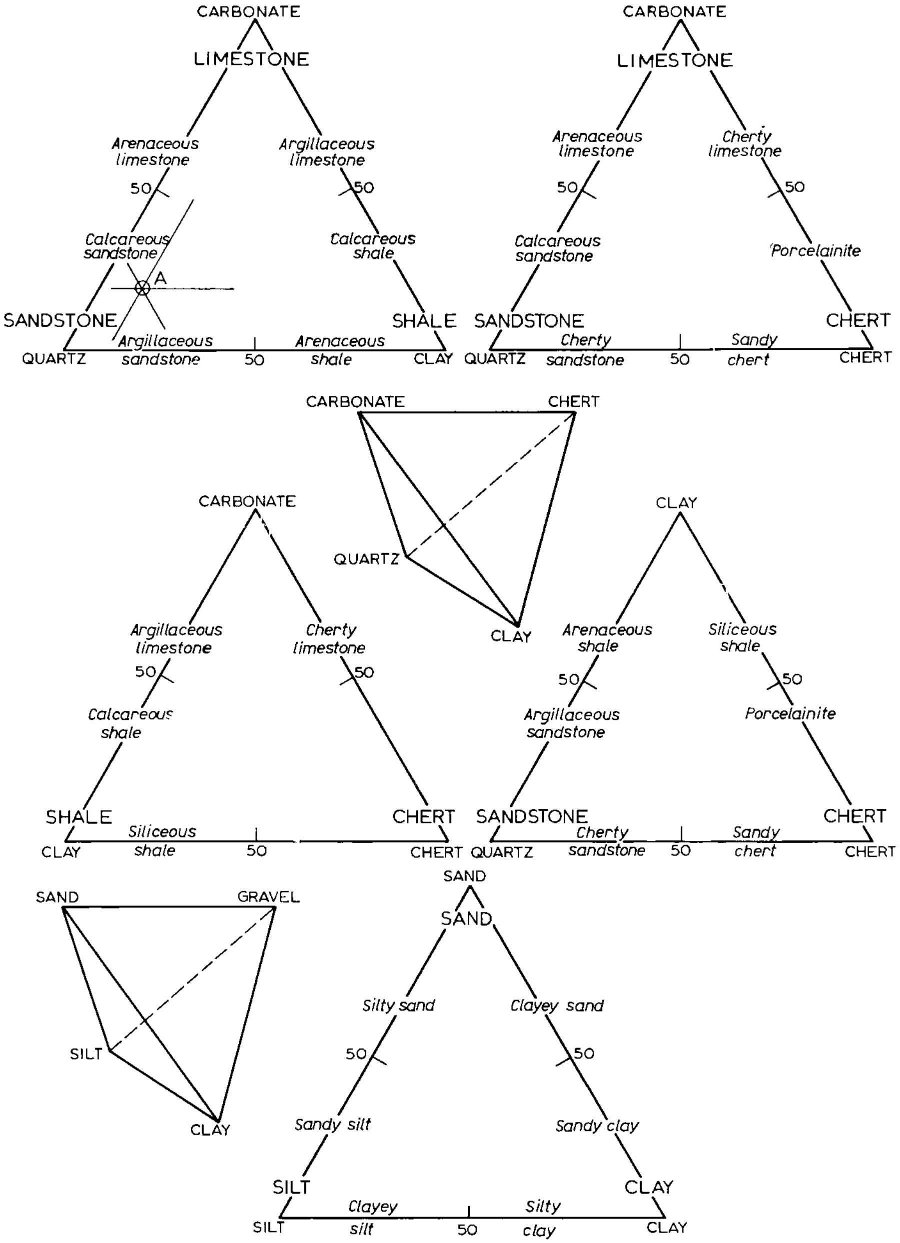

Fig. 1. Tetrahedral representation of the common sedimentary families and textures.

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 mining geologist, in the search for hidden ore deposits, may resort to geochemical prospecting methods for the detection of certain "tracer" elements commonly associated with ore bodies. For this purpose, stream waters are tested or, in the case of dry stream-beds, the sediments may respond to micro-chemical or colorimetric tests that will indicate anomalies of tracer-metals several miles from a mineral deposit. Spectrographic procedures have also been applied for such studies (CRUFT, 1964).

Exploitation of sediments of the sea bed is being carried out in various localities (MERO, 1964). Magnetite sands off the coast of Japan are being dredged from depths of 90 ft.; diamonds are being recovered from sediments off the western coast of South Africa; glauconite and phosphorite are being produced off the coast of California, and manganese nodules are being recovered at various localities.

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.

Table I gives criteria for the description or identification of sedimentary rocks. The clastic rocks (aggregates of broken particles) are classified as *rudites* of mixed constituents, as *arenites* of sandy composition, and as *lutites* of clayey composition. The non-clastic rocks are classified according to their texture and mineral or chemical composition.

Fig.1 shows the two fundamental tetrahedra, according to composition and texture, and some of their plane sides. If, for example, a rock is composed of quartz 70%, carbonate 20%, and clay 10%, these percentages would be plotted from their respective bases, and intersection of the lines would determine the point A.

In the case where there are four constituents, the point would lie within the tetrahedron (KRUMBEIN and SLOSS, 1963).

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Chapter 2

SIZE ANALYSIS

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 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 having 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 H. GREEN (1921) 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 diameters 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:

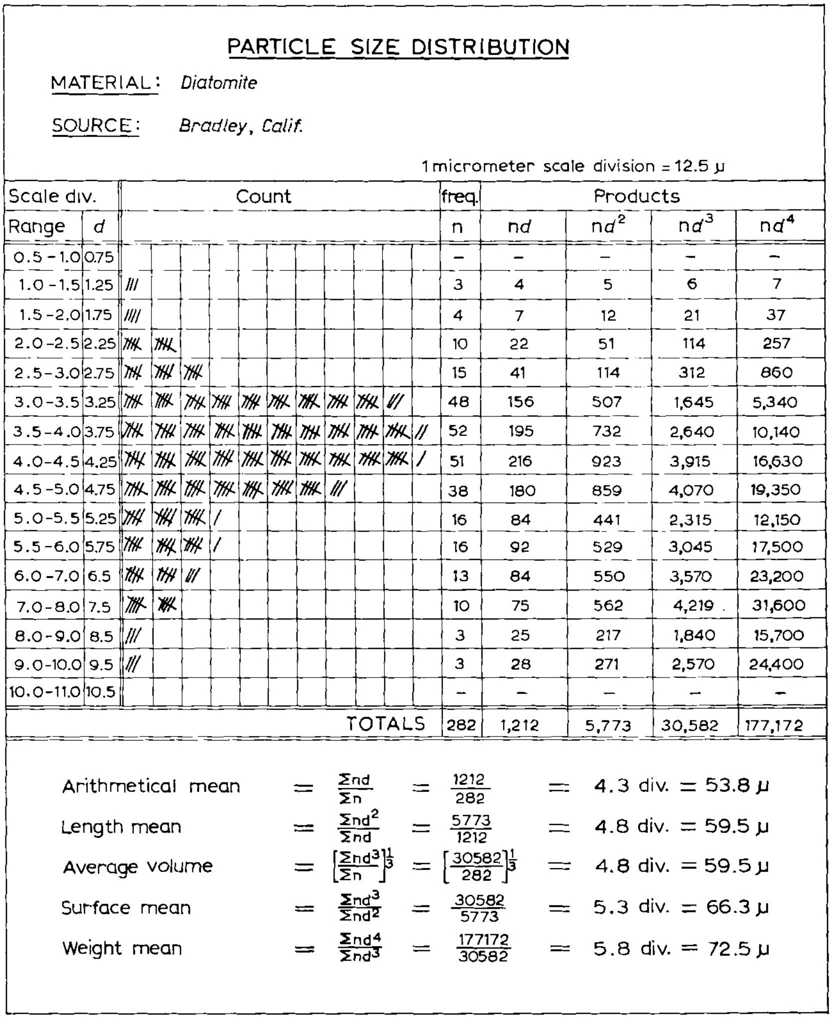
$$d = \frac{3lbt}{lb + lt + bt}$$

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

$$d = \sqrt{l \cdot b}$$

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 (1923) and by WEIGEL (1924). 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.



PARTICLE SIZE DISTRIBUTION

MATERIAL: *Diatomite*

SOURCE: *Bradley, Calif.*

1 micrometer scale division = 12.5 μ

Scale div.		Count	freq.	Products			
Range	*d*		n	n*d*	n*d*^{2}	n*d*^{3}	n*d*^{4}
0.5 - 1.0	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	𝍸 𝍸	10	22	51	114	257
2.5 - 3.0	2.75	𝍸 𝍸 𝍸	15	41	114	312	860
3.0 - 3.5	3.25	𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 ///	48	156	507	1,645	5,340
3.5 - 4.0	3.75	𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 //	52	195	732	2,640	10,140
4.0 - 4.5	4.25	𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 /	51	216	923	3,915	16,630
4.5 - 5.0	4.75	𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 ///	38	180	859	4,070	19,350
5.0 - 5.5	5.25	𝍸 𝍸 𝍸 /	16	84	441	2,315	12,150
5.5 - 6.0	5.75	𝍸 𝍸 𝍸 /	16	92	529	3,045	17,500
6.0 - 7.0	6.5	𝍸 𝍸 ///	13	84	550	3,570	23,200
7.0 - 8.0	7.5	𝍸 𝍸	10	75	562	4,219	31,600
8.0 - 9.0	8.5	///	3	25	217	1,840	15,700
9.0 - 10.0	9.5	///	3	28	271	2,570	24,400
10.0 - 11.0	10.5		–	–	–	–	–
		TOTALS	282	1,212	5,773	30,582	177,172

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

Length mean $= \frac{\Sigma nd^2}{\Sigma nd} = \frac{5773}{1212} = 4.8$ div. $= 59.5\ \mu$

Average volume $= \left[\frac{\Sigma nd^3}{\Sigma n}\right]^{\frac{1}{3}} = \left[\frac{30582}{282}\right]^{\frac{1}{3}} = 4.8$ div. $= 59.5\ \mu$

Surface mean $= \frac{\Sigma nd^3}{\Sigma nd^2} = \frac{30582}{5773} = 5.3$ div. $= 66.3\ \mu$

Weight mean $= \frac{\Sigma nd^4}{\Sigma nd^3} = \frac{177172}{30582} = 5.8$ div. $= 72.5\ \mu$

Fig.2. Log and computation sheet for particle size determination with the microscope.

The particle-size record is made on some such form as is shown in Fig.2, 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 in the section "Characterization of curves" of this chapter.

AVERAGES OF PARTICLE SIZES

In Fig.2, the average particle size is computed by five different formulas. 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.

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.

The *average volume mean* may be considered as that diameter whose corresponding volume divided into the total volume equals the total number 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.2, 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 by various methods. The roundness numbers shown in Fig.3 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 (1941) 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.

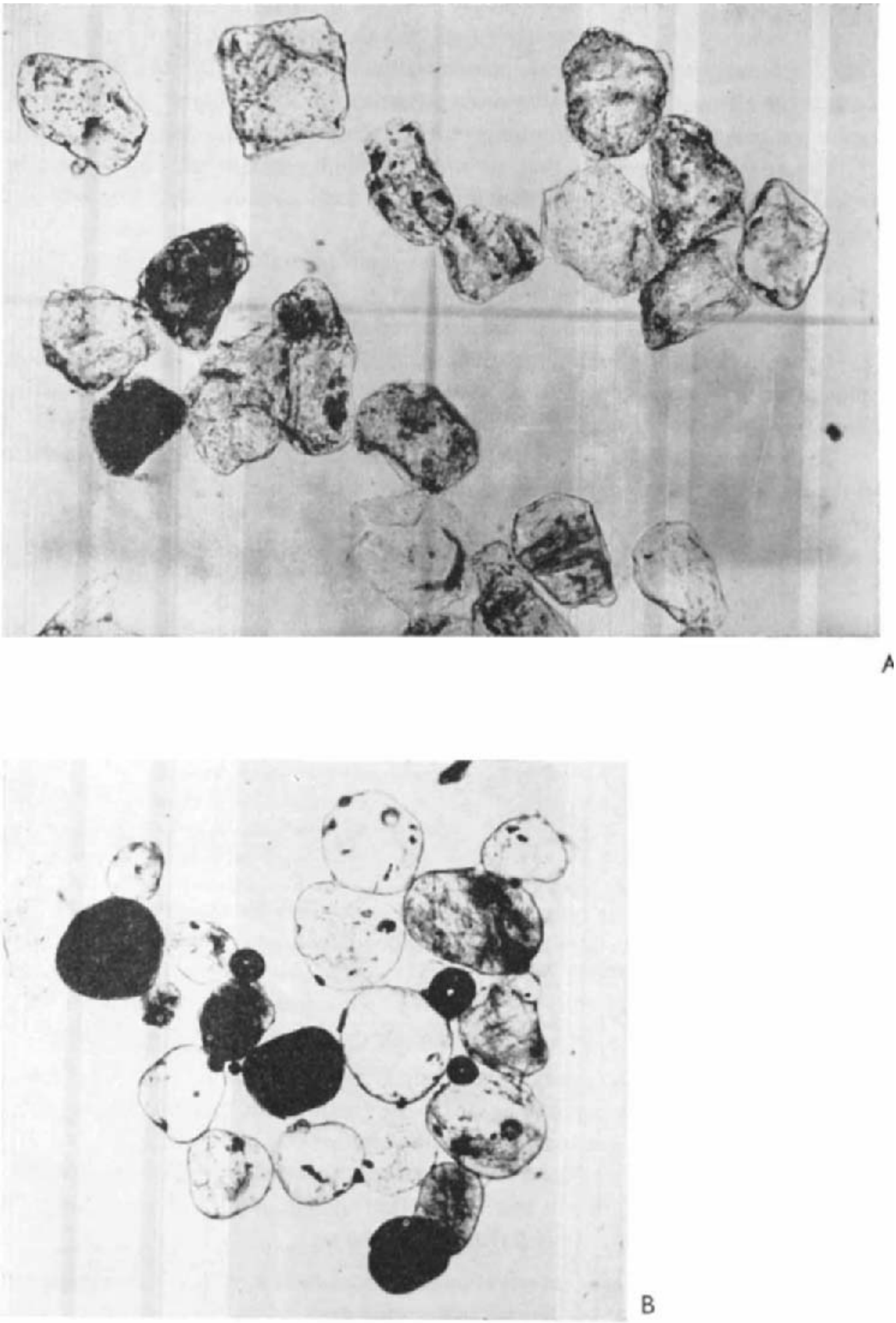


Fig.3. Roundness of grains. A. Average roundness number = 0.69, Galveston, Texas, beach sand; × 110. B. Average roundness number = 0.80, Whitehorse Sandstone, Oklahoma, × 35.

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 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.

SIZE DESCRIPTION OF MINERALS

For the description of sediments, the Wentworth scale (Table II) has gained rather wide adoption.

The United States Bureau of Soils has also defined the limits of grades as in Table III.

The standard sieves of American practice (Table IV) are based upon the 18-mesh sieve, with openings 1 mm in width and with a constant ratio between the successive sides of $\sqrt[4]{2}$.

TABLE II

THE WENTWORTH SCALE FOR GRADES OF SEDIMENTS

Sediment	*Size of particles (mm)*	
Boulder gravel	>256	
Cobble gravel	256–64	
Pebble gravel	64–4	
Granule gravel	4–2	
Very coarse sand	2–1	
Coarse sand	1–$^{1}/_{2}$	
Medium sand	$^{1}/_{2}$–$^{1}/_{4}$	(= 0.5–0.25)
Fine sand	$^{1}/_{4}$–$^{1}/_{8}$	(= 0.25–0.125)
Very fine sand	$^{1}/_{8}$–$^{1}/_{16}$	(= 0.125–0.0625)
Silt	$^{1}/_{16}$–$^{1}/_{256}$	(= 0.0625–0.0039)
Clay	$<{}^{1}/_{256}$	(= <0.0039)

The Wentworth grade-scale (Table II) was transformed by KRUMBEIN (1934a) to a scale that has integers for the class-limits and increases with decreasing grain

TABLE III

UNITED STATES BUREAU OF SOILS
SIZE CLASSIFICATION OF SOILS

Sediment	*Size of particles (mm)*
Pebbles	> 10
Gravel	10–1
coarse	10–2
fine	2–1
Sand	1–0.05
coarse	1–0.5
medium	0.5–0.25
fine	0.25–0.05
Silt	0.05–0.005
Clay	< 0.005

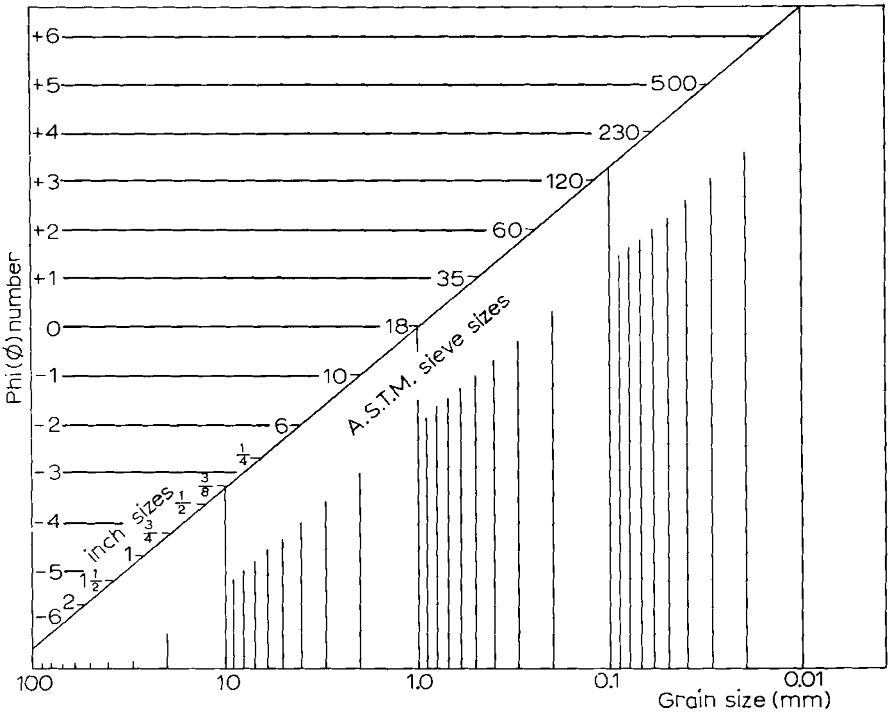


Fig.4. Grain size — Phi number conversion chart.

TABLE IV

AMERICAN STANDARD (A.S.T.M.) SIEVE SIZES

(After TYLER CO., 1963)

Mesh no.	*Aperture (mm)*	*Phi no. ϕ*
6	3.36	−2
7[1]	2.83	
8	2.38	
10[1]	2.00	−1
12	1.68	
14[1]	1.41	
16	1.19	
18[1]	1.00	0
20	0.84	
25[1]	0.71	
30	0.59	
35[1]	0.50	+1
40	0.42	
45[1]	0.35	
50	0.297	
60[1]	0.25	+2
70	0.21	
80[1]	0.177	
100	0.149	
120[1]	0.125	+3
140	0.105	
170[1]	0.088	
200	0.074	
230[1]	0.062	+4
270	0.053	
325[1]	0.044	
400	0.037	+5

[1] Mesh numbers conform to the I.S.O. series, proposed as an International Standard by the International Standards Organization.

size. This is a statistical device permitting direct application of conventional statistical practices to sedimentary data.

The result of this transformation is the phi (ϕ) scale in which: $\phi = -\log_2$ grain-diameter in millimeters.

Phi numbers corresponding to the standard sieve sizes are shown in Table IV, and Fig.4 also shows this relationship.

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 through sieves; (*2*) water classification. Employment of the latter method rests upon the assumption that all particles in the sample have the same density.

Sieve analysis

Mechanical analysis by means of sieves is a matter of everyday practice in ore dressing, cement testing, and other industrial operations. The sieves 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 sieves for the sizing of mineral grains if such is compatible with the requirements. It has been pointed out by GARDESCU and BILLINGS (1937) that the use of uncalibrated sieves may lead to erroneous results but, on the other hand, KRUMBEIN (1934a) found that the error of sampling is likely to be much greater than the error of testing.

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 V.

TABLE V

WENTWORTH SIEVE SCALE FOR GRADES OF SEDIMENTS

Sediment	*A.S.T.M.*	*Mesh no.*
Pebble gravel	+ 5	
Granule gravel	− 5	+ 10
Very coarse sand	− 10	+ 16
Coarse sand	− 16	+ 30
Medium sand	− 30	+ 60
Fine sand	− 60	+120
Very fine sand	−120	+230
Silt and clay	−230	+400

The separation into its constituents of the −400-mesh material is best accomplished by a method other than screening, such as air-elutriation, as described on page 22.

Liquid classification

Liquid 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:

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

where r = radius of settling particle (cm); μ = absolute viscosity (poise); h = distance settled (cm); t = time (seconds) for particle to fall h cm; Δ = density of falling particle (g/cm^3); δ = density of settling medium; g = acceleration due to gravity (980 cm/sec^2).

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/sec).

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

The viscosity of a liquid may be defined as the force per unit area necessary to maintain a unit velocity gradient between two parallel planes unit distance apart with liquid occupying the space between the planes. The unit of viscosity is the *poise*, although the *centipoise* is more commonly stated. The viscosity of water at 20.20 °C = 1 centipoise.

There are different methods of liquid classification: (*a*) elutriation; (*b*) undisturbed settling.

(*a*) In *elutriation* the principle of rising currents is applied in which, for a given water velocity the larger particles settle and the smaller ones are carried into the discharge.

(*b*) *Undisturbed settling* is accomplished 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.

The Andreasen pipette

Very widely used in liquid sizing is the Andreasen pipette, depicted in Fig.5. The graduated cylinder is about 6-cm inside diameter and has a capacity of about 550 ml. The ground-glass stopper has a small vent-hole to let in air while withdrawing samples, and carries a 10-ml pipette with a 3-way stop-cock. The stem of the pipette ends at the level of the zero-mark, so that the settling depth from the top of suspension to tip of pipette is read directly on the engraved scale. For work with very fine particles the instrument should be housed in a constant-temperature cabinet.

The powder sample is weighed (5.5 g for a 1% suspension), treated for dispersion, washed into the cylinder, and diluted to the 20-cm height. The exact volume to fill the cylinder to this height should be known, so that the initial concentration of the suspension can be calculated accurately. The apparatus is closed and inverted repeatedly with the air-vent closed by a finger, to insure thorough mixing.

The stop-cock is turned so as to connect the cylinder with the 10-ml pipette, and fluid is drawn into the pipette to the graduation-mark by mouth suction through the rubber tube that is attached to the top of the pipette. The stop-cock is then turned

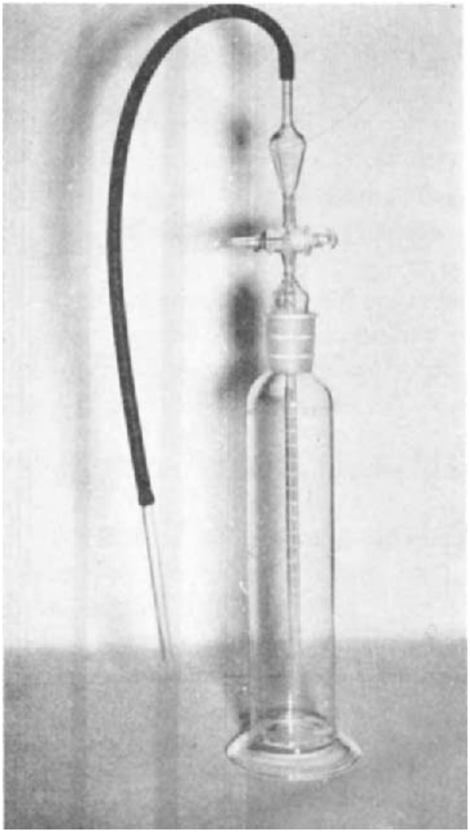


Fig.5. The Andreasen pipette.

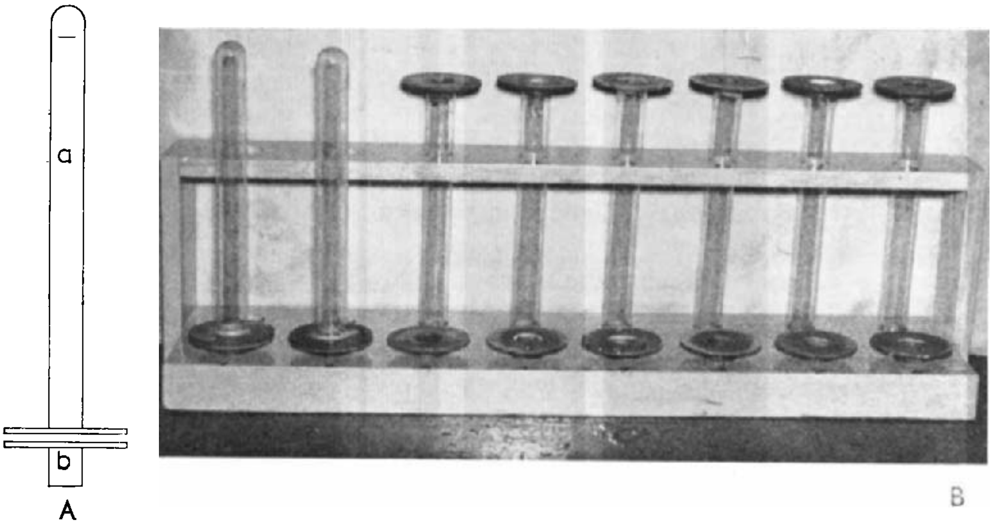


Fig.6.A. Apparatus for sedimentation method of analysis, B. Sedimentation device described on p. 18 and following.

so as to deliver the contents of the pipette into a suitable glass container, where it is dried and later weighed to the nearest 0.1 mg.

Samples are withdrawn after 1, 2, 4, 8, 16, 32, and 64 min. Weights are corrected for amount of dispersing agent and other dissolved materials.

The settling depth decreases as samples are withdrawn, and should be recorded with the data. In the apparatus of Fig.6 it will be noted that the settling depth is constant and, as another advantage, the liquid is not disturbed when the sedimented particles are separated from the rest of the suspension.

In 1937, Casagrande described a hydrometer method in which a specially designed hydrometer is suspended in the dispersion and readings taken at geometrically spaced time-intervals. The principle is the same as that of the pipette method, except that concentration of solids is measured indirectly, and calculations are made from the specific gravities of the suspension.

A source of errors could originate as follows: Eddy-resistance occurs if the Reynolds number $dv\sigma/\mu$ is greater than 0.6 and, according to WADDELL (1934), it should not exceed 0.2 for consistent results in the sizing of non-spherical particles. The Reynolds criterion is a dimensionless number, expressed as the product of capillary-diameter (d), fluid velocity (v), and fluid density (σ) divided by the fluid viscosity (μ); all expressed in c.g.s. units. If the particle has a specific gravity of 5.0 and is sedimented in water, the maximum size is 45 μ; in glycerine 3,680 μ.

Test-tube or microscopic tests should be made in order to select a suitable dispersing agent that will effect complete wetting and dispersion throughout the test. Some of the commonly used dispersion agents are sodium silicate, quebracho, tannic acid, and the various formulas of aerosol.

Wall effects are caused by slow-moving particles near the walls of the sedimentation-tube. The tube should have a diameter of at least 5 cm.

The author's method

Another method of undisturbed settling is based upon Stokes' Law and the work of ODÉN (1916), SVEDBERG (1928), and SCHRAMM and SCRIPTURE (1925). This method may be described as follows:

The sedimentation apparatus is shown in Fig.6 in which A is a 1 × 12 inch pyrex tube, to the open end of which an annular brass disk is affixed by means of epoxy-cement. 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 ensures 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 0.5% 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 and a certain amount of differential settling has taken place.

(*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 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, ..., min.

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 $(w_2 - w_1)/w \cdot 100$ = 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 $t\,dP/dt$, and of the first group, S. We may, therefore, write:

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

In Fig.7 for a time (t) the total amount sedimented is P. A tangent drawn from this point on the P–t curve makes an angle α with the abscissa. The slope of this tangent is dP/dt and the distance on the ordinate from the tangent intercept to P is equal to $t\,dP/dt$, and the distance to the origin is S. The distance S, then, represents the

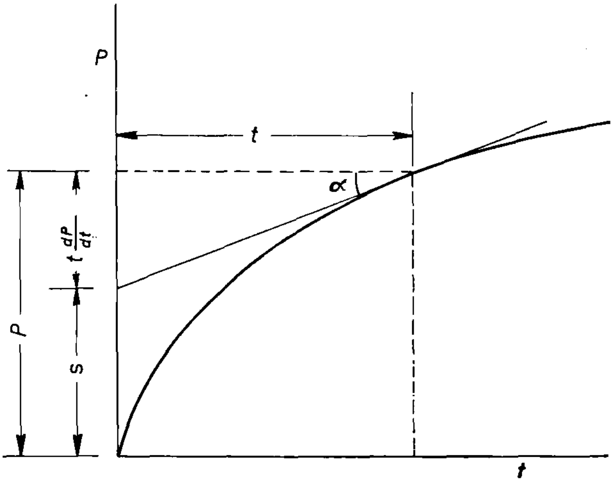


Fig.7. Graphical method for solution of the Odén sedimentation equation.

amount of sediment composed of particles of the first class that accumulated in the time t. The rate of accumulation of these particles is $v = S/t$; and their diameter, by the Stokes' equation, is

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

For example, two points, m_1 and m_2, on a curve give the measurements depicted in Table VI.

TABLE VI

RATES OF SEDIMENTATION ACCORDING TO THE ODÉN EQUATION

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

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

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

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

$$d_1 = \sqrt{\frac{11.5}{700}} = 0.128 \text{ mm}$$

and

$$d_2 = \sqrt{\frac{4.2}{700}} = 0.077 \text{ mm}$$

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.8. The data for Sample No.3 are given in Table VII and VIII.

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

The cumulative percentage curves for these two samples are shown in Fig.9, the results of the sieve analysis for Sample No.3 being combined with those from the

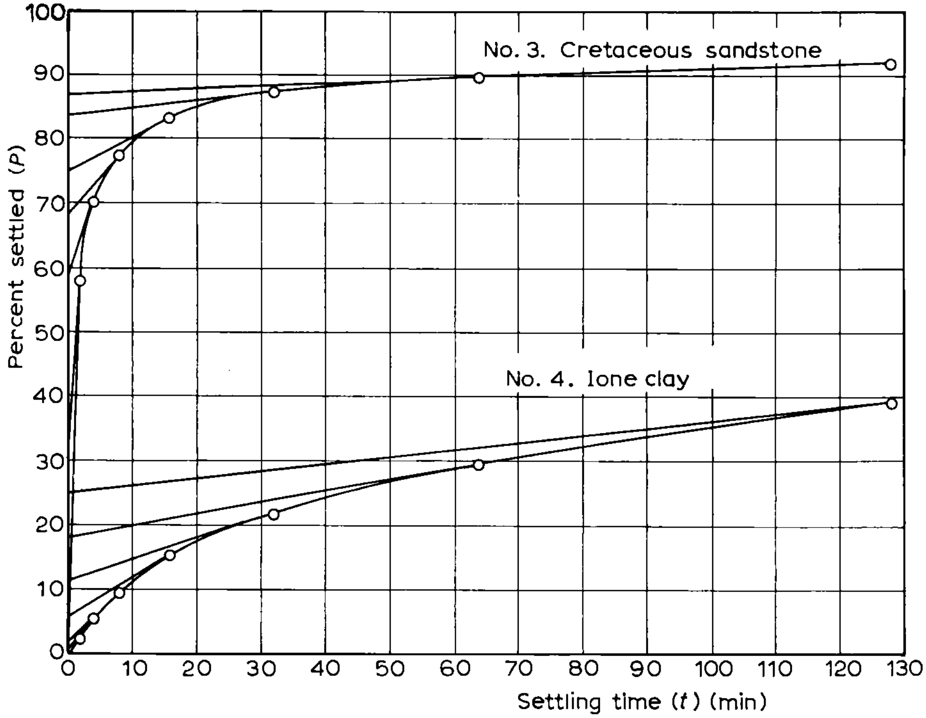


Fig.8. Sedimentation curves, showing graphical method of interpretation.

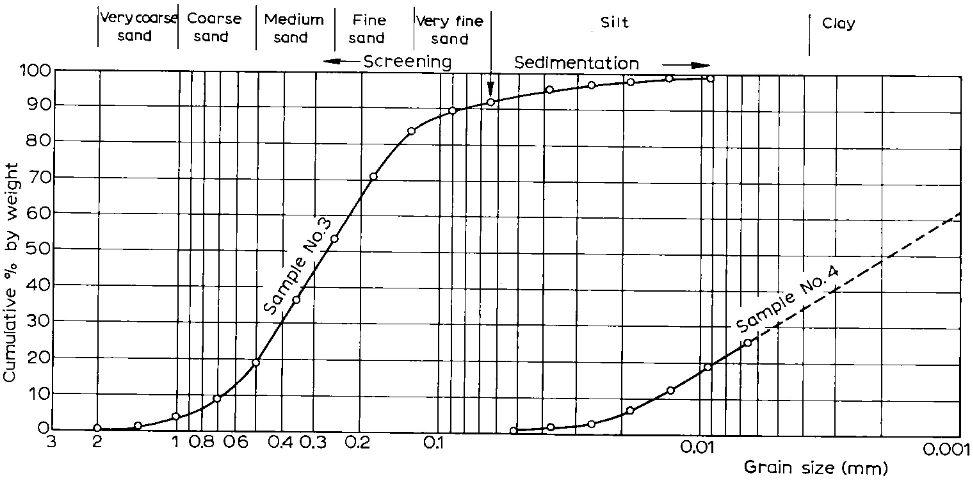


Fig.9. Cumulative percentage sizing curves, based upon both sieving and sedimentation.

TABLE VII

SAMPLE NO. 3 : CRETACEOUS SANDSTONE

Settling time (min)	*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

TABLE VIII

SAMPLE NO. 3 : STATEMENT FROM CURVE

Size range (mm)	*Percentage*
>0.074	0
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
0.00925	13

sedimentation test. It will be noted from the extrapolation of these curves (dotted lines) that Sample No.3 probably has no material as fine as 0.004 mm (no clay), while Sample No.4 probably has 40 % that is finer than 0.001 mm.

Air elutriation

Air elutriation has been frequently used for fractionating material in a very fine state of comminution, such as diatomite and tuff. The Hultain Infrasizer is an important instrument using this principle. It consists of a series of six vertical cones, with diameters varying from one another by the ratio of $\sqrt{2}$ and connected in series. Material under a constant air pressure is fed into the bottom of the smallest tube, where the coarser fraction is retained, and passes through the other cones in sequence, the finest material being recovered in a filter-bag after the largest cone.

The Coulter counter

A unique principle for particle-size analysis is applied in the Coulter counter. The particles are suspended in an electrically conductive liquid. The suspension flows through a minute hole of precise dimensions. Platinum electrodes on each side of the hole supply a d.c. voltage, with accompanying current-flow through the sensing-zone hole. Each particle passing through the hole changes the electrical resistance of the hole in proportion to the volume of that particle, thus producing a voltage-pulse of magnitude proportional to particle volume. The resultant series of pulses is electronically amplified, scaled, and counted.

The voltage-pulses are displayed on an oscilloscope screen as a pattern of vertical "spikes". The pulse-pattern serves as a guide for measurement and as a monitor of instrument performance. Application of a vacuum causes the dispersed particles and the suspended liquid to flow through the hole. By sequentially setting the particle-size selector-dial, in steps, and taking counts at several size-levels, data are gathered for plotting a cumulative frequency curve of micron sizes.

Comparison of methods

A comparison of particle-size analyses made by different instruments has recently been made (BHRANY and BROWN, 1962). Particle-size analyses of crushed quartz were compared as made by the following instruments: Coulter counter, Hultain infrasizer, Andreasen pipette, Whitby centrifuge, and sieve analysis. It was observed that if sizing is accomplished by one technique down to a certain size, and then by a different technique from that point on, displacements in the size-distribution lines would be expected, but that the slopes of the various lines may not be affected to any appreciable extent. The largest variation in slope was observed in the case of the Whitby centrifuge, a sedimentation technique that is considered to be a fairly rapid method. It was concluded that the size of a particle is a defined quantity and is dependent on the method of analysis. The question of the relationship between the method of sizing and the inherent regularity that may be present when a homogeneous material is fractured was left open for further study.

STATEMENT OF MECHANICAL ANALYSIS

The statement of a mechanical analysis may include the data of sieve analysis, liquid classification, or both, according to the material and the purpose in view.

In the following two sieve analyses (Tables IX and X), columns *1*, *3*, and *5* are the ones customarily included in the analytical statement. Column *1* states the openings in millimeters as given approximately by the sieves selected from the A.S.T.M. series to fit the Wentworth scale.

The histograms of Fig.10 show the same statement of these analyses in graphic

TABLE IX

SAMPLE NO. 1: CORE SAMPLE FROM OIL WELL[1]

	1 Sieve openings (mm)	2 ϕ	3 %	4 Log %	5 Σ%	6 Log Σ%
Retained on	8	−3	1.0	0.301	1.0	0.301
Retained on	4	−2	6.2	0.792	7.2	0.857
Retained on	2	−1	10.6	1.025	17.8	1.250
Retained on	1	0	15.2	1.182	33.0	1.518
Retained on	0.5	+1	18.2	1.260	51.2	1.709
Retained on	0.25	+2	20.9	1.320	72.1	1.858
Retained on	0.125	+3	15.9	1.201	88.0	1.945
Retained on	0.062	+4	6.1	0.785	94.1	1.974
Passed through	0.062		5.9		100.0	

[1] Field: Huntington Beach, California; Well: Calpet–Macklin No. 1; Depth: 3,828 ft.

TABLE X

SAMPLE NO. 2: CORE SAMPLE FROM OIL WELL[1]

	1 Sieve openings (mm)	2 ϕ	3 %	4 Log %	5 Σ%	6 Log Σ%
Retained on	2	−1	2.8	0.447	2.8	0.447
Retained on	1	0	3.7	0.568	6.5	0.813
Retained on	0.5	+1	6.7	0.826	13.2	1.121
Retained on	0.25	+2	20.3	1.307	33.5	1.525
Retained on	0.125	+3	36.8	1.566	70.3	1.847
Retained on	0.062	+4	17.1	1.233	87.4	1.942
Passed through	0.062		12.6		100.0	

[1] Field: Seal Beach, California; Well: Marland–Bixby No.2; depth: 4,423 ft.

form, and from them the percentages of the various grades (pebbles, sand, silt, etc.) established by the Wentworth scale may be read.

CHARACTERIZATION OF CURVES

Fig.11 and 12 portray, as curves, the percent by weight and cumulative percent by weight of Samples No.1 and 2 respectively. The cumulative curve, sometimes called the *ogive*, facilitates visualization of the type of sample represented, and reveals its characteristics.

The high peak of the frequency curve (lower curves) is called the *mode*. It rep-

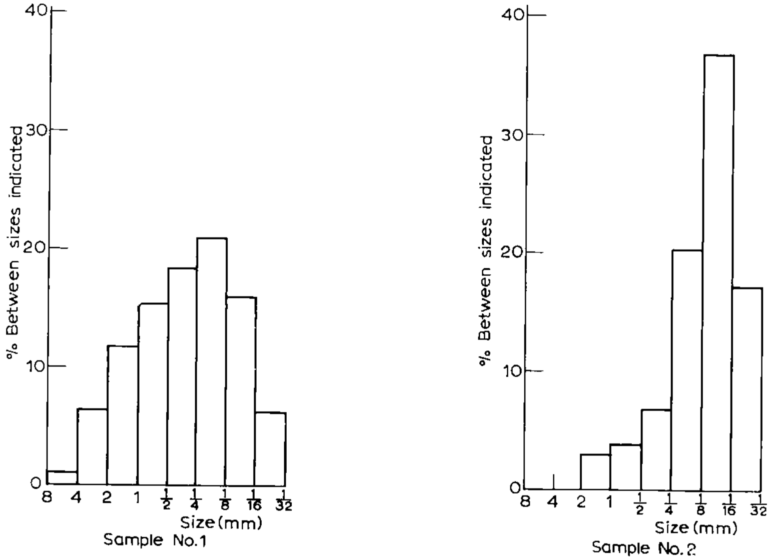


Fig.10. Histograms.

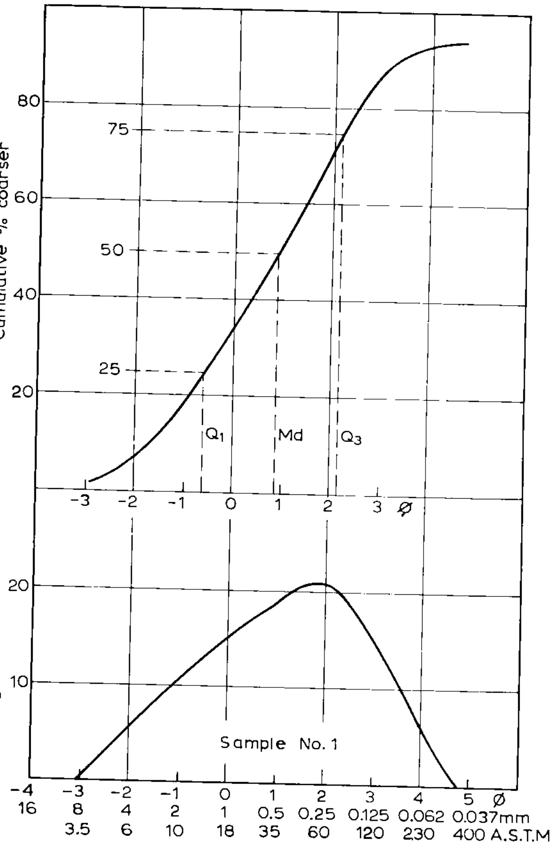


Fig.11. Sample No.1.

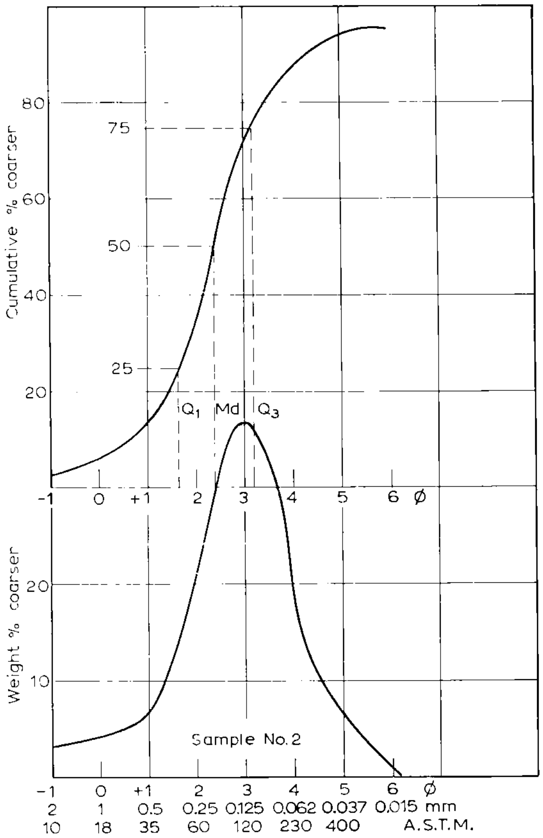


Fig.12. Sample No.2.

resents the size of grain that is, by weight percent, most abundant. The relative height of the mode, and the way in which the frequencies are grouped on each side of it, is characteristic of the material. On the cumulative curves (upper curves) the mode is more accurately shown as the 50 percentile (Md). The 25 and 75 percentiles (Q_1 and Q_3), are called the first and third "quartiles", respectively. The way in which they are grouped about the mode reveals the frequency-curve's degree of symmetry.

Departure from perfect symmetry is called "skewness", and may be calculated in either millimeter-size or in phi terms.

Quartile skewness:

$$Sk_Q = \tfrac{1}{2}(Q_1 + Q_3 - 2Md)$$

Phi skewness:

$$Sk = \tfrac{1}{2}(D_1 + D_9 - 2Md)$$

Using phi values for the D_1, the 10%, and D_9, the 90% deciles, and Md the median.

Negative value of the phi-skewness indicates that the coarse side of the decile distribution is more widely spread (poorer sorting); positive values indicate poorer sorting on the fine side.

TRASK (1932) and others have proposed different measures of the curve. The arithmetic quartile deviation:

$$QD_a = \tfrac{1}{2}(Q_3 - Q_1)$$

The geometric quartile deviation, which Trask called a "sorting coefficient",

$$QD_g = Q_3/Q_1$$

He found, on the basis of about 200 analyses, that a value less than 2.5 indicates a well-sorted sediment, a value of about 3.0 a normally sorted sediment, and a value greater than 4.5 a poorly sorted sediment. That is not to say, however, that a value of 4.0 represents a sediment twice as widely dispersed as one of value 2.0.

A close bunching of frequencies at the mode (high, narrow peak) is called kurtosis, and has been defined by KELLY (1924) as follows:

$$K_Q = \tfrac{1}{2}\frac{P_{25} - P_{75}}{P_{10} - P_{90}}$$

where P is the percentile, measured in millimeters. See Fig.11 and 12 for values of skewness that apply to Samples No.1 and 2.

TABLE XI

SIEVE ANALYSES OF BEACH AND DUNE SANDS
(Illustrative of size-variation of sands)

Locality	*Percent finer than American Standard mesh number*											
	10	*14*	*18*	*25*	*35*	*45*	*60*	*80*	*120*	*170*	*230*	*325*
Pittsburg, Calif.; fine	0.1	0.1	0.1	0.2	0.5	5.0	18.0	39.1	28.0	11.5	3.9	1.0
Pittsburg, Calif.; coarse			0.2	5.6	12.8	22.6	26.0	18.9	10.0	2.8	0.2	
Overton, Nev.	0.5	1.0	3.7	17.3	39.1	26.0	10.0	4.9	2.0	0.8	0.2	
Del Monte, Calif.; fine			0.1	0.2	1.9	12.0	46.2	25.0	6.6			
Del Monte, Calif.; coarse	1.0	2.1	4.0	6.0	9.3	26.9	38.8	5.1	0.3			
Oceana, Calif.				0.1	0.3	1.0	9.7	64.0	49.3	15.0	6.1	
Eugene, Oreg.					0.2	16.0	45.0	30.0	5.5	1.5	0.8	0.2
Sacramento River, Calif.	0.2	0.4	2.0	7.2	19.1	22.0	23.0	18.8	12.6	6.0	2.0	
Nev.; dune		0.1	0.4	0.5	0.6	0.7	2.0	41.0	40.0	19.8	5.2	
San Francisco, Calif.; dune			0.2	0.6	1.3	5.5	24.0	44.2	21.3	5.7	0.6	

The average spread of the curve is expressed as the "standard deviation" of the distribution. It is analogous in physics to the radius of gyration of a system. It has been expressed in various arithmetic and logarithmic terms, both in millimeter and phi values.

Recent studies of sorting of beach sands has led one investigator (FOLK, 1962) to state that:

$$S = \frac{P_{84} - P_{13}}{4} + \frac{P_{95} - P_5}{6.6}$$

"is an inclusive graphic, standard deviation" that is more accurate than any measure heretofore proposed, because it takes in 90% of the distribution, and is the most efficient graphic approximation now in use for sorting in sediments. It will serve to differentiate between beach, dune, and river sands."

Reading from the curve for Sample No.1, the value of this interpretation of standard deviation is 1.90; for Sample No.2 it is 1.86.

Chapter 3

BULK PROPERTIES

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.

POROSITY

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 "absolute 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. The petroleum engineer, for example, will be interested only in the voids that are accessible to liquid and gaseous hydrocarbons.

Table XII gives typical porosities of various rocks. **Fraser** (1935) gives the porosities of various spheroidal and crushed substances under different types of packing.

TABLE XII

AVERAGE POROSITIES OF ROCKS

(After MEINZER, 1923)

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

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 for the cases of two- and three-component mixtures.

Degree of compaction is one of the factors affecting the density of sedimentary rocks. This relationship was investigated by BRANNER (1937) for the Paleozoic sandstones of Arkansas. He showed that the densities of 82 samples varied between 2.1 and 2.7 g/cm^3, and the porosities between 0 and 22.5%. The distribution of his plotted points is found to be substantially linear, so that the relation may be empirically stated:

$$p = 104 - 40d$$

where p is porosity (%); d is density (g/cm^3).

DAVIS (1954) found a linear relationship in testing 370 samples from other localities, which indicates the equation:

$$p = 106 - 40d$$

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 material, 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, 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 2-l 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 since 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

A method proposed by MELCHER (1921) was one of the first in use. It required weighing the coherent specimen, dipping it in barely melted paraffin-wax, weighing it again, first in air and then suspended by a fine wire in distilled water. 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. From a previous determination of the density of the 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 of the sample and the paraffin volumes gives the volume of the rock.

The simplest form of bulk-volume device may be machined from 2-inch diameter lucite (or plexiglass) to form a cylindrical cup with a flanged top edge. A flat cover is made of the same material. Cup and cover are ground together with fine abrasive to insure a tight joint. The cover should have three steel pins (1/16 × 1/2 inch) inserted on the inner side, equally spaced, so as to hold the rock specimen down and submerged in mercury.

The cup is set in a 6-inch evaporating dish and filled with clean mercury; the cover is slid on in such a way as not to leave an air-bubble. The cover is then removed and the rock specimen is pressed down into the mercury by the cover. The overflow mercury is weighed, and from this weight and the density of mercury at the operating temperature, the bulk-volume of the specimen may be calculated.

The Russell Volumeter

The Russell volumeter is described by the AMERICAN PETROLEUM INSTITUTE (1960). In this device the specimen is submerged in tetrachlorethane (acetylene tetrachloride) to saturation and the liquid-displacement volume is read on the stem of an all-glass apparatus.

The Aminco Porosimeter

For extremely fine-grained aggregates the "Aminco Penetrometer Porosimeter"[1] is available. In this instrument advantage is taken of the non-wetting properties of mercury and the fact that it will enter capillary pores only under pressure.

The approximate formula is:

$$d = 175/p$$

where d = diameter of a cylindrical pore (μ), and p = pressure required to force mercury into the pore (lb./sq.inch).

The American Petroleum Institute bulk volume meter[2]

Bulk volume is more rapidy and conveniently, if more expensively, determined by the use of an apparatus recommended and described by the American Petroleum Institute. This instrument measures bulk volume by displacing a suitable liquid into an inclined graduated glass tube by submerging the core sample under mercury in an adjacent connected vessel. The apparatus is shown in Fig.13.

The bulk-volume meter is calibrated by submerging a steel blank in the mercury chamber. The mercury volume in the cylinder is adjusted until the oil column reads exactly a definite point on a suitable scale mounted behind the oil column. The meter is previously calibrated with a series of blanks of known volume over the range of interest and a curve drawn for volume versus scale readings. If room temperature is constant, practically no variation in calibration will be noted after the first two or three samples have been measured.

A sample of the core to be examined is submerged in the mercury cylinder and the resultant liquid level is read on the scale. The value read on the scale is converted to volume through use of the calibration curve. The values may be taken from the curve and used in chart form for convenience.

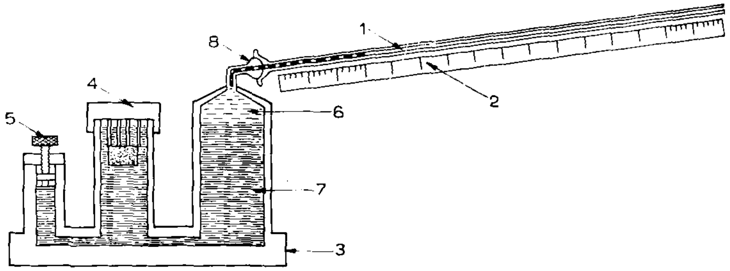


Fig.13. Bulk-volume meter. *1* = precision tubing — bore approximately 3 mm ID; *2* =calibrated scale, reading in cubic centimeters; *3* steel vessel; *4* = cap with sample holddown prongs; *5* = mercury volume adjustment; *6* = oil; *7* = mercury; *8* = ground joint connection.

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[1] American Instrument's Company, Silver Springs, Md.

[2] Description and Fig.13 reproduced by permission from American Petroleum Institute "API RP 40: Core Analysis Procedure".

TABLE XIII

DENSITY OF WATER AND MERCURY

Temperature (°C)	*Water (g/cm³)*	*Mercury (g/cm³)*
15	0.99913	13.5584
16	0.99897	13.5560
17	0.99880	13.5535
18	0.99862	13.5511
19	0.99843	13.5486
20	0.99823	13.5461
21	0.99802	13.5437
22	0.99780	13.5412
23	0.99756	13.5388
24	0.99732	13.5363
25	0.99707	13.5339
26	0.99681	13.5314
27	0.99654	13.5290
28	0.99626	13.5265
29	0.99597	13.5241
30	0.99567	13.5216

The meter is calibrated every 6–10 samples. More frequent calibration is necessary when measuring either friable sandstones (mercury becomes dirty and volume increases), or vugular limestones (vugs trap mercury as sample is removed and mercury volume decreases).

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.

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.

Volumetric pore-volume

The gas-porosimeters operate on the principle of the combination of Boyle's and Charles' combined gas laws, which may be stated as follows:

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$$

where p_1, v_1, and T_1 represent pressure, volume, and absolute temperature in one case and p_2, v_2, and T_2 the same quantities for the same mass of gas in another.

TABLE XIV

GRAIN VOLUME DATA AND CALCULATION (GRAVIMETRIC) FOR SAMPLE NO. 3[1]

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 XIII)		0.9978 g
6	Volume of water	(3: 5)	14.6751 cm³
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/cm³
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 cc
16	Grain density	(8:15)	2.5775 g/cm³

[1] See Fig.9.

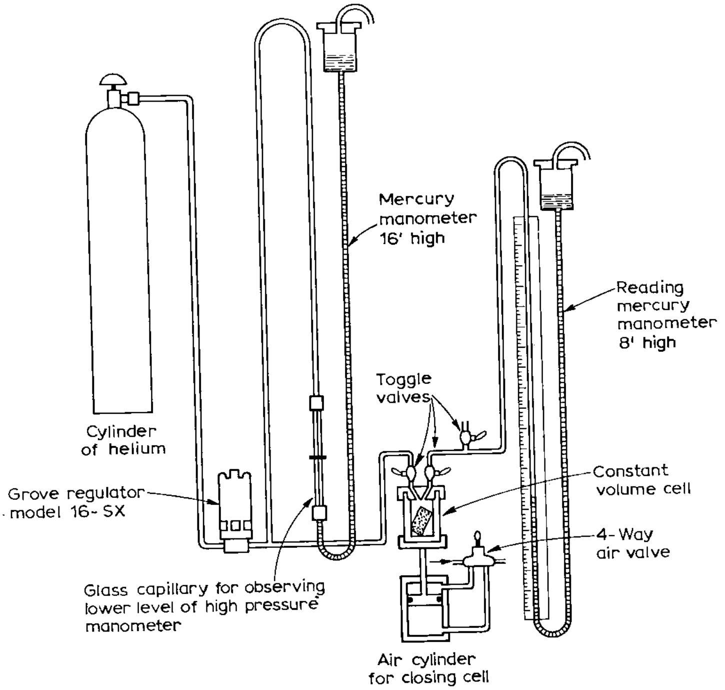

Fig.14. Boyle's law double-cell porosimeter. (Reproduced by permission from A.P.I. RP40 *Core Analysis Procedure.*)

The Kobe porosimeter and Boyle's Law double-cell porosimeters are described by the AMERICAN PETROLEUM INSTITUTE (1952).

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 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 p. 30 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 (1930) 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 (TICKELL and HIATT, 1938) that permeability has the dimensions of an area,

$$\frac{(L^3T^{-1})(ML^{-1}T^{-1})L}{L^2(MLT^{-2})(L^{-2})} = L^2$$

where M, L, and T are respectively the dimensions mass, length, and time. In c.g.s. units, therefore, the unit of permeability is:

$$\frac{1 \text{ cm}^3/\text{sec} \cdot 1 \text{ poise} \cdot 1 \text{ cm}}{1 \text{ cm}^2 \cdot 1 \text{ dyne/cm}^2}$$

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

$$1 \text{ darcy} = \frac{1 \text{ cm}^3/\text{sec} \cdot 1 \text{ centipoise} \cdot 1 \text{ cm}}{1 \text{ cm}^2 \cdot 1 \text{ atm/cm}^2}$$

In other words, a porous substance has a permeability of 1 darcy for all conditions of viscous flow, if a fluid having a viscosity of 1 centipoise will flow through a sample of it having a length of 1 cm and a cross-sectional area of 1 cm^2, under a differential pressure of 1 atm, at the rate of 1 cm^3/sec.

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: A = Cross-sectional area of sample, at right angles to which the fluid flows (cm^2); L = length of sample, parallel to direction of fluid flow (cm); P_1 = absolute pressure at the fluid intake (atm); P_2 = absolute pressure at the fluid outlet (atm); P = mean pressure in the system = $(P_1 + P_2)/2$ (atm); Q = rate of fluid flow, referred to pressure P (If an incompressible liquid is flowing, its volume does not vary with the pressure.); μ = viscosity of the fluid (centipoise); k = permeability (darcy).

For the viscous regime, D'Arcy (1856) developed the empirical relationship which can most conveniently be expressed in the following form:

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

If the flow is viscous, the velocity Q/A is a linear function of the pressure gradient $(P_1 - P_2)/\mathrm{L}$, so that if from the experimental data values of Q/A be plotted against corresponding values of $(P_1 - P_2)/\mathrm{L}$, 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 (Table XV):

TABLE XV

VELOCITY, CAUSING TURBULENCE IN CAPILLARIES

Diameter of capillary (mm)	*Velocity (cm/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 (1952) a tentative standardization code for permeability determination, in order to define the conditions of test and point out sources of errors. A quotation from the code follows.

A.S.T.M. air permeability determination[1]

The dimensions of the core sample must be obtained to calculate its permeability. The

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[1] Quotation reproduced by permission from American Petroleum Institute "API RP 40: Core Analysis Procedure".

length and cross-sectional dimensions may be measured directly by calipering or from measuring the length and computing the cross-sectional area by dividing the bulk volume by the length. These measurements are made before the sample is measured for permeability. If the sample is to be mounted in plastic or pitch, it must be measured before mounting. However, if a mounted core is cut or sectioned to clean the ends, the length must be remeasured after the cutting.

The clean sample is placed in an appropriate holder in the permeameter so that any bypassing of air around the sides of the sample or the mounting is eliminated. Dry air is passed through the core and the rate of flow of the air determined from the pressure difference across a calibrated orifice or other suitable flow-rate measuring device. The differential pressure across the sample may be adjusted to give appropriate or convenient rates of air flow. The inlet air pressure and the air flow rates are recorded. From these measurements and the sample dimensions, the permeability may be calculated. The dry-air permeability may be calculated by the following formula:

$$k = \frac{2{,}000\, Q_o p_o \mathrm{L} \mu}{(p_i^2 - p_o^2)A}$$

wherein k = permeability to dry air (millidarcies); Q_o = rate of flow of outlet air (cm^3/sec); p_o = outlet pressure, absolute (atm); p_i = inlet pressure, absolute (atm); μ = viscosity of air (centipoises); L = length of sample (cm); A = cross-sectional area perpendicular to direction of flow (cm^2).

Calculations may be simplified by any one of several methods. One method is to use specific inlet pressures and such a low pressure drop across the rate-measuring orifice that the outlet pressure is essentially 1 atm.

The formula then reduces to the following:

$$k = \frac{QF\mathrm{L}}{A}$$

wherein

$$F = \frac{2{,}000 \mu p_o}{p_i^2 - p_o^2} = \frac{2{,}000\, \mu}{p_i^2 - 1}$$

(a constant for each fixed inlet pressure, where $p_o = 1$ atm).

The viscosity, μ, is the viscosity of air under the conditions used to calibrate the orifice. The permeameter compares the pressure differences across the core and the orifice. Since the same air flows through both, any change in air viscosity from either temperature changes or water vapor will have no effect on the relative pressure readings.

A second method of simplifying calculations involves preparing calibration charts or tables showing the permeance[1] versus the outlet pressure for given inlet pressures and orifices. The following formula applies:

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[1] The permeance, usually referred to as "apparent permeability," is the proper term for flow capacity. Its use is analogous to the term "conductance" for the flow of current through an electrolyte solution. Permeance bears the same relationship to permeability as conductance to conductivity.

$$k_c = \frac{L_c}{A_c}\left(\frac{k_{or}}{L_{or}/A_{or}} \cdot \frac{\Delta p_{or} Q_c}{\Delta p_c Q_{or}}\right)$$

wherein k_c, k_{or} = permeability of the coie and the equivalent permeability of the orifice, respectively (millidarcies); Δp_c, Δp_{or} = pressure drop across the core and orifice, respectively (atm); Q_c, Q_{or} = flow rate through the core and orifice, respectively (cm^3/sec); L_c, L_{or} = length of the core and orifice, respectively (cm); A_c, A_{or} = cross-sectional area of the core and orifice, respectively (cm^2).

This equation can be reduced to:

$$k_c = \frac{L_c}{A_c} \cdot \frac{Q_c}{\Delta p_c} \cdot \text{orifice constant}$$

A standard permeable plug can be used to determine the orifice constant directly. If one prepares tables or nomographs from measured outlet pressures, p_o, for given inlet pressures and orifices, then the equation can be reduced further to:

$$k_c = \frac{L_c}{A_c} K_c^{\Theta}$$

wherein K_c^{Θ} is the permeance of the core.

The permeance, obtained as described above, is multiplied by the L/A ratio, or L^2/bulk volume ratio of the core to give the permeability k_c.

Further simplifications may be made by the use of nomographs, calibration charts, or tables. The value of μ may be fixed for an average room-temperature condition and p_o may be made equal to 1 atm.

VISCOSITY OF CLAY–LIQUID MIXTURES

Clays have important use in the petroleum industry, where they are used in the rotary-method drilling of wells for the purpose of cooling and lubricating the drill-pipee removing rock-cuttings from the hole, building a wall on the sides of the hole to prevent fluids from entering while drilling is in progress, overcoming formation-pressures, and preventing caving.

Drilling fluids (so-called "muds") consist of clays, mixed with either water or oil, to which various substances are frequently added to improve the bulk properties as to viscosity, density, thixotrophy, gel-strength, and hydrogen-ion concentration (pH).

The viscosity of a drilling fluid is determined, approximately, with a slim-tapered funnel (the Marsh Funnel), 14 inches in length, with a screen covering near the top. The funnel is held vertically with a finger stopping the outlet. The mud-fluid is stirred vigorously and poured into the funnel to the level of the screen, an amount equal to 1,500 ml. A stop-watch is started as the flow begins and is stopped when 1,000 ml are recovered. (Some operators use 1,000 ml in and 1 quart out.) The elapsed time in seconds is referred to as the "Marsh viscosity", (70°F in temperature is assumed).

TABLE XVI

VISCOSITY OF AQUEOUS GLYCEROL SOLUTIONS

(After SHEELY, 1932)[1]

S.g.at 25°C	*Glycerol (%)*	*Viscosity (centipoise)*		
		20°C	*25°C*	*30°C*
1.00000	0	1.005	0.893	0.800
1.00235	1	1.029	0.912	0.817
1.00475	2	1.055	0.935	0.836
1.00710	3	1.083	0.959	0.856
1.00950	4	1.112	0.984	0.877
1.01185	5	1.143	1.010	0.900
1.01425	6	1.175	1.037	0.924
1.01660	7	1.207	1.064	0.948
1.01900	8	1.239	1.092	0.972
1.02135	9	1.274	1.121	0.997
1.02370	10	1.311	1.153	1.024
1.02620	11	1.350	1.186	1.052
1.02865	12	1.390	1.221	1.082
1.03110	13	1.431	1.256	1.112
1.03360	14	1.473	1.292	1.143
1.03605	15	1.517	1.331	1.174
1.03850	16	1.565	1.370	1.207
1.04100	17	1.614	1.411	1.244
1.04345	18	1.664	1.453	1.281
1.04590	19	1.715	1.495	1.320
1.04840	20	1.769	1.542	1.360
1.05095	21	1.829	1.592	1.403
1.05350	22	1.892	1.644	1.447
1.05605	23	1.957	1.699	1.494
1.05860	24	2.025	1.754	1.541
1.06115	25	2.095	1.810	1.590
1.06370	26	2.167	1.870	1.641
1.06625	27	2.242	1.934	1.695
1.06880	28	2.324	2.008	1.752
1.07135	29	2.410	2.082	1.812
1.07395	30	2.501	2.157	1.876
1.07660	31	2.597	2.235	1.942
1.07925	32	2.700	2.318	2.012
1.08190	33	2.809	2.407	2.088
1.08455	34	2.921	2.502	2.167
1.08715	35	3.040	2.600	2.249
1.08980	36	3.169	2.706	2.335
1.09245	37	3.300	2.817	2.427
1.09510	38	3.440	2.932	2.523
1.09775	39	3.593	3.052	2.624
1.10040	40	3.750	3.181	2.731
1.10310	41	3.917	3.319	2.845
1.10575	42	4.106	3.466	2.966
1.10845	43	4.307	3.624	3.094
1.11115	44	4.509	3.787	3.231
1.11380	45	4.715	3.967	3.380
1.11650	46	4.952	4.165	3.540
1.11915	47	5.206	4.367	3.706
1.12185	48	5.465	4.571	3.873
1.12450	49	5.730	4.787	4.051
1.12720	50	6.050	5.041	4.247
1.12995	51	6.396	5.319	4.467
1.13265	52	6.764	5.597	4.709
1.13540	53	7.158	5.910	4.957
1.13815	54	7.562	6.230	5.210
1.14090	55	7.997	6.582	5.494
1.14365	56	8.482	6.963	5.816
1.14640	57	9.018	7.394	6.148
1.14915	58	9.586	7.830	6.495
1.15185	59	10.25	8.312	6.870
1.15460	60	10.96	8.823	7.312
1.15735	61	11.71	9.428	7.740
1.16010	62	12.52	10.11	8.260
1.16285	63	13.43	10.83	8.812
1.16560	64	14.42	11.57	9.386
1.16835	65	15.54	12.36	10.02
1.17110	66	16.73	13.22	10.68
1.17385	67	17.96	14.18	11.45
1.17660	68	19.40	15.33	12.33
1.17935	69	21.07	16.62	13.27
1.18210	70	22.94	17.96	14.32
1.18480	71	25.17	19.53	15.56
1.18755	72	27.56	21.29	16.88
1.19025	73	30.21	23.28	18.34
1.19295	74	33.04	25.46	19.93
1.19565	75	36.46	27.73	21.68
1.19840	76	40.19	30.56	23.60
1.20110	77	44.53	33.58	25.90
1.20380	78	49.57	37.18	28.68
1.20655	79	55.47	41.16	31.62
1.20925	80	62.0	45.86	34.92
1.21190	81	69.3	51.02	38.56
1.21455	82	77.9	56.90	42.92
1.21720	83	87.9	64.2	47.90
1.21990	84	99.6	72.2	53.63
1.22255	85	112.9	81.5	60.05
1.22520	86	129.6	92.6	68.1
1.22790	87	150.4	106.1	77.5
1.23055	88	174.5	122.6	88.8
1.23320	89	201.4	141.8	101.1
1.23585	90	234.6	163.6	115.3
1.23850	91	278.4	189.3	134.4
1.24115	92	328.4	221.8	156.5
1.24380	93	387.7	262.9	182.8
1.24645	94	457.7	308.7	212.0
1.24910	95	545	366.0	248.8
1.25165	96	661	435.0	296.7
1.25425	97	805	522.9	354.0
1.25685	98	974	629	424.0
1.25945	99	1197	775	511.0
1.26201	100	1449	945	624

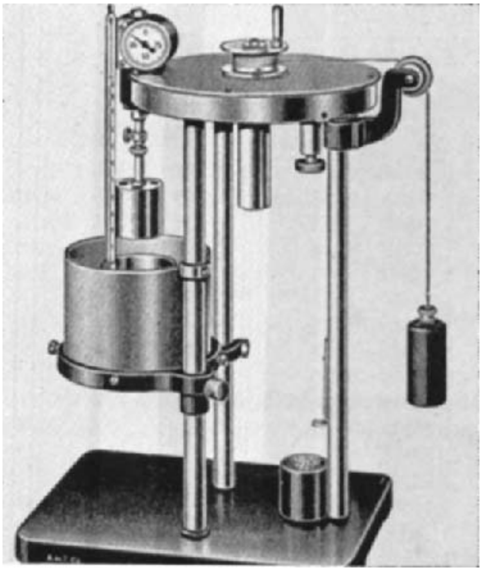

Fig.15. The Stormer viscosimeter.

A more accurate determination of viscosity is by the employment of the Stormer Viscosimeter (Fig.15).

With this instrument, the mud is placed in a cup that rests in a water-bath. Above it is a hollow cylinder (open at the bottom), supported by a spindle that is connected through a gear-train in such a way that the suspended weight (shown at right of figure) causes a rotation of the cup as it descends. A hand-crank at the top serves to rewind the cord. Lead-shot are added to the weight-box until the revolution-counter indicates a speed of 600 rounds/min. A calibration-chart reduces this weight to centipoise units. Calibration of the instrument is effected by the use of glycerol–water mixtures, for values of which consult Table XVI.

The Fisher Electroviscosimeter is a direct-reading instrument, covering the range between 0 and 5,000 centipoise.

Clay–water mixtures exhibit thixotropy, which is the property of forming a gel that can be broken by agitation, but which reforms upon standing. This property can be measured with the Stormer Viscosimeter and by the aid of a chart shown by ROGERS (1948, p. 233).

Chapter 4

PREPARATION OF SPECIMENS

The preparation of specimens for 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 inch thick), a hammer, and a $1\frac{1}{2}$-inch ring cut from a $1\frac{1}{2}$-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. Acetic acid (15%) is effective for this purpose, as are oxalic, tartaric, and phosphoric acids for removing iron oxide coatings from grains. Alternate freezing and boiling is sometimes efficaceous. HANNA and DRIVER (1924) suggest 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.

HOLMES (1921) points out that many accessory minerals resist attack by hydrofluoric acid sufficiently to permit their isolation. Such minerals include anatase, brookite, rutile, perovskite, andalusite, sillimanite, kyanite, hematite, magnetite, corundum, spinel, cassiterite, topaz, tourmaline, axinite, staurolite, and zircon. The process must be carried out in a lead or platinum dish, the crushed material being slowly added to the cold, concentrated acid. Caution should be observed, as much heat is generated by the reaction. A large excess of water is later added and the gelatinous silica washed away. The residue is then treated with sodium or potassium hydroxide to remove the rest of the silica. The method is not recommended except as a last resort.

SIZING

Sizing for sample preparation usually consists in passing the material through two or more sieves in order to secure grains of uniform size for mounting and examination. Grains that are between −120 and +170 mesh are of about the right size.

The standard 8-inch diameter sieve 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 2.5 inches in diameter and 2 inches high makes a good sieve. 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 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*) dielectric strength; (*5*) surface energy (flotation separation; not applicable on a very small scale); (*6*) detection of radioactive mineral grains.

Density

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 concentration.

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 1 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 g 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.

The Superpanner, made by Infrasizers, Ltd., Toronto, Canada, is a mechanical panning device with which the tilt of the pan and the period of vibration may be varied, thus making possible very accurate gravity separations in an aqueous medium.

For dry separations an asymmetric vibrator has been described (FAUL and

DAVIS, 1959) which consists of an aluminum plate mounted with a 15° slope on a vibrating feeder. Rounder grains tend to roll off of the plate, leaving the flat grains behind.

Heavy liquid concentration

Heavy liquids may be used for mineral concentration by the sink-and-float method up to specific gravities of 5.3. Various liquids have been used for this purpose, but it seems advisable and sufficient to limit the number to four, as serving all practical purposes.

Bromoform has a specific gravity of 2.89, is liquid at room temperatures, and is soluble in carbon tetrachloride, alcohol, acetone, and various organic liquids. The vapors are toxic if breathed in quantity or repeatedly, so that reasonable precautions should be observed in its use. Acetone is preferred as a diluent, as being cheap, non-toxic, and soluble in water.

Tetrabromo ethane (otherwise called acetylene tetrabromide) has a specific gravity of 2.96, is liquid at room temperatures. Solubility and toxicity are similar to bromoform.

Methylene iodide (diiodo methane), CH_2I_2 has a specific gravity of 3.32 and is soluble in alcohol.

Clerici solution is a mixture of aqueous solutions of thallium formate and thallium malonate. If 80 g of each are added to 10 ml of water there will be a partial solubility, and the specific gravity will be 4.25 at 20°C. When heated to 50°C more of the salts will dissolve and the specific gravity will be increased to 4.65. At 95°C the specific gravity is about 5.0.

Thallium compounds are extremely poisonous, so that great care should be exercised in their use. Vapors are not given off, but contact with the skin should be avoided.

Fused salts such as lead chloride (specific gravity 5.0) and mercurous nitrate (specific gravity 4.3) are sometimes useful. The salt and mineral grains are placed in a 0.5-inch pyrex test-tube and heated in a bunsen burner or water-bath. After cooling and solidification of the contents, the tube is broken and the melt is cut so as to divide the heavy grains from the light, and these are separated from the salt by water solution.

In discussing the techniques of heavy liquid concentration, it is assumed that bromoform will be used as the liquid; these techniques are also applicable with other liquids. The most common methods are the following: (*1*) the dish method, and (*2*) the centrifuge method.

(*1*) A porcelain evaporating dish of about 5-inch diameter is used. The mineral grains are added to about 50 ml 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

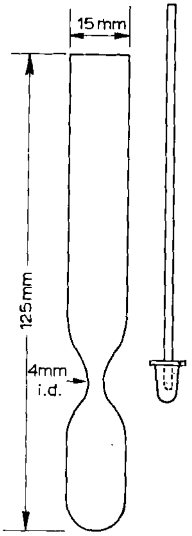

Fig.16. Centrifuge-tube and closure-rod.

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 acetone and dried on a hot plate. It is well to save the filtrate from the 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 U.S.$ 3.50 a pound.

Glass separatory funnels of special design for carrying out heavy liquid concentration are advocated by some workers (ROSS, 1926), and there are great advantages in the use of these where a number of concentrations are being carried out at the same time.

(*2*) In the centrifuge method, for very finely divided sediments such as silts, heavy mineral concentration fails unless a procedure is followed similar to the one described for fine soils by BROWN (1929). According to this method, the material is first separated, by means of settling and decantation (see p. 15), into sand, silt, and clay grades. The silt grade is then dried very thoroughly at 150°C, and 1 or 2 g samples are placed in 15-cm^3 centrifuge tubes, which are one-half filled with bromoform. The samples are centrifuged for 5 min, 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 5 min, and the heavy minerals are removed from the bottoms of the tubes by means of a bulb-pipette.

The relative efficiencies of gravity and centrifuge separation have been investigated (RITTENHOUSE and BERTHOLF, 1942). For the separation of heavy minerals from sand it is claimed that the percentage of "heavies", by weight, differs significantly and the number-frequencies do not. Gravity separation is said to effect a cleaner separation of high than of low density minerals; centrifuge separation being equally effective for all minerals.

An improvement in the centrifuge method was devised by C.O. Hutton at Stanford University by shaping a pyrex test-tube in a blow-torch to the shape shown in Fig.16. After centrifugation the tube is plugged at the neck by a rubber stopper during decantation of the liquid from the upper part of the tube. This method is very successful, not only in the routine separations of heavy fractions in bromoform, but also for the recovery of certain minerals by the use of other liquids, such as methylene iodide or Clerici solution.

Bromoform, and the organic liquids in general, are soluble in many organic solvents, such as alcohol, benzene, carbon tetrachloride, acetone, etc. Acetone is especially desirable as being relatively cheap and soluble in water, but very volatile and inflammable. It is not highly toxic as are bromoform, the benzinoid compounds and carbon tetrachloride.

When sufficient bromoform and acetone mixture have accumulated to make recovery worthwhile, it is transferred to a separatory-funnel, with water added, and allowed to stand until there is a clear line of separation apparent. The bromoform is then drained into a stock-bottle. If it is very dark colored it is contacted with alcoholic potassium hydroxide; otherwise with fuller's earth. Thereafter it is filtered and calcium chloride is added to remove water. It is then ready for re-use.

Magnetic susceptibility

Minerals vary greatly in their magnetic susceptibilities. A *paramagnetic* mineral is one that, when placed in a magnetic field, becomes magnetized in the same direction as the field, in proportion to it, and is attracted into the field. A *ferromagnetic* mineral becomes magnetized in the same direction as the field, but much more strongly, and

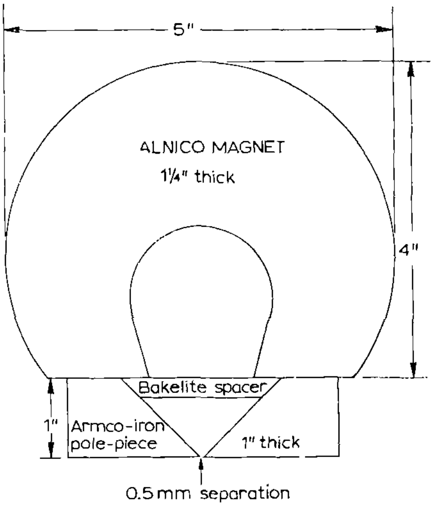

Fig.17. 5-inch Alnico magnet.

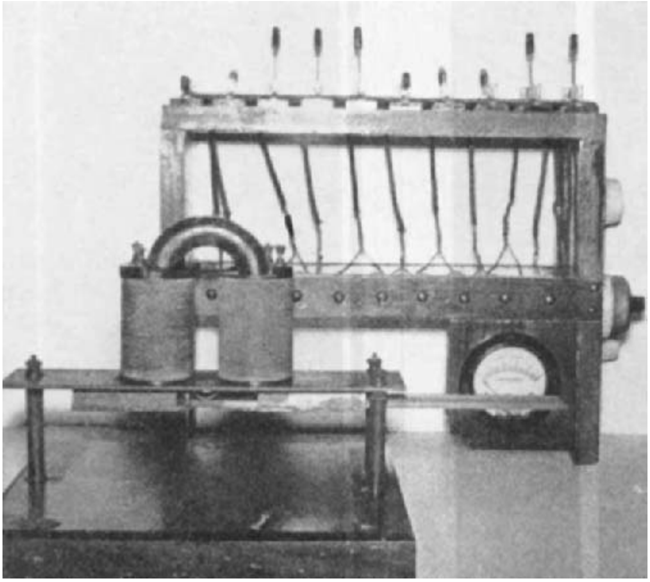

Fig.18. Electro-magnet.

not in proportion to it. A *diamagnetic* mineral (of which there are very few, like molybdenite) becomes magnetized in a direction opposed to that of the field and in proportion to it.

The highly magnetic minerals may be removed from the others by means of a permanent "horseshoe" magnet, over the pole-pieces of which is held a piece of filter-paper. The less magnetic minerals require the use of an electro-magnet.

A permanent magnet, however, that is strong enough to lift moderately magnetic minerals may be made from a 5-inch Alnico magnet, as illustrated in Fig.17. In use, a piece of paper is held under the pole-pieces while minerals are being lifted, and means may be devised to control and vary the distance between minerals and pole-pieces. Alternatively, the minerals may be placed in covered Petri dishes.

A simple electro-magnet is shown in Fig.18. The 1-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 copper 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 may be 110 V d.c., with an external variable resistance of 500 Ω, 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 mineral grains and 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.

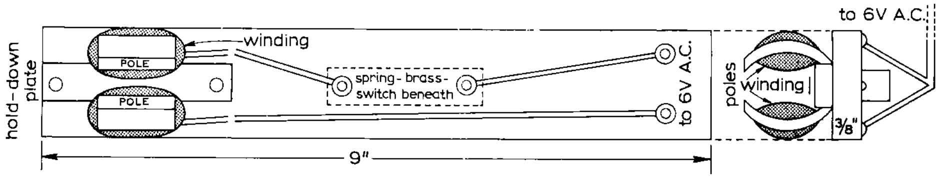

Fig.19. Alternating-current hand-magnet.

With this magnet, separation of grains is carried out by sprinkling the sized material on the long brass tray that is shown in the figure as resting on guides beneath the pole-pieces. When the current is switched on, the tray is drawn out slowly so as to expose all of the minerals to the poles. The current is then switched off, while a dish is held under the poles, and a brush is applied in order to clean the pole-pieces. The rheostat is then changed to less resistance, the brass tray is re-inserted, and the process repeated, thus continuing until the greatest strength of the magnetic flux is reached, the residue being non-magnetic.[1]

In the preliminary treatment of field-samples of fragmental material, a magnet of the kind illustrated in Fig.19 is very convenient and is as designed by C. O. Hutton of Stanford University. The base is a wooden slat, to which are fastened the pole-pieces, switch, etc. The pole-pieces are made from a single cut (1 inch long) of 1 inch diameter iron pipe, which has shape as shown in the figure. The winding consists of about 250 turns (on each pole) of No.30 lacquered, copper wire. The winding is clockwise on one pole and counter-clock-wise on the other.

Alternating current is taken from a 6-V bell-transformer. Holding the switch closed, the pole-pieces are applied to the batch of grains, stirring them with the magnet, thus picking up a load of magnetite, which drops as soon as the switch is released.

The Frantz isodynamic magnetic separator

The Frantz Isodynamic Separator is an electromagnetic device (Fig.20) with which precision mineral separations may be made. Gaudin and Spedden (1943) describe the instrument as consisting of:

(*1*) A powerful magnet, controlled by a variable transformer, which supplies power through a silicon rectifier, with provisions for current control and measurement.

(*2*) A vibrating chute of non-magnetic metal upon which the mineral to be separated is made to flow, with a potentiometer for adjusting the intensity of vibration.

(*3*) The chute is located in the air-gap between the pole-pieces and is divided, part way down, into two passages by a splitting-ridge, thus directing the products into two separate containers.

(*4*) The longitudinal slope of the chute may be varied between 0 and 90°, and the cross-slope may be varied between 0 and 90° in either direction.

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[1] If direct current is not available from the house-current it may be obtained from the alternating current supply by means of a diode rectifier at moderate cost.

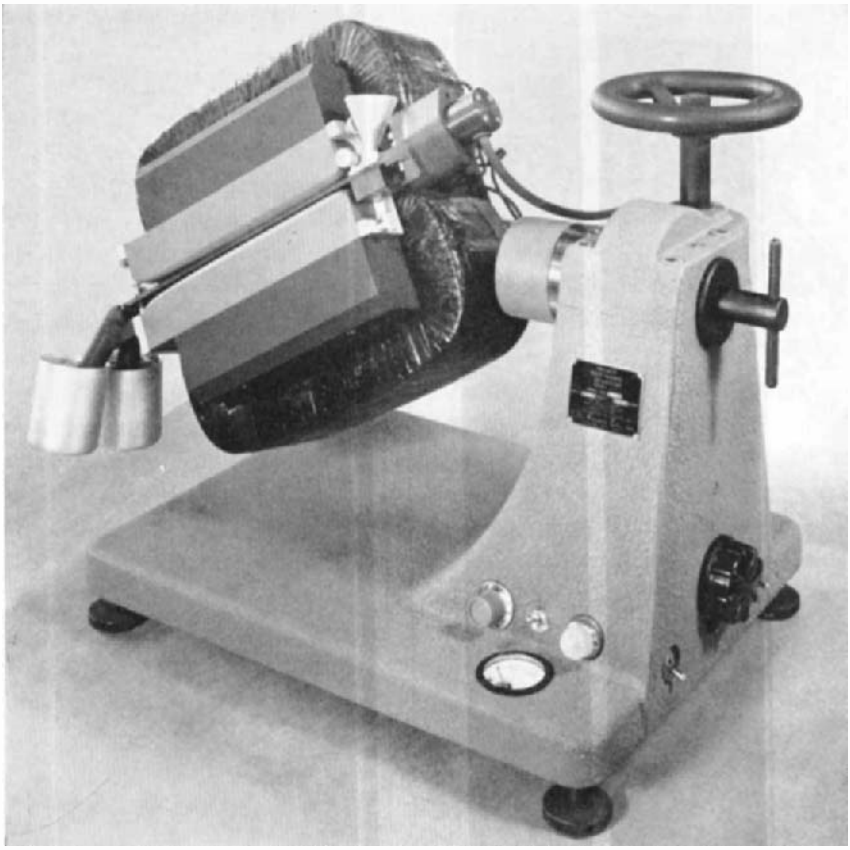

Fig.20. Isodynamic magnetic separator. (By permission from S.G. Frantz Co., Inc.)

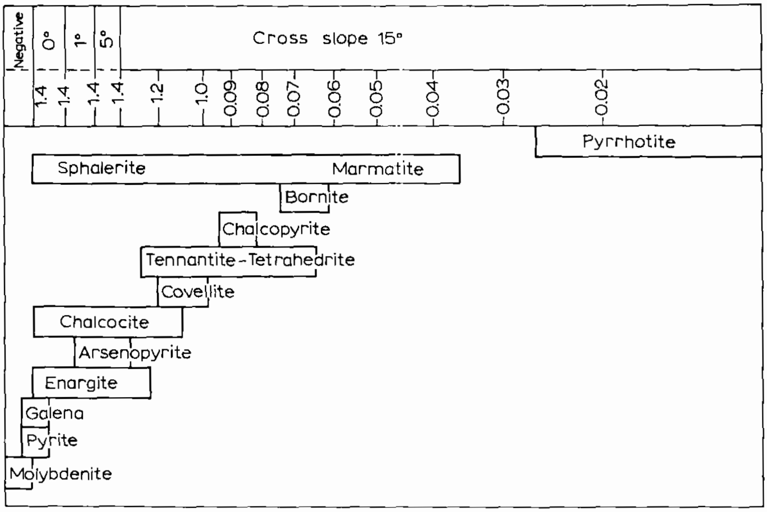

Fig.21. Magnetic response of the sulphide minerals in the Frantz isodynamic magnetic separator. (After GAUDIN and SPEDDEN, 1943.)

TABLE XVII

COMMON MINERALS OF SEDIMENTARY ROCKS ARRANGED IN GROUPS BASED ON MASS MAGNETIC SUSCEPTIBILITY[1]

(After FLINTNER, 1959)

Side slope 20°			*Side slope 5°*			*Reversed side slope*
A hand magnet	*B* magnetic at 0.4 A	*C* magnetic at 0.8 A	*D* magnetic at 1.0 A	*E* magnetic at 1.2 A	*F* non-magnetic at 1.2 A	*G* diamagnetic 1.2 A
Magnetite	Chloritoid	Actinolite	Clinozoisite	Andalusite	Anatase	Galena
Pyrrhotite	Chromite	Augite	Diopside	Apatite	Anhydrite	Molybdenite
	Garnet	Biotite	Enstatite	Leucoxene	Beryl	Pyrite
	Ilmenite	Chlorite	Muscovite	Monazite	Brookite	
	Olivine	Epidote	Spinel	Sphene	Corundum	
		Hornblende	Staurolite(light)	Xenotime	Fluorite	
		Hypersthene	Tourmaline(light)		Kyanite	
		Staurolite	Tremolite		Pyrite	
		Tourmaline(dark)	Zoisite		Rutile	
					Sillimanite	
					Topaz	
					Zircon	

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[1] As determined with the Frantz isodynamic magnetic separator.

When the chute is used in a vertical position the separator is suitable for treating free-flowing sands in the range of 30 – 100 mesh, and these can be fed at rates up to 20 lb./h for heavy sands. Repeated passes may be necessary for best results.

For precise separations the sample should be sized in the range −80 to +100 or −100 to +120 mesh. The largest advisable size is about 30 mesh, and +400 mesh is about the smallest.

The sample should be washed in water to remove dust, and magnetite or iron filings removed with a hand-magnet previous to this to avoid staining of the grains by iron oxide.

Normally, side-slope of 20° and forward-slope of 30° is used, although FLINTNER (1959) recommends a side-slope of 25°. He claims that the effective separation of minerals according to their mass-magnetic susceptibilities depends principally upon a fine balance between gravity (controlled by variation in the side-slope) and field strength (controlled by the current used). Other factors, such as forward-slope, rate of feed, and grain size, are subsidiary provided that they fall within certain broad limits.

Reversed side-slope may be used for the separation of such non-magnetic minerals as galena, pyrite, and zircon, and for the diamagnetic mineral molybdenite. Fig.21 shows graphically the response of the sulphide minerals in the Frantz Isodynamic Separator (Fig.20).

Electric conductivity

Electrical high tension mineral separation

High tension mineral separation is used in ore-beneficiation experiments and for commercial beneficiation of certain ores and crude mineral products. The method has been fully explained by BARTHELEMY and MORA (1960), and a rotary-type separator is made by Carpco Mfg. Co. of Jacksonville, Florida, and by Westinghouse Mfg. Co.

In the application of this method a corona field develops between an electrically charged cable and a grounded surface. The surrounding air is ionized and the negative ions come in contact with any particles that may rest on the grounded surface. If such a particle is a conductor, anions (+) will leak to the ground, but if the particle is a perfect insulator there will be no leakage. With a perfect conductor, no charge could build up on it, but with a perfect insulator the charge would reach a maximum. As a result of these forces the non-conducting particles will stay on the plate and the conducting particles will be lifted from the plate by the electrical forces. The Carpco instrument is shown diagrammatically in Fig.22.

Dielectric strength

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

TABLE XVIII

HIGH TENSION MINERAL SEPARATION WITH THE CARPCO HIGH TENSION LABORATORY SEPARATOR

S.g.	*Non-conductors (attracted)*			*S.g.*	*Conductors (not attracted)*		
	magnetic		*non-magnetic*		*magnetic*		*non-magnetic*
	strongly	*weakly*			*strongly*	*weakly*	
>8			Thorianite	>8			Copper Gold Iridosmine Platinum Silver
8			Cinnabar	8			
7½				7½		Wolframite	Galena
7				7	Ferberite	Ferberite	Cassiterite
6½				6½			
6			Scheelite	6		Columbite Tantalite	Arsenopyrite
5½			Baddeleyite Chalcocite Cuprite	5½		Martite	Chalcocite
5		Bastnäsite Monazite		5	Magnetite	Euxenite Hematite Samarskite	Bornite Marcasite Pyrite
4½	Xenotime	Fayalite Hematite Romeite	Barite Molybdenite Rutile Scheelite Zircon	4½	Davidite Ilmenite Pyrrhotite	Chromite Pyrolusite Pyrrhotite	Corellite Molybdenite
4	Garnet Siderite	Chromite Epidote Xenotime	Celestine Corundum Kyanite Perovskite Psilomelane	4		Goethite	Chalcopyrite Sphalerite
3½	Staurolite	Aegirine Apatite Hornblende Olivine Riebeckite	Axinite Diamond Diaspore Sillimanite Sphene Spinel Staurolite Topaz	3½		Diopside Enigmatite Hornblende Hypersthene Piedmontite	Anatase Brookite Chrysoberyl Limonite
3		Biotite Crossite	Andalusite Anhydrite	3		Actinolite Augite	Apatite Euclase

TABLE XVIII (continued)

S.g.	*Non-conductors (attracted)*			*S.g.*	*Conductors (not attracted)*		
	magnetic		*non-magnetic*		*magnetic*		*non-magnetic*
	strongly	*weakly*			*strongly*	*weakly*	
3		Epidote Tourmaline	Ankerite Chlorite Fluorite Muscovite Sillimanite Spodumene	3		Barkevikite Biotite Glaucophane Oxyhornblende	
2½		Cordierite Glauconite	Beryl Calcite Dolomite Feldspars Gypsum Quartz	2½		Iddingsite Phlogopite	Graphite
<2			Chrysotile Sulphur	<2			Amber

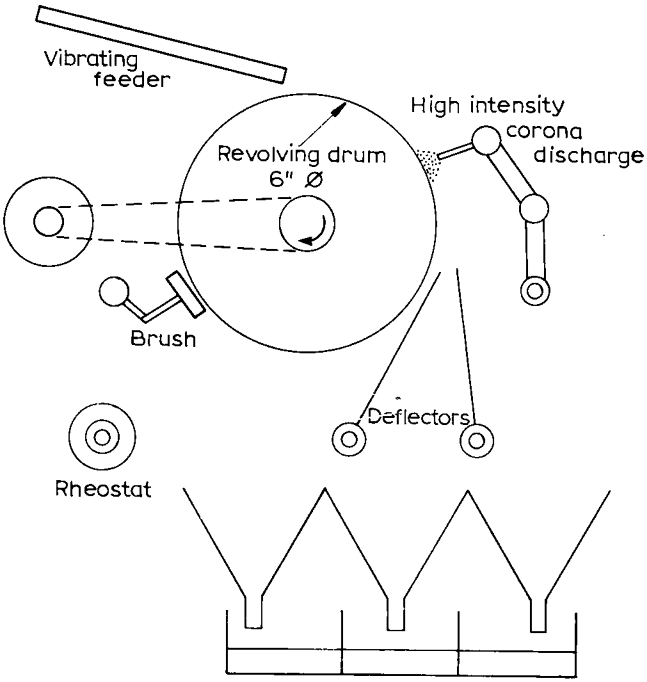

Fig.22. Carpco high tension laboratory separator.

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 and HOLMAN (1924), 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.

Fig.23. 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; × 70.

Fig.23 illustrates the effect as carried out on a very small scale in the laboratory, with nitrobenzene as liquid.

BRIEN (1963) refers to a russian paper describing laboratory experiments with this method in which the electrodes are two horizontal plates, so arranged that the minerals of greater dielectric constant are attracted to the upper electrode and those of lower dielectric constant to the lower electrode. Experiments using tantalite, tourmaline, beryl, quartz, and a number of other minerals were said to be highly satisfactory. Mixtures of nitrobenzene and kerosine were used as liquid medium.

POHL and PLYMALE (1959) describe a glass cell for continuous di-electrophoresis, and experiments on the separation of such minerals as corundum, quartz, fluorite, rutile, and zircon. They used a dielectric mixture of carbon tetrachloride and benzene.

Surface energy

Flotation separation of sulphide or metallic minerals from silicates, quartz, or certain other minerals may be accomplished on a laboratory scale with a suitable cell that provides for mechanical agitation of the finely divided minerals in an aqueous suspension and on a sample of mineral-mixture as small as 20 g.

In general, three kinds of reagents are added: (*1*) a frothing agent, such as pine-oil; (*2*) a collecting agent, such as sodium xanthate, which alters the surface of the sulphide mineral so as to make it less easily wet by water; (*3*) a reagent to increase the wetting of the non-sulphide minerals by water and to decrease their flotability. The reagents are added in very small proportions as, otherwise, a heavy scum may form, incorporating the sulphide minerals and sinking to the bottom of the cell.

Upon mechanical agitation of such a mixture the sulphide minerals are coated with thin oil films, making them less readily wetted by water. The froth produced during agitation makes air-bubbles adhere to the oiled surfaces of the sulphide minerals and causes them to float, while the other minerals sink to the bottom. The froth is repeatedly skimmed from the surface until the separation is complete, after which the froth is treated with a suitable solvent to remove the oil and other additives.

Detection of radioactive mineral grains

A method for the determination of radioactive mineral grains is described by TYLER and MARAIS (1941). They say that Geiger–Muller counters are not well adapted for accessory-mineral concentrates because they have a background level that must be surpassed by emanations from the sample before reliable recordings can be made. Measurements cannot be made upon samples that fall below a certain level in radioactivity.

A photographic method is recommended, in which the mineral grains are scattered on a glass plate and taken to the dark-room. A fine-grained glass negative is placed for 1 min in distilled water to soften the emulsion and then laid down, emulsion-side up, and the glass slide held over it and tapped so as to make the grains fall onto the emulsion and be imbedded into it. The exposure period depends upon the radioactivity of the sample and the number of alpha-particle-tracks desired. The plate is developed in a high-contrast developer. It should be examined through a microscope with a magnification of 200 ×.

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 and BERMAN (1934) recommend 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 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 (Ny).

Permanent mounts are usually made in Canada balsam ($N_D = 1.54$). Hyrax, another synthetic resin ($N_D = \pm 1.80$), is excellent where a highly refringent medium is desired.

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. Solidification of the balsam in the mount may be hastened by curing in an oven for 6 or 8 h at 65–70°C.

For microscopic oil-immersion studies, LANGFORD (1962) recommends a transparent epoxy mounting medium, (such as Lepage's or Borden's), spread on a slide in a very thin film so that only *part* of the grain is imbedded. Index-liquids may then be applied. After application of the cement, it is heated at 80°C for 2 h. The refractive index is 1.55 and it is not affected by xylene or ordinary solvents.

If the grains are 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 12 h 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 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. The refractive index of 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 2 h at 85°C, and for 8 h 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 (1928) and HEAD (1929).

Making of thin sections

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.

(*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 Lakeside 70C[1]. 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 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 p. 78).

(*5*) The section has a cover-glass placed thereon with liquid Canada balsam or Permount ($N_D = 1.53$).

The clay minerals may be distinguished in either thin section or polished surface

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[1] Lakeside 70C brand of thermoplastic, transparent cement in bar form. Hugh Courtright and Co., Chicago, Ill. This resin has the same refractive index as Canada balsam (1.54), and is much superior to it as an adhesive and cement for thin section mounting.

by soaking for about 10 min in malachite green dissolved in xylene. 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 lucite 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./sq. inch until resin has melted. The temperature is then raised to about 290°F and the pressure to 2,500 lb./sq. inch 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.

A method not requiring use of a briquetting-press makes use of an epoxy-type resin, such as "Casto-Mold" (procurable from chemical supply houses). It consists of a pink powder and a colorless liquid. They are mixed in equal parts by volume. After a few minutes the mixture becomes syrupy and the mineral grains or fragments are stirred in, and the whole is poured into a silicone-greased mold or onto a glass microslide. The material hardens in 30 min and is red in color and opaque in bulk, but semitransparent in thin-section, and is hard and strong. If a thin-section is to be made the mineral grains should have quartz added to the mixture, in order to be able to judge, from the interference color, the proper thickness (0.03 mm) to attain in grinding.

The colorless, transparent epoxy material obtainable from hobby-shops may also be used. It takes longer to harden than the Casto-Mold and is inferior.

For the examination of opaque minerals the cast must be flattened by rubbing on the several grades of Turkish emery paper (1/0, 2/0, 3/0, and 4/0), followed by polishing on a glass plate with Linde A ruby-powder (corundum) and, for the very best results, on 2-μ diamond-grit paste on a copper lap or vibrating plate.

For microscopic study of the polished surface, etch reactions may be produced by the application of chemical reagents. CAMERON (1961) states that in many anisotropic, opaque minerals zonal growths, twinning, and texture become clearly visible only after etching, and that etching even of isotropic minerals reveals significant features. He points out that structure-etching is based on the fact that the solubility of minerals varies both with direction and composition, and that for successful etching the concentration of the reagent and the time of etching are both critical.

If the concentration is too high or the etching is too prolonged the surface will be deeply corroded and will appear black in reflected light.

Insoluble residues

Limestones, dolomites, and other non-clastic rocks are sometimes studied from their hydrochloric acid insoluble residues. Geologists commonly find this method valuable in stratigraphic correlation where paleontological evidence is lacking.

The insoluble minerals separated by this method are most frequently chert, chalcedony, disseminated silica, clastic and crystalline quartz, aluminous matter, and

TABLE XIX

REAGENTS USED AS ETCHANTS

(After SHORT, 1940)

Chemical composition	*Concentration (%)*
HNO_3	50
HCl	50
KCN	20
$FeCl_3$	20
KOH	40
$HgCl_2$	5
Aqua regia ($HCl + HNO_3$)	50
H_2O_2	commercial

replaced fossils. Other minerals sometimes encountered are anhydrite, gypsum, feldspars, glauconite, hematite, pyrite, fluorite, and sphalerite.

IRELAND (1936) treats this subject at considerable length.

Peel-prints

Limestones, sandstones, and other indurated sediments may be flattened, polished, and lacquer-coated for textural examination. MCCRONE (1962) explains how such a surface may be wet with acetone and cellulose acetate film applied to the wet surface. After drying for a few minutes the film is peeled off and will be found to contain a casting of the rock surface. Such peels may be used like photographic negatives to make enlarged positive prints.

Chapter 5

IDENTIFICATION OF MINERALS

THE NATURE OF MINERALS

A mineral may be defined as a crystalline substance, occurring in nature, formed by inorganic processes, and composed of an inorganic element or compound, which may be definite and specific, as for example quartz (SiO_2), or there may be other elements in the formula that are not always found. An example is iron in sphalerite (ZnS), sometimes as much as 36%. A mineral also has definite and specific physical properties, which may vary within a narrow range.

Substances, such as opal ($SiO_2.nH_2O$) are often referred to as amorphous, but are more recently regarded as microcrystalline. Naturally occurring organic compounds are often crystalline, but they are non-mineral. Mercury, as usually found in nature, is a liquid, but it crystallizes at $-39°C$ and is a mineral.

For the purpose of this book it is not thought necessary to discuss types of ionic bonding nor the ultimate composition of mineral space-lattices.

Minerals are commonly identified by a variety of properties. These, as well as the methods that are used for determination will be treated hereafter.

SPECIFIC GRAVITY

Specific gravity of mineral fragments of a size down to 1 cm^3 is readily determined with a laboratory balance by weighing in air and weighing as suspended by a thread in a liquid, such as distilled water, toluene, or carbon tetrachloride, for which the density is known. The following formula is then applied:

$$\text{Specific gravity} = \frac{\text{weight in air} \cdot \text{density of liquid}}{\text{weight in air} - \text{weight in liquid}}$$

The torsion microbalance (Berman, 1939) makes use of the same principle, but applies it with a minute mineral specimen resting first on a diminutive platinum pan attached to the platinum suspending-wire, for the weighing in air, and then resting in a minute platinum-wire basket and suspended from the lower end of the same wire. At this stage a cylinder of the liquid (usually toluene or carbon tetrachloride) is elevated from below until the specimen is submerged, after which it is again weighed by the torsion microbalance. Berman (1939) states that a microbalance with a sensitivity of 0.01 mg, handling 25 mg of material, where the density of the liquid is correctly known

TABLE XX

HARDNESS SCALE

Hardness No.	*Representative mineral*	
1	Talc	to be scratched by finger-nail
2	Gypsum	
3	Calcite	to be scratched by knife-blade
4	Fluorite	
5	Apatite	
6	Orthoclase	
7	Quartz	
8	Topaz	
9	Corundum	
10	Diamond	

to 0.001, and the sample has a specific gravity of 5.0, will yield an accuracy of about 0.2%, not taking into consideration a surface tension effect, but that experience with such a balance has shown that this effect can be minimized by using a suitable pan and liquid.

TWENHOFEL and TYLER (1941) mention the "sink-float" method wherein a mineral particle is immersed in a liquid of known density so as to observe as to whether it sinks, floats, or does neither. One should know the density/temperature relationship for the liquid used in order to attain any degree of accuracy. SULLIVAN (1927) gives values for a number of liquids at various temperatures. The author experimented with this method and does not recommend it, for it is inaccurate, difficult to manipulate with small specimens, and requires, for high density liquids, the use of very poisonous liquids such as thallous formate and thallous malonate.

SCRATCH HARDNESS

The scratch-hardness test is often indicative of mineral species. The hardness scale is given in Table XX.

Fig.24 shows the relationship between scratch-hardness and resistance to abrasion.

It should be noted that some minerals are harder to scratch in one direction than in another. Kyanite, notably, has a hardness of 4.5 parallel to crystallographic *c* and a hardness of 7.0 normal to *c*.

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.

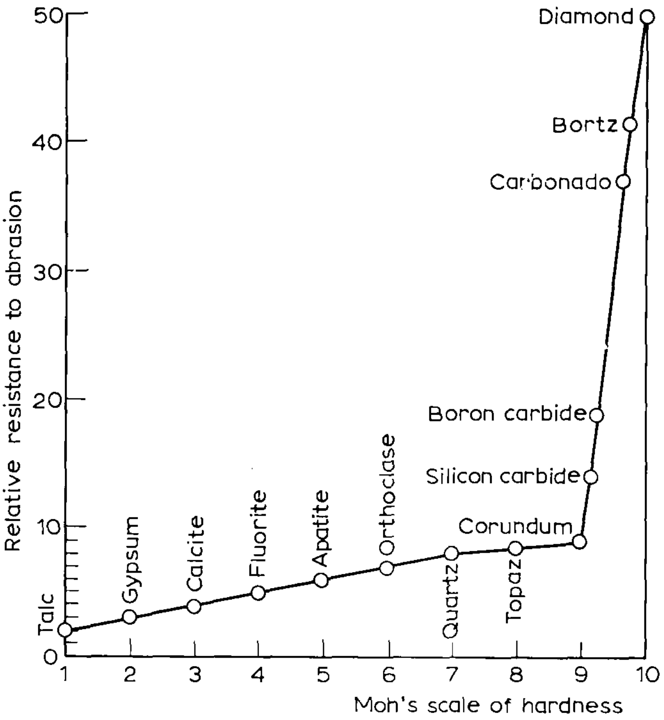

Fig.24. The Moh's scale of hardness. (After Dana and Hurlbut, 1959.)

Cleavage in a crystal is always parallel to a possible crystal face 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.

Prismatic cleavages in a mineral often make dihedral angles that are character-

TABLE XXI

CLEAVAGE FORMS

System	*Cleavages*	*Most characteristically parallel to*
Isometric	cubic	(001), (010), (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)

istic of the mineral or group. Thus the amphiboles have a prismatic angle of 124°, while pyroxenes have a prismatic angle of 87°. Also, in orthoclase there is cleavage parallel to (001) and to (010), making an angle of 90°, while in plagioclases the corresponding angle is about 86°.

TWINNING

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

Mineral grains can sometimes be identified by the type of twinning exhibited. Some of the notable ones are tabulated (see Table XXII).

TABLE XXII

CHARACTERISTIC TWINNING FORMS

Mineral	*Type of twinning*	*Name of twinning*	*Twinning plane*
Rutile	contact	knee	(101)
Staurolite	penetration	cruciform	(032) and (232)
Orthoclase	contact and penetration	Carlsbad	(010)
Plagioclase	contact	albite (polysynthetic)	(010)

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

Cleavage fragments of plagioclase will show either the (001) or the (010), but usually the (001) face. Polysynthetic albite twinning can be seen (with the polarizing microscope) on the (001), but not on the (010) face. It is always parallel to the (001)-(010) edge. Pericline twinning is also polysynthetic and is always, when present, shown on the (010) and (100) faces. It is parallel to the basal cleavage only in the case of andesine. This is shown in Fig.25. 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.26.

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

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

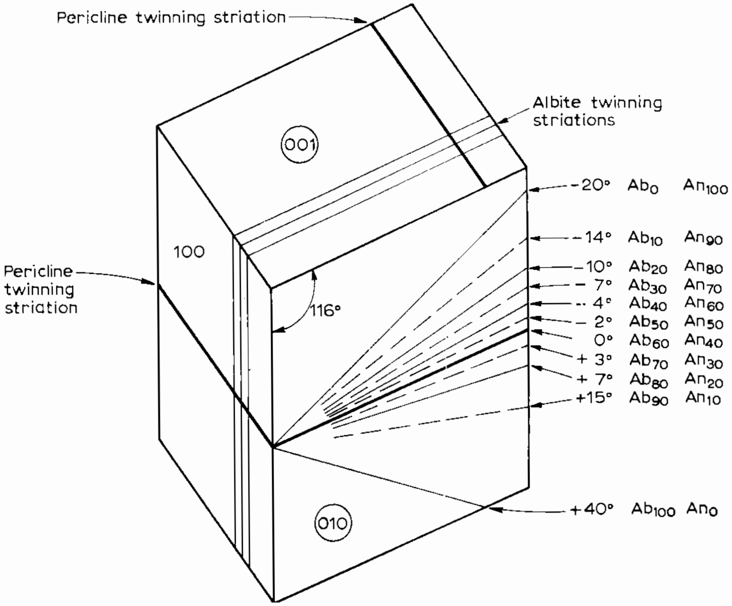

Fig.25. Plagioclase cleavage flake, showing relation of pericline twinning striations to cleavage flakes. Faces with symbols encircled (on their opposites) are the ones seen in cleavage flakes.

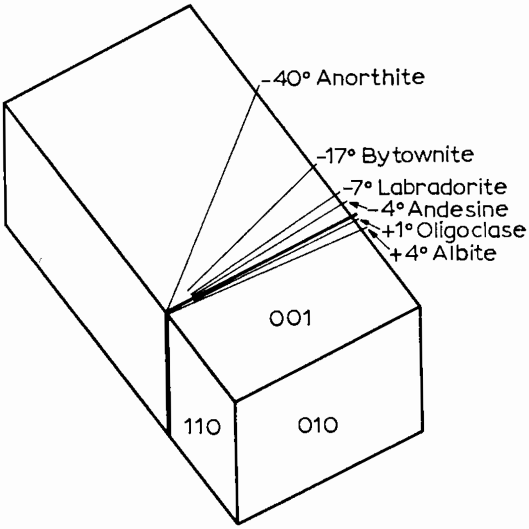

Fig.26. Plagioclase cleavage flake, showing angles between albite twinning striations (heavy line) and vibration direction on the fast ray.

CRYSTALLOGRAPHY, SYSTEMS AND CLASSES

The fourteen lattices

The ions or atoms constituting a crystal are arranged in repeating three-dimensional units (Fig.27). In 1848 Bravais proved that there could be only fourteen kinds of these units, and they are known as the *Bravais space-lattices* (Fig.28).

There are limited ways in which ions or atoms may be arranged so as to constitute a unit of a space-lattice, thus limiting the possible number of lattices to fourteen.

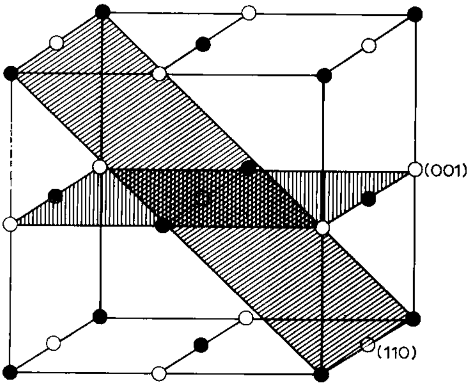

Fig.27. Cubic space-lattice of sodium chloride, with two of the many possible atomic-planes. ● = sodium ion; ○ = chlorine ion.

The crystal systems

A crystal is characterized by its symmetry, which results from the arrangement of the ions or atoms within the unit-cell of the space-lattice. It is usually described with respect to three axes of reference: a vertical (*c*) axis, a right–left (*b*) axis, and a front–back (*a*) axis. If these are not at right angles to one another the convention is to name as beta (β) the angle between *c* and *a*, name as alpha (α) the angle between *c* and *b*, and as gamma (γ) the angle between *a* and *b*. The axes may or may not be of equal length. In the case of one system (the hexagonal) there are three horizontal axes at 60° to one another and at right angles to the vertical (*c*) axis.

Isometric system: the *a*, *b*, and *c* axes are of equal length and at right angles to one another.

Tetragonal system: the axes are at right angles to one another, one being longer or shorter than the other two.

Hexagonal system: three equal axes are in the same plane and at angles of 60° to one another. The other axis, shorter or longer than the others, and at right angles to them.

Orthorhombic system: three axes are at right angles to one another and all of different lengths.

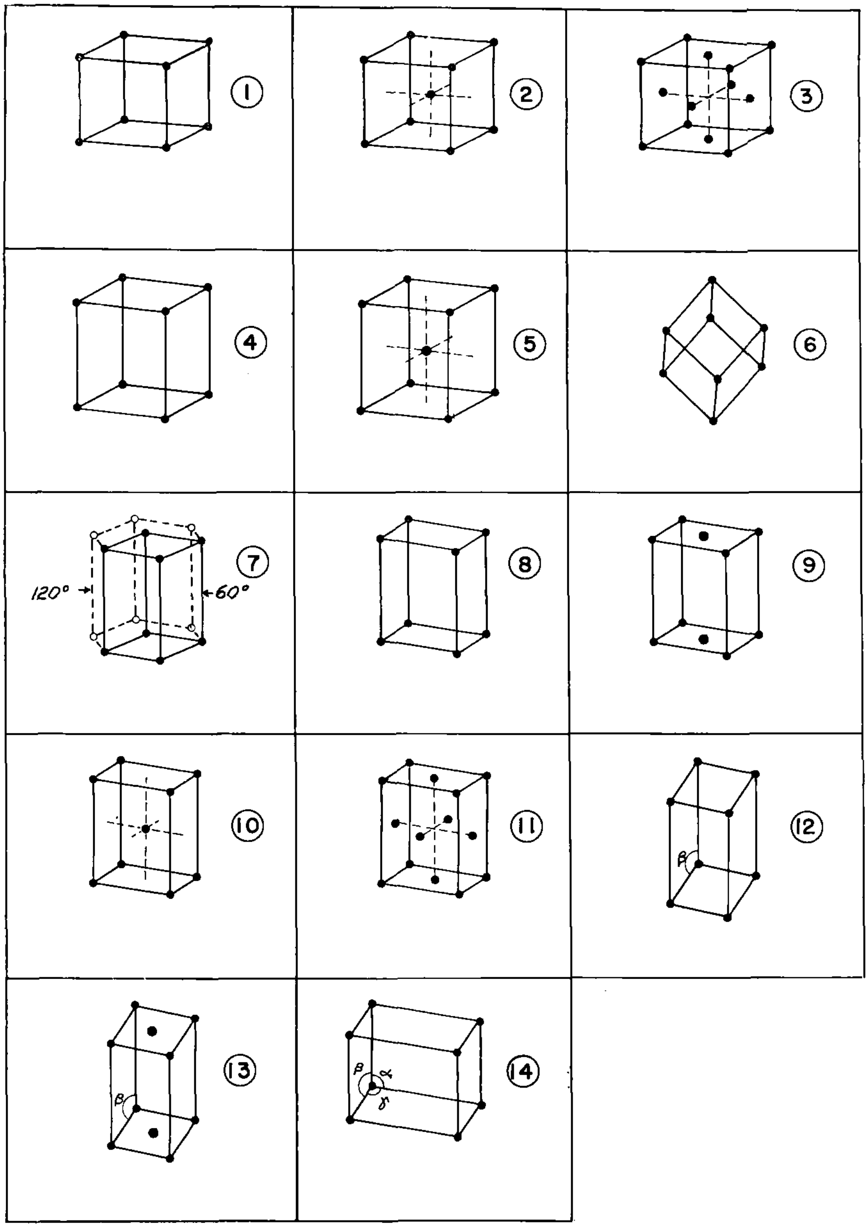

Fig.28. The Bravais space-lattices.

System	*Form*	*System*	*Form*
1. Isometric	simple cube	8. Orthorhombic	simple prism
2. Isometric	body-centered cube	9. Orthorhombic	base-centered prism
3. Isometric	face-centered cube	10. Orthorhombic	body-centered prism
4. Tetragonal	simple prism	11. Orthorhombic	face-centered prism
5. Tetragonal	body-centered prism	12. Monoclinic	simple prism
6. Hexagonal	rhombohedron	13. Monoclinic	base-centered prism
7. Hexagonal	prism	14. Triclinic	prism

Monoclinic system: three unequal axes, two of which are not at right angles, and a third that is normal to the plane of the other two.

Triclinic system: three unequal axes, all intersecting at oblique angles.

Symmetry

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 given in Table XXIII.

Tetragonal system: A crystal is tetragonal if it has one, and only one, rotational axis of fourfold symmetry. Common tetragonal forms are given in Table XXIII.

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 given in Table XXIII.

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

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 given in Table XXIII.

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.29)

Hand specimens of crystals are conventionally oriented as follows:

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

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

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

TABLE XXIII

THE THIRTY-TWO CRYSTAL CLASSES

System	*Class*	*Symmetry*[1]	*Example*
Isometric	Hexoctahedral	$3A_4:4A_3:6A_2:9P$	Galena
	Gyroidal	$3A_4:4A_3:6A_2$	NH_4Cl
	Hextetrahedral	$3A_2:4A_3:6P$	Tetrahedrite
	Diploidal	$C:3A_2:4A_3:3P$	Pyrite
	Tetradoidal	$4A_3:3A_2$	Cobaltite
Tetragonal	Ditetragonal–dipyramidal	$A_4:4A_2:5P:C$	Cassiterite
	Tetragonal–trapezohedral	$A_4:4A_2$	Phosghenite
	Ditetragonal–pyramidal	$A_4:4P$	Diaboleite
	Tetragonal–scalenohedral	$3A_2:2P:AP_4$	Chalcopyrite
	Tetragonal–dipyramidal	$A_4:P:C$	Scheelite
	Tetragonal–pyramidal	A	Wulfenite
	Tetragonal–disphenoidal	AP_4	Cahnite
Hexagonal (Rhombohedral division)	Hexagonal–scalenohedral	$C:A_3:3A_2:3P$	Calcite
	Trigonal–trapezohedral	$A_3:3A_2$	Quartz
	Ditrigonal–pyramidal	$A_3:3P$	Tourmaline
	Rhombohedral	$C:A_3$	Dioptase
	Trigonal–pyramidal	A_3	$NaIO_4\cdot3H_2O$
Hexagonal (Hexagonal division)	Dihexagonal–dipyramidal	$A_6:6A_2:7P:C$	Beryl
	Hexagonal–trapezohedral	$A_6:6A_2$	Quartz
	Dihexagonal–pyramidal	$A_6:6P$	Zincite
	Ditrigonal–dipyramidal	$1A_3:3A_2:3P:(P)$	Benitoite
	Hexagonal–dipyramidal	$A_6:P:C$	Apatite
	Hexagonal–pyramidal	A_6	Nepheline
	Trigonal–dipyramidal	$A_3:1P:C:A_6$	Ag_2HPO_4
Orthorhombic	Rhombic–dipyramidal	$C:3A_2:3P$	Barite
	Rhombic–disphenoidal	$3A_2$	Epsomite
	Rhombic–pyramidal	$1A_2:2P$	Hemimorphite
Monoclinic	Prismatic	$C:1A_2:1P$	Gypsum
	Sphenoidal	$1A_2$	Sucrose
	Domatic	1P	Clinohedrite
Triclinic	Pinacoidal	C	Chalcanthite
	Pedial	none	$CaS_2O_3\cdot6H_2O$

---

[1] Symmetry notation. A, A_2, A_3, etc., indicate 1, 2, or 3 rotation-axes of symmetry; P = plane of symmetry; C = center of symmetry; *AP* = axis of rotary inversion or reflection.

Example: $A_6:6A_2:7P:C$ denotes a 6-fold axis of rotation; six 2-fold axes of rotation; 7 planes of symmetry; and a center of symmetry.

The Hermann–Maguin symmetry symbols are not used here, although they have been accepted by international agreement, but they are less easy to understand and do not seem suitable for this book.

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

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.30.

The crystal classes

Within each crystal system there are two or more crystal classes, according to their symmetries, as identified by axes, planes, and center of symmetry, axis of rotation and axes of rotary inversion or reflection.

TABLE XXIV

THE CRYSTAL CLASSES

System	*Number of classes*
Isometric	5
Hexagonal	
Hexagonal division	7
Rhombohedral division	5
Tetragonal	7
Orthorhombic	3
Monoclinic	3
Triclinic	2

Thus, there are only 32 possible variations of the symmetry elements, that is to say, there are 32 and only 32 crystal classes. The space-lattices are represented in the different crystal systems as shown in Fig.28.

Crystal notation

Crystal faces are designated by their intercepts on three axes (four in the case of the hexagonal system). Fig.30 shows the conventional form with a crystal-face intercepting the positive axes. The letters *a*, *b*, and *c* also designate the axial intercepts, and these are called the *parameters* of the face, $a : b : c$ being its parametric ratio.

Crystal faces of a given crystal cannot be in any random position. They are

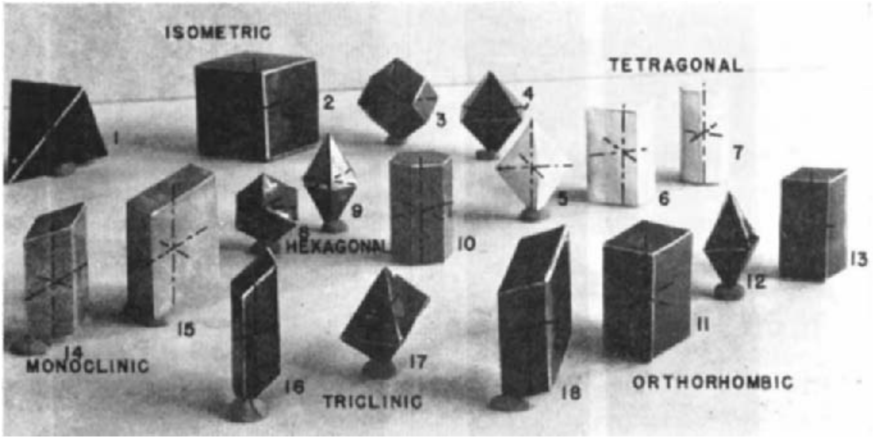

Fig.29. Crystal forms.

System	*Form*	*System*	*Form*
1. Isometric	Tetrahedron	10. Hexagonal	Prism
2. Isometric	Cube	11. Orthorhombic	Prism
3. Isometric	Rhombic dodecahedron	12. Orthorhombic	Bipyramid
4. Isometric	Octahedron	13. Orthorhombic	Prism
5. Tetragonal	Bipyramid	14. Monoclinic	Prism
6. Tetragonal	Prism	15. Monoclinic	Prism
7. Tetragonal	Ditetragonal prism	16. Triclinic	Prism
8. Hexagonal	Rhombohedron	17. Triclinic	Bipyramid
9. Hexagonal	Bipyramid	18. Triclinic	Prism

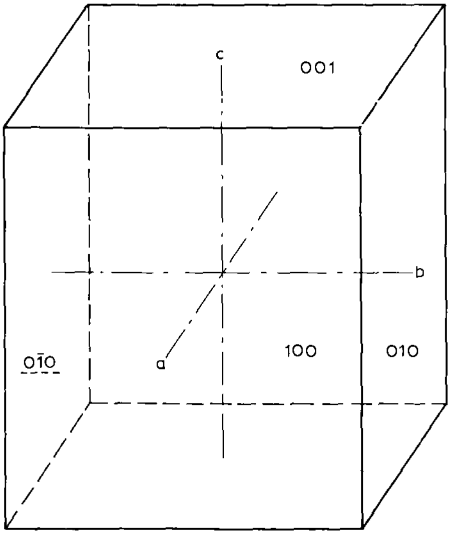

Fig.30. Orientation of an orthorhombic crystal.

dependent on the configuration of their space-lattices of the Bravais classification (Fig.28).

The intercepts of a crystal face on the axes is usually expressed by the *Miller indices*, which are derived by taking the reciprocals of the parameters of the crystal face and clearing of fractions, so that the symbols are in unit numbers. If the parameters are $a : b : c = 1 : 1/2 : \infty$, the reciprocals are $1 : 2 : 1/\infty = 1 : 2 : 0$, and the Miller indices are written (120). The generalized expression is (hkl), so that if not all are known we may write (hol), (hko), (o$\bar{k}$l), etc.

The most common forms taken by the symbols are illustrated by the examples given in Table XXV.

TABLE XXV

COMMON MILLER INDICES

Crystal face	*Miller symbol*
A front cube or prism face	(100)
Aside cube or prism face	(010)
A diagonal (45°) prism face	(110)
A base	(001)
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*.

OPTICAL PROPERTIES

Polarization

(*1*) The mineral remains dark at all positions of the stage when nicols are crossed. (*a*) Conoscopic observation 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 incomplete extinction for white light is due to dispersion. 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 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.

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 (Fig.31).

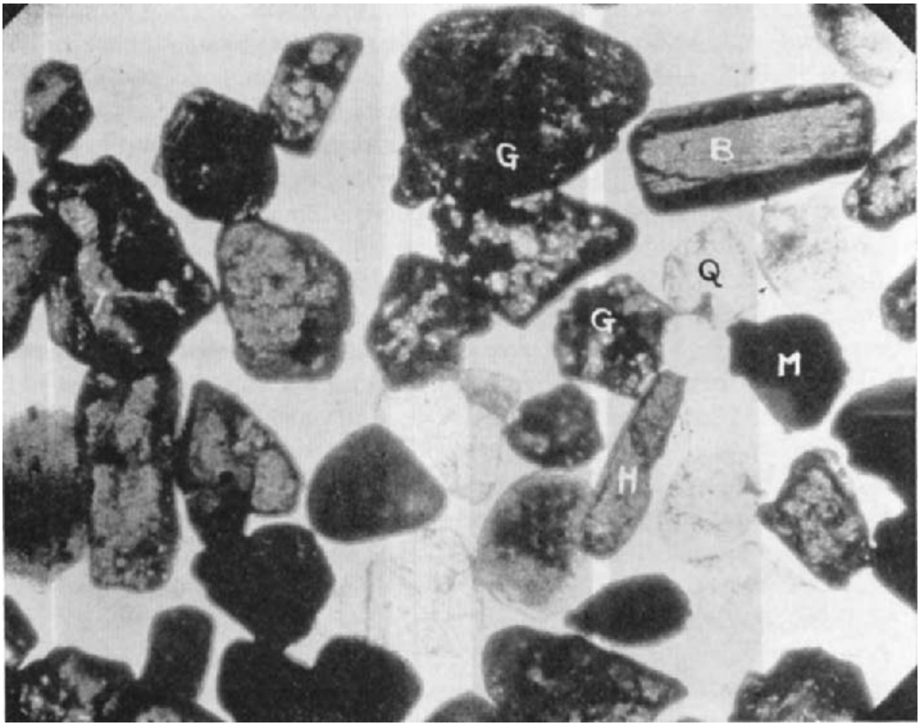

Fig.31. Mineral grains showing degrees of relief; × 45. *B* = basaltic hornblende with high relief; *G* = garnet with very high relief; *H* = hypersthene with high relief; *M* = magnetite with opaque relief; and *Q* = quartz with low relief.

TABLE XXVI

RELIEFS IN CANADA BALSAM

Refractive index (N_D)	*Relief*
1.49	very low
1.50–1.59	low
1.60–1.69	medium
1.70–1.74	high
1.75–1.99	very high
2.00–2.60	extremely high

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 and BERMAN (1934), a set of liquids may be compounded that differ in index from one another by 0.005 up to 1.70. Such a set may be purchased in sets of $\frac{1}{4}$ fluid ounce bottles with applicator-rods, and ranging in index from 1.40–1.70 with intervals of 0.01, 0.002, or 0.004, depending on the cost.

A set of immersion liquids (Table XXVII) consists of pure organic compounds that 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.

Index liquids are likely to change slightly with the passage of time and it may be

TABLE XXVII

REFRACTIVE INDICES (N_D) OF SOME COMMON LIQUIDS

Liquid	*Index*
Water	1.33
Alcohol	1.36
Kerosine	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-Monobromonaphtalene	1.65
Methylene iodide	1.74
Methylene iodide and sulphur	1.79
Tetra-iodo-ethylene	1.81
Phenyl di-iodo arsine	1.84

desirable to test them periodically. The Abbé refractometer is the preferred instrument for this purpose because only one drop of the liquid to be tested is required and because provisions are made for accurate temperature control and compensation of white light to standard monochromatic light.

For liquids of index greater than 1.71 the Jelley microrefractometer is available, with monochromatic light provided by a built-in lamp and filter, so that the sodium line may be isolated.

General procedure

For dry, granular, sized material, sprinkled on a glass slide and observed through a low-power microscope, individual grains may be lifted by a slightly oiled needle and transferred to another slide, immersed in a test liquid. If the index of the mineral does not match that of the liquid the grain is transferred to another slide, with another liquid, and the process is repeated.

Indices of 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 ($N\varepsilon > N\omega$) and the mineral is said to be optically (+). If $N\omega > N\varepsilon$, the mineral is (—). If the mineral lies on a prism face or cleavage, the index for the extraordinary ray ($N\varepsilon$) 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 ($N\omega$). 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 ($N\omega$). The other index ($N\varepsilon$) can be obtained only by taking for a number of grains the maximum or minimum index, according as the optical character is (+) or (—). If the mineral is known to be negative, e.g., scapolite:

(*1*) Place the grain in subtractive position with respect to the accessory-plate.

(*2*) Rotate to extinction in the plane of the polarizer, and remove the analyzer.

(*3*) One now views the ordinary ray, and can measure the index of the same as the maximum index.

Biaxial minerals

Biaxial minerals have two optic axes, neither of which is parallel with *c*. There are three directions in which light travels at different velocities, and hence three indices. *Nx*, *Ny*, and *Nz* are the three indices in order of decreasing magnitude, *Ny* being

Fig.32. Biaxial; section cut normal to acute bisectrix; crystal 45° to extinction.

intermediate but not necessarily having a mean value. *Nx* is the index of the *fast ray* and *Nz* the index of the *slow ray*.

When *Nz* is parallel to the line bisecting the acute angle between the optic axes the mineral is optically (+). If *Nx* is parallel to this line, the mineral is (—). If the optic axes intersect at 90°, the mineral is optically neutral. If a grain can be found that gives an acute bisectrix interference figure (Fig.32) 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 *Nz* or *Nx* according as the mineral is optically (+) or (—). The index for a vibration direction normal to the axial plane will be *Ny*.

LARSEN and BERMAN (1934) state: "If β[1] is measured, the other indices can be estimated from the birefringence and the axial angle. For any grain or any orientation, β lies between the highest and the lowest values measured. Therefore, β can be measured on a grain that shows no measurable birefringence. Such a grain is nearly normal to an optic axis and is usually suitable for observing the optical character, the size of the axial angle, and the dispersion of the optic axes. If the dispersion is considerable, it will give abnormal interference colors without extinction."

Birefringence

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

The light transmitted through an anisotropic mineral in any direction 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 ($\pm N\varepsilon \mp N\omega$ or $Nz - Nx$), 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

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[1] To avoid confusion with the angles, the indices of the biaxial minerals are given in this book as *Nx*, *Ny*, and *Nz*, instead of α, β, and γ.

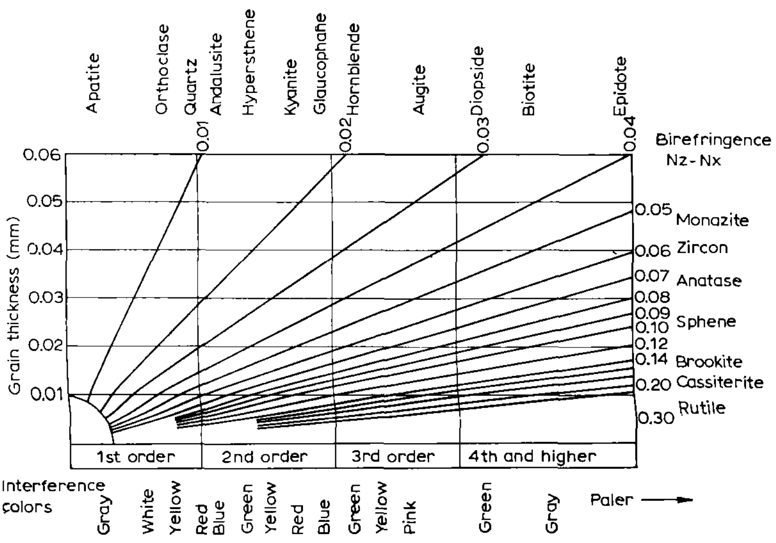


Fig.33. Birefrigence chart (model).

minerals is known and, by observing the interference colors, their birefringences may be calculated:

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

The usual thickness of a thin section is 0.03 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 (Fig.33). Practice brings good judgment in this respect (see Fig.34).

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 subtractive position (see Fig.35). 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 gray and white colors with crossed nicols will give respectively yellow to brownish and reddish brown to light red colors with parallel nicols.

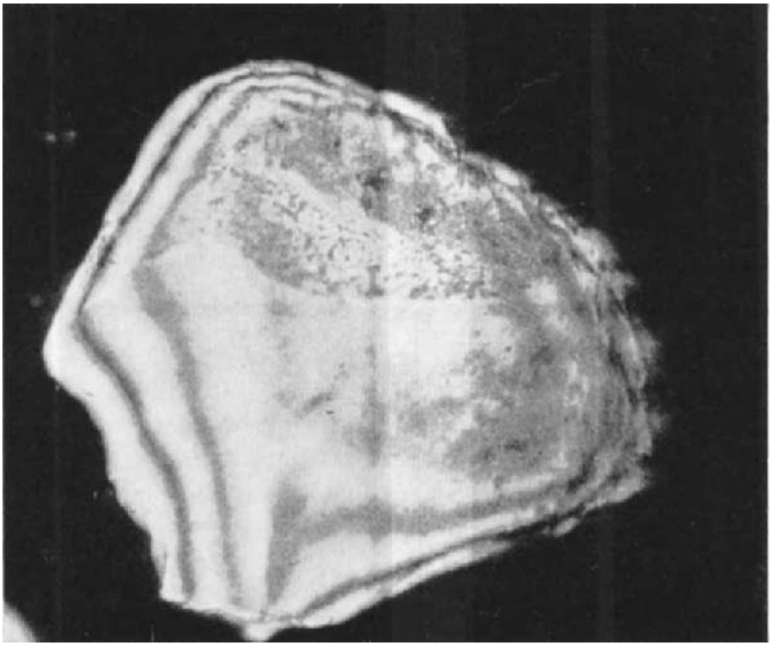
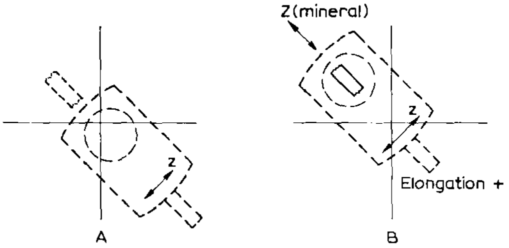
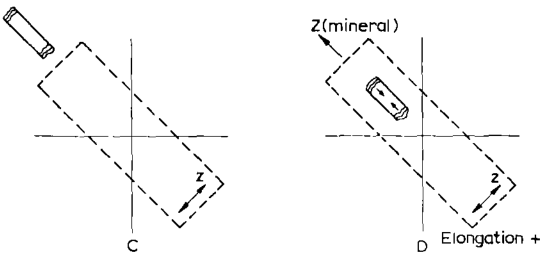


Fig.34. Quartz grain between crossed nicols, showing interference color bands. Four orders of red are shown; × 150.



(Color becomes of lower order)



(Color bands move inward)

Fig. 35. Method of determining elongation character with mica (1/4 λ) 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.

TABLE XXVIII

TABLE OF INTERFERENCE COLORS

Order	*Color*	*Retardation (mμ)*
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

Elongation character

By definition: When the vibration direction of the slow ray (z) is parallel (or nearly parallel) to the crystallographic long axis (c), the elongation is (+); otherwise, it is (—).

The elongation sign of uniaxial minerals is usually the same as the optical sign, but a uniaxial prismatic crystal, elongated parallel to b, may have elongation (+) as viewed on one prism-face and elongation (—) on a different prism face.

For minerals with inclined extinction, the sign of the elongation is determined by the relative velocity of that ray whose vibration direction is nearest the axis of elongation.

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 goes down, subtractive (see Fig.35A and 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.35C, D).

(*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 z in the mineral and z in the plate or wedge are at right angles.

(*4*) Knowing the direction of z in the plate or wedge, we then know the direction of z 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.

Extinction

(*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.36A).

(*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.36B).

(*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.36C).

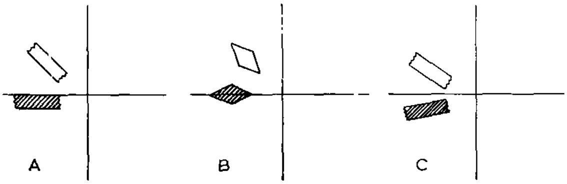


Fig.36. Types of extinction. A = parallel; B = symmetrical; C = inclined.

TABLE XXIX

TYPES OF EXTINCTION

Crystal system	*Extinction*
Tetragonal	parallel
Hexagonal	parallel
Orthorhombic	parallel in prismatic sections
Monoclinic	parallel only in sections parallel to *b* axis
Triclinic	inclined

Angular measurements

(*1*) Between cleavage directions, as amphiboles, angle between prismatic cleavages = 124°; pyroxenes, angle between prismatic cleavages = 87°.

(*2*) Extinction angles, usually measured between an optical direction and a crystallographic direction; e.g., for spodumene, $z/c = +24°$.

The angle measured will be the apparent angle z/c or x/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 many monoclinic minerals with $y = b$.

In the crystal drawing of spodumene (Fig.117) the maximum extinction angle ($z/c = +23$–$27°$) for spodumene is a positive 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.

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 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: x = red, y = brown, and z = 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, $\omega > \varepsilon$, 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 ε parallel to c, so that when it appears dark when c ($= \varepsilon$) is normal to the vibration direction of the polarizer, the formula is stated $\omega > \varepsilon$. The pleochroism formula for the same mineral might be: ε = yellow and ω = 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.37A).

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*) Section at some angle to the optic axis.

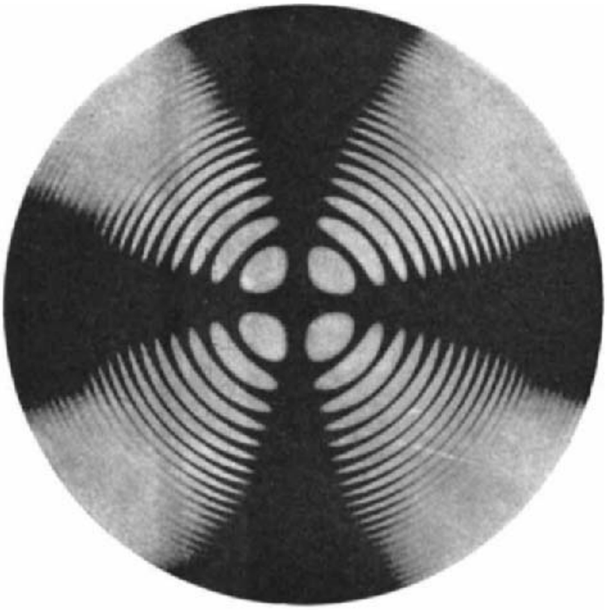
The latter is not in the center of the field and may be altogether outside of the field. If, however, the section is not inclined at too great an angle from the optic axis, the arms of the dark cross will move across the field as the stage is rotated, the center rotating in the same direction as the 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.37B).

When 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.

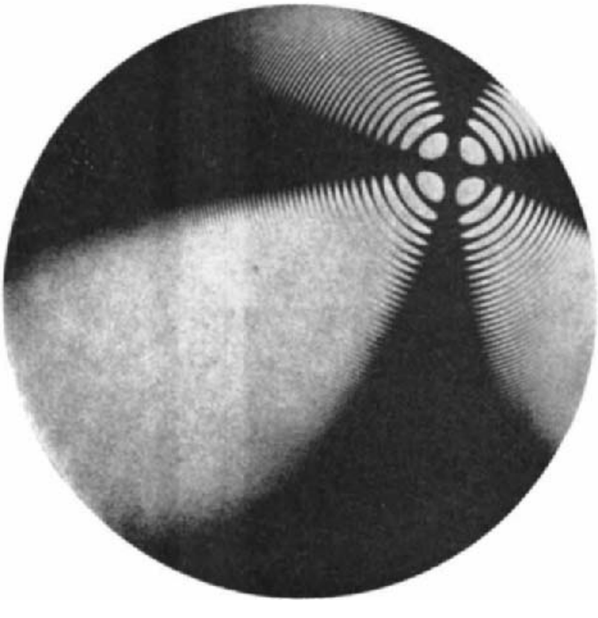
In sections parallel, or nearly parallel, to the optic axis, the bars are dim and are only visible at exact position of transit of the cross-wires, after which they pass rapidly from the field as hyperbolas. This is called a "flash" figure because the bars are not visible during the greater part of the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



A



B

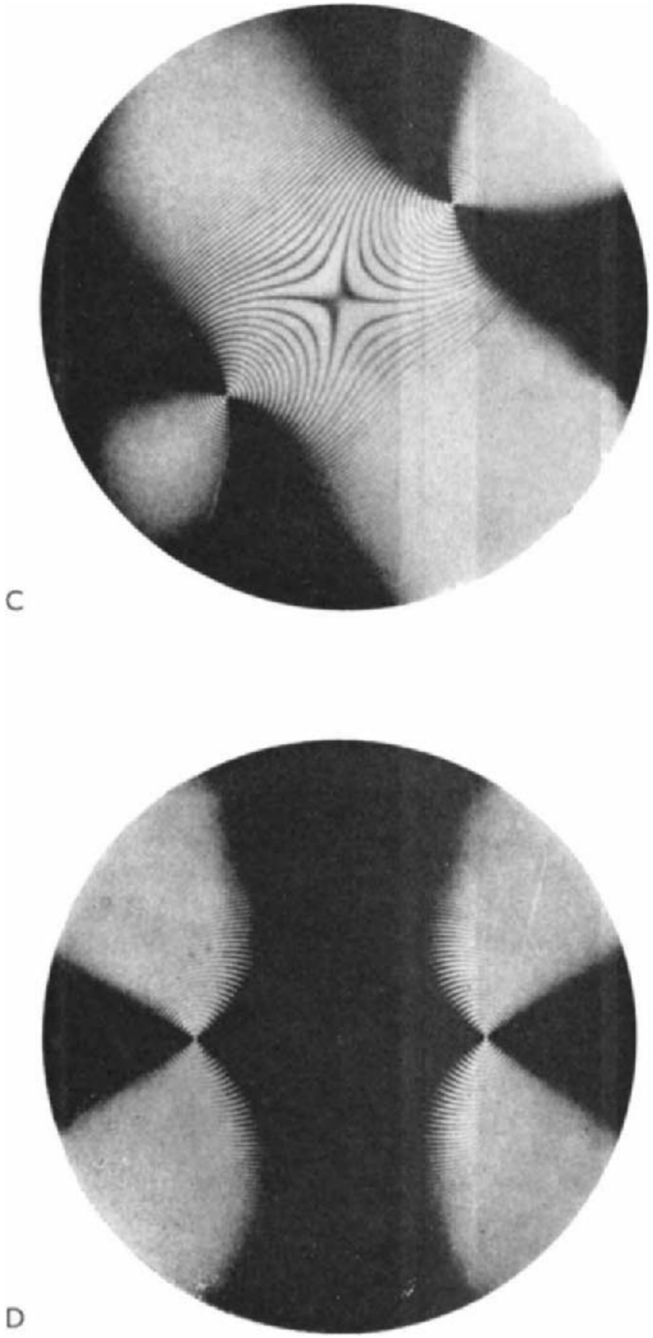


Fig.37. Interference figures from oriented sections.
A. uniaxial, section cut normal to optic axis.
B. uniaxial, section cut at an angle to optic axis, crystal at 45° extinction.
C. biaxial, section cut normal to acute bisectrix, crystal at 45° to extinction.
D. biaxial, section cut normal to acute bisectrix, crystal at extinction.

Fig.38. Biaxial, section cut at 80° to optic axis, crystal at 45° position.

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 (Fig.37C and 37D).

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 seen in the field (Fig.38D); 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 hyperbola 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 when the optic axial angle is large, 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 Fig.37 and 38. They are usually distorted by the uneven or lenticular shape of the grain, and are more like the ones shown in Fig.39.

Interference figures are useful principally for the following purposes: to determine the sign of the mineral; to measure the axial angle; to determine the dispersion, and to determine the relationship between optical and crystallographic directions.

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

(*1*) Optic axis figure (centered cross)

(*a*) Test with mica ($\frac{1}{4}\lambda$) plate. Insert plate. Cross is obliterated and two dark dots or blurs appear, the line joining which, for negative minerals, is parallel to the slow direction of the plate, and for positive minerals is normal thereto.

(*b*) 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.

(*c*) 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 northwest and southeast quadrants, and toward the optic axis in the other quadrants (Fig.40).

(*2*) Uncentered cross in field. The same tests apply.

(*3*) Uncentered cross with center out of field. Test (*a*) will not apply. Test (*b*) may apply if region near optic axis can be seen. Test (*c*) will apply if colored rings can be seen.

(*4*) The optic normal section gives a flash figure and, in mineral grains, sometimes it is 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 (+).

Biaxial

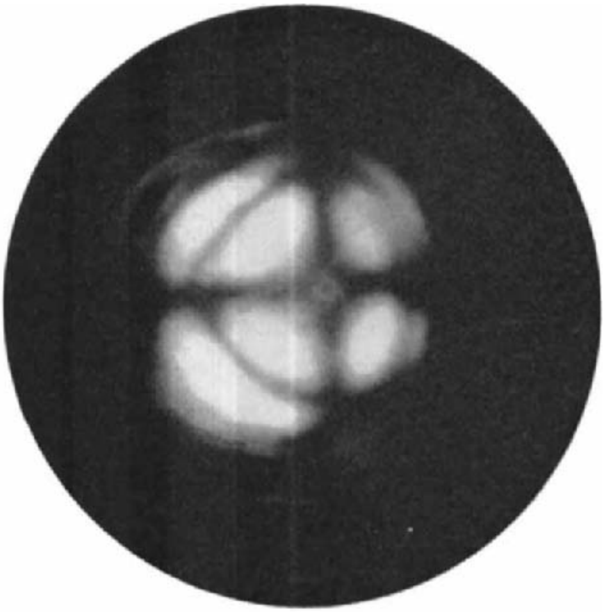
(*1*) Centered acute bisectrix figure

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

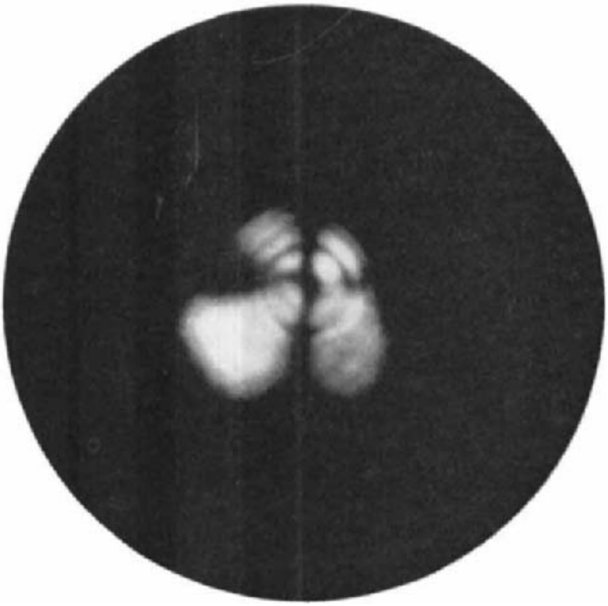
(*b*) Gypsum plate. Same phenomenon as for uniaxial minerals.

(*c*) Quartz wedge. Same phenomenon as for uniaxial minerals (Fig.41).

(*2*) Inclined acute bisectrix figure. Test (*a*) will not apply. Test (*b*): when a hyperbola is in southeast quadrant (slow direction of plate being northeast–south-



A



B

Fig.39. Interference figures photographed with an ordinary petrographic microscope. The visual figures are somewhat better than the photographs portray.
A. uniaxial, similar to Fig.37A.
B. uniaxial (distorted), similar to Fig.37B.
C. biaxial, similar to Fig.37C.
D. biaxial, similar to Fig.37D.

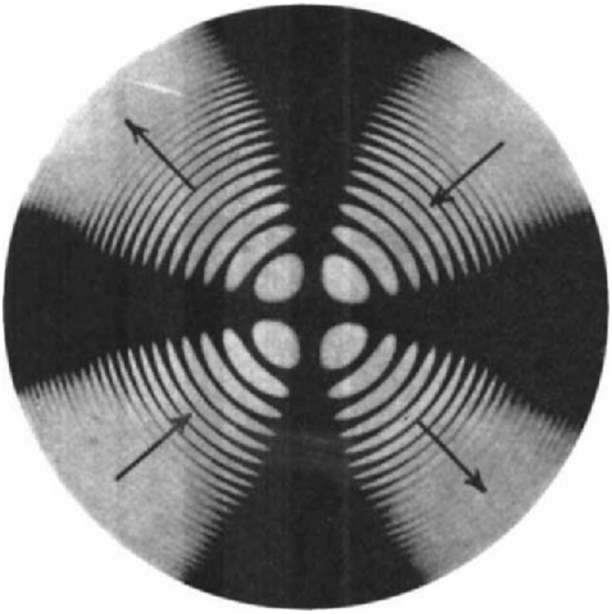


Fig.40. Uniaxial positive interference figure, showing direction of movement of colored rings when a length-fast quartz wedge is inserted from the southeast quadrant, thin edge foremost. Directions are reversed for (1) a negative crystal or, (2) a length-slow wedge.

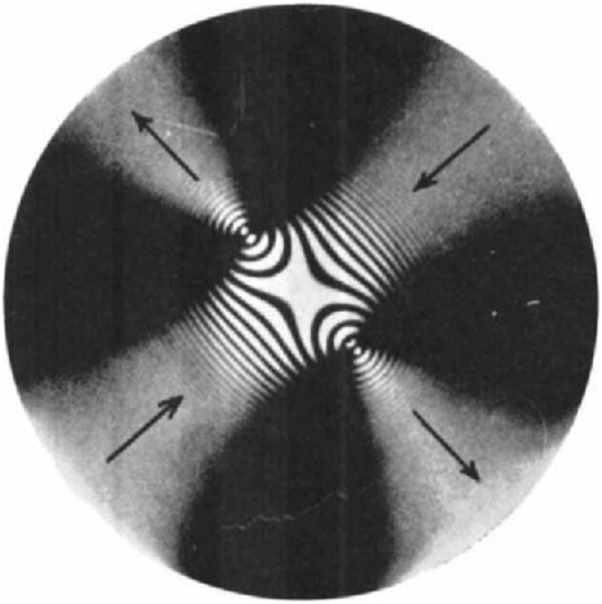


Fig.41. Biaxial positive interference figure, showing direction of movement of the colored bands when a length-fast quartz wedge is inserted from the southeast quadrant, thin edge foremost. Direcitons are reversed for (1) a negative crystal, (2) a length-slow wedge or, (3) orientation of the figure at 90° to the position shown.

west); the color on the concave side of the hyperbola will be yellow or blue according as the mineral is (+) or (—). Test (*c*) will, for (+) mineral, show the colors moving from convex to concave side of hyperbola when the latter is in southeast or northwest quadrants, and from concave to convex in other quadrants.

If none of the above tests is 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 y, and the plane itself will contain either z or x, 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.

(*3*) Optic axis figure. If the bar has no curvature, the axial angle is 90° and the sign is neutral. 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 (*c*).

If the curvature of the bar is apparent, Test (*b*) or (*c*) may determine the sign, as in Fig.38.

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

(*4*) 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.

(*5*) 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, applicable where $2V < 90°$.

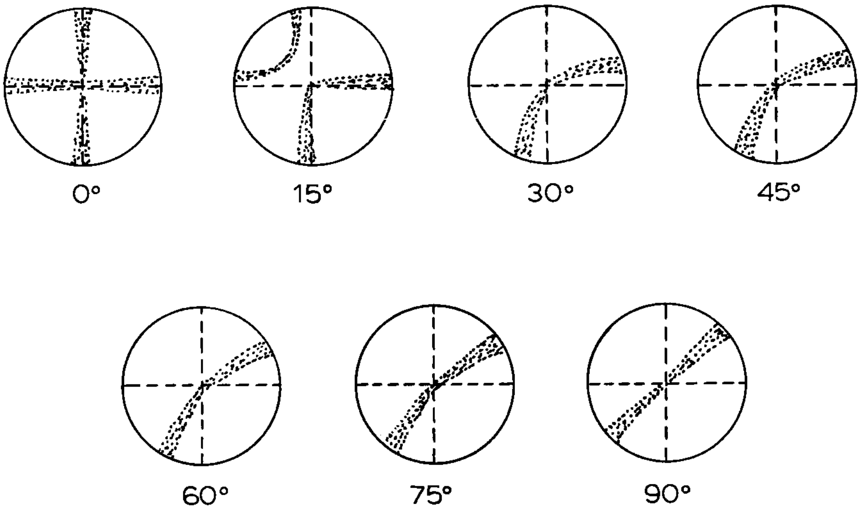
(*1*) In the acute bisectrix figure, measure, with a micrometer ocular, the distance between hyperbolas. Then

$$\sin E = cd$$

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:

$$\sin V = \frac{\sin E}{y}$$



0° 15° 30° 45°

60° 75° 90°

Fig.42. Curvature of the bar in optic axis interference figures. The amount of curvature serves for an estimate of the axial angle.

(*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 figures (Fig.42) are self-explanatory.

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 X, Y, and Z at right angles to one another and of lengths proportional to the three indices Nx, Ny, and Nz, as shown in Fig.43. The ellipsoid is then considered to envelop these three axes. The three mid-sections are ellipses; the horizontal one having $XX' = Nx$ as major axis and $YY' = Ny$ as minor axis. Now this latter ellipse may be imagined to rotate on YY′, but maintaining the extremities of its major axis on the surface of the ellipsoid. This major axis (XX′) will then elongate until it is equal to Nz, but at some intermediate position in length it will be equal to Ny and hence, the section will be circle (AYBY′). Rotation of the ellipse the same angular amount in the opposite direction will produce another circle (A′YB′Y′).

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 (XX′ or ZZ′) bisecting this angle is the *acute bisectrix*, and the mineral is optically (+) or (—) according as this is ZZ′ or XX′. It should be

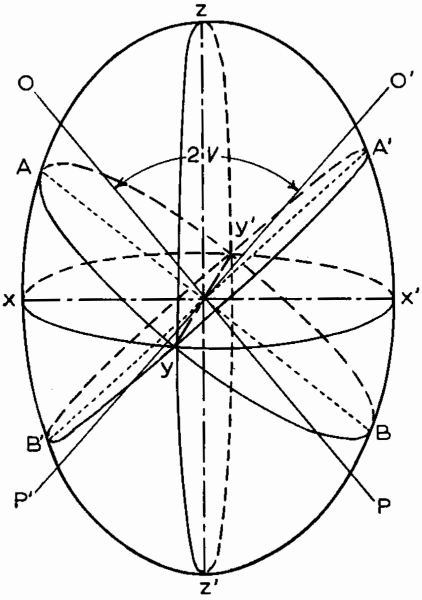


Fig.43. The triaxial ellipsoid.

noted also that when Ny is more nearly equal to Nx than it is to Nz, 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.

The angle between the optic axes is closely related to the relative values of Nx, Ny, and Nz, the exact relationship being:

$$\text{Tan } V_z = \sqrt{\frac{\dfrac{1}{Nx^2} - \dfrac{1}{Ny^2}}{\dfrac{1}{Ny^2} - \dfrac{1}{Nz^2}}}$$

Approximation formulas are:

For (+) crystals:

$$\text{Tan } V = \sqrt{\frac{Ny - Nx}{Nz - Ny}}$$

For (—) crystals:

$$\text{Tan } V = \sqrt{\frac{Nz - Ny}{Ny - Nx}}$$

Unless the values in these computations are stated to the fourth decimal, large discrepancies in the values of V may result (A. N. WINCHELL, 1931).

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 (wave length 589 mμ). 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,

(*1*) Orthorhombic has a crossed axial plane, and optic axis dispersion.

(*2*) Monoclinic has an inclined, horizontal, or crossed dispersion.

(*3*) Triclinic has an asymmetrical dispersion.

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 acute bisectrix, and (*c*) symmetrical to the point of emergence of the acute bisectrix.

(*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 acute bisectrix.

(*4*) Crossed dispersion is indicated when the colors are symmetrical only to the point of emergence of the acute bisectrix.

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, the extinction will be sharp but, in a section normal to an optic axis, dispersion is much more easily noticed. 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 $\varrho > v$. Where the blue color appears on the convex side and red on the concave, the formula is $\varrho < v$.

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 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.

Diagrams for 99 minerals are depicted on pp. 178–196.

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.44).

(*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 north–south 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 is dependent upon the objective

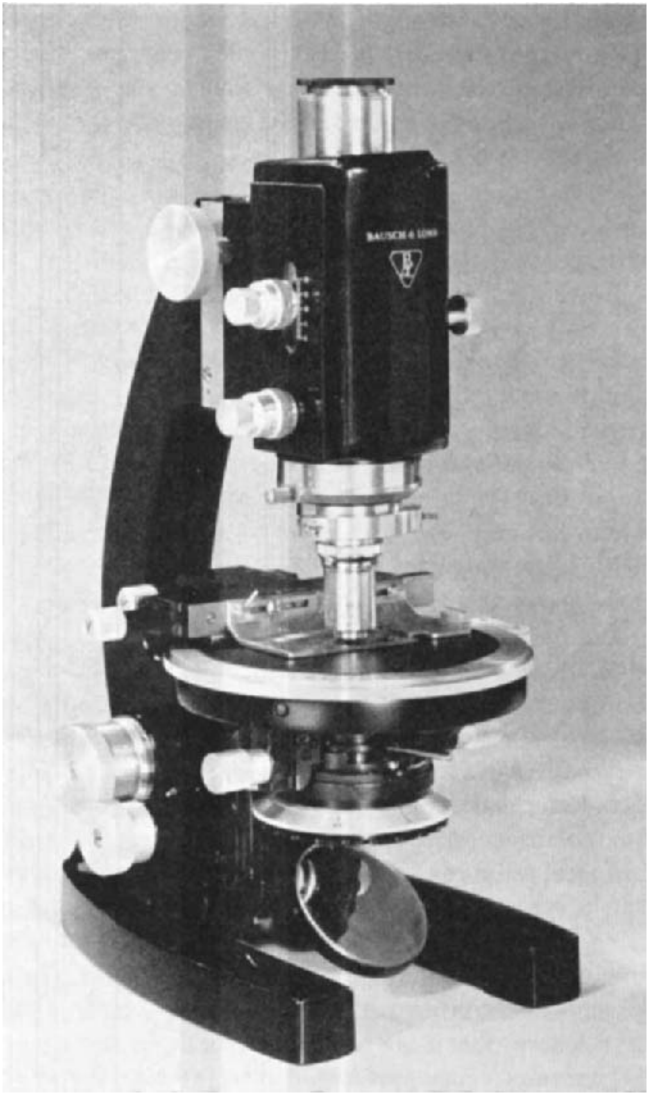


Fig.44. Bausch and Lomb model LR petrographic microscope (by permission).

Objectives for petrographic purposes are often specially corrected for polarization. The most useful sizes are: 40, 16, 4, and 2 mm, the respective power being low, medium, high, and 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. $NA = N \sin \mu$; where μ is one-half the angle between the extreme rays of the cone of light entering the objective and N is the refractive index of the immersion medium.

The high-power objectives have short *working distances* (distances between front lens and the object), so that thin objects and thin cover-glasses are necessary. High-power objectives also have short *depths 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 north–south, the accessory slot usually points northwest–southeast.

(*7*) *The upper nicol prism* (analyzer), which transmits only part of the light vibrating in a direction (usually east–west) 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 it 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 north–south and east–west, 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.

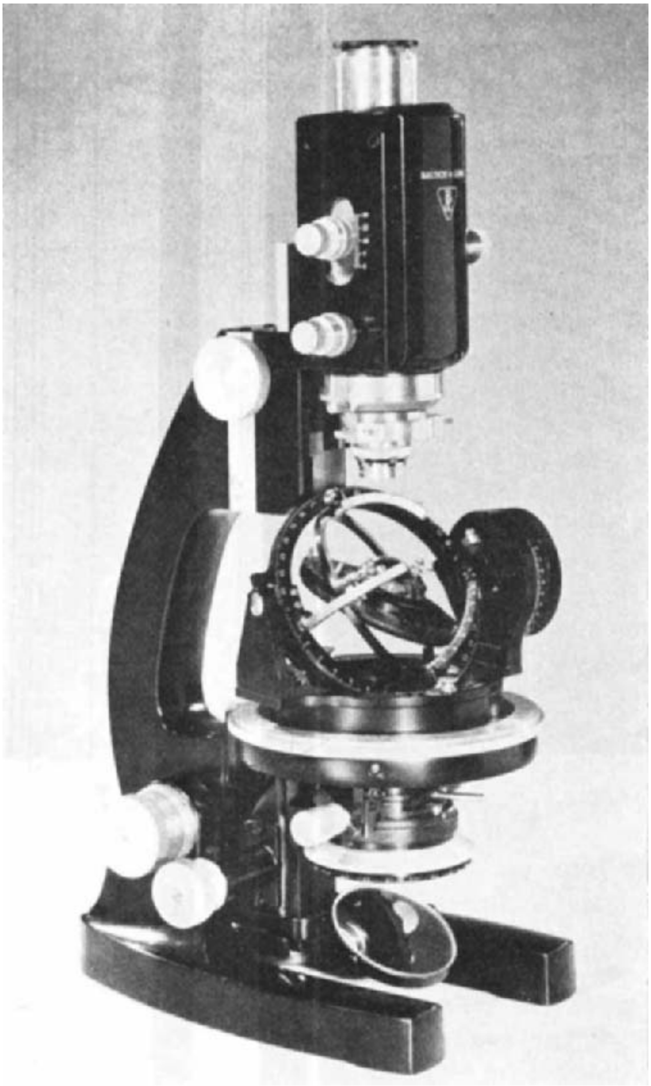


Fig.45. Bausch and Lomb petrographic microscope equipped with Fedoroff universal stage (by permission).

(*3*) *Rotating upper nicol.* This is useful for observations with parallel nicols, and obviates the necessity of rotating the lower nicol.

(*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 necessary 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: ocular and stage micrometers; mica (¼λ) plate; Johannsen (or Wright) quartz–gypsum wedge.

THE UNIVERSAL STAGE

The Fedoroff universal stage (A. N. WINCHELL, 1937) is a valuable device for advanced students in the examination of mineral grains or thin-sections of minerals or rocks. It is an attachment for the petrographic microscope and rests upon the stage of the latter (Fig.45). The mineral slide rests upon a smaller stage of the instrument. Above and below the slide, glass hemispheres are attached, and there is a film of glycerine between them and the slide. The various elements of the stage are mounted in bearings, so that the mineral slide may be tipped and revolved into any position, and the various horizontal and vertical angles read from graduated scales.

The object in view is the determination of the complete optic orientation of the mineral, so that it may be described with respect to the exact positions of the crystallographic and optic axes, the optic axial angle, and the optic sign. Thus may be attained the identification of the mineral and its complete description.

EMMONS (1943) has used the universal stage in connection with his "Double Variation Method" for the determination of refractive index of an anisotropic mineral. Two methods are used to vary the index of the immersion liquid, namely, change of temperature and change of wave-length (color) of the incident light.

ULTRAMICROSCOPY

The limit of magnification attainable with the microscope and visible (blue–violet) light is about 1,000×. This can be increased to 2,500× by means of a carbon-arc source of light and a dark-field illuminator, thus attaining a magnification of about 20,000×. Such is called the ultramicroscope.

The use of ultra-violet light to illuminate, with a microscope equipped with quartz lenses, permits greater magnification, but the procedures are difficult because focussing must be by trial and error on photographic film.

ELECTRON MICROSCOPY

The electron microscope opened a new domain in microscopy and has permitted magnifications up to 100,000×, together with great depth of field and high resolving power.

In this instrument electron rays are made to converge and are brought to a focus by means of magnetic coils. Focus is obtained on a fluoroscopic screen and the image is exposed on photographic film.

The method has been successfully applied in the study of clays (BATES, 1949), special preparation-techniques being required (DWORNIK and ROSS, 1955).

Notable success has been achieved by KRINSLEY and TAKAHASHI (1962) in the study of fragmental quartz crystals. Electron micrographs were made at magnifications of 5,000×. In the case of aeolian sands the quartz particles exhibited meandering ridges on the surfaces. In the case of littoral sands, there were V-shaped patterns and in the case of glacial sands there were arc-shaped steps and semi-parallel steps with very high relief.

PHOTOMICROGRAPHY

Transparent or opaque preparations of mineral grains may be photographed readily on 35-mm film and enlarged on paper to an optimum magnification of 600×. The requirements are a single-lens reflex camera with penta-prism focusing-screen and bellows-attachment permitting variation of the distance between microscope-ocular and focal-plane of the camera. The camera should be attached by a clamp to a vertical rod in such a way as to permit varying the height.

The bellows-extension required for a given magnification may be determined from a chart, constructed through experimentation, and as suggested in Fig.46. One must determine, by means of a stage micrometer, the magnification of each objective and ocular combination for two bellows-extension settings. The chart is drawn on semi-logarithmic ruled paper. Values from such a chart enable one to determine the proper bellows-extension for a required magnification.

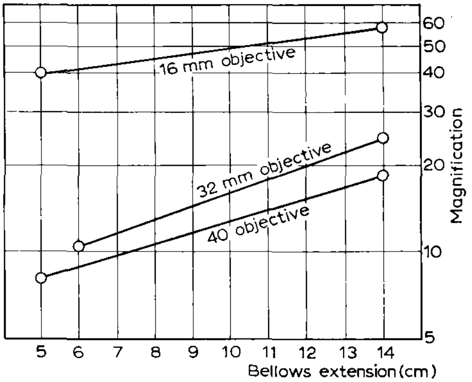


Fig.46. Illustration of the way to construct a chart for determning camera bellows-extension for 35 mm photomicrography. (Two magnification to be determined for each objective by means of a stage-micrometer.)

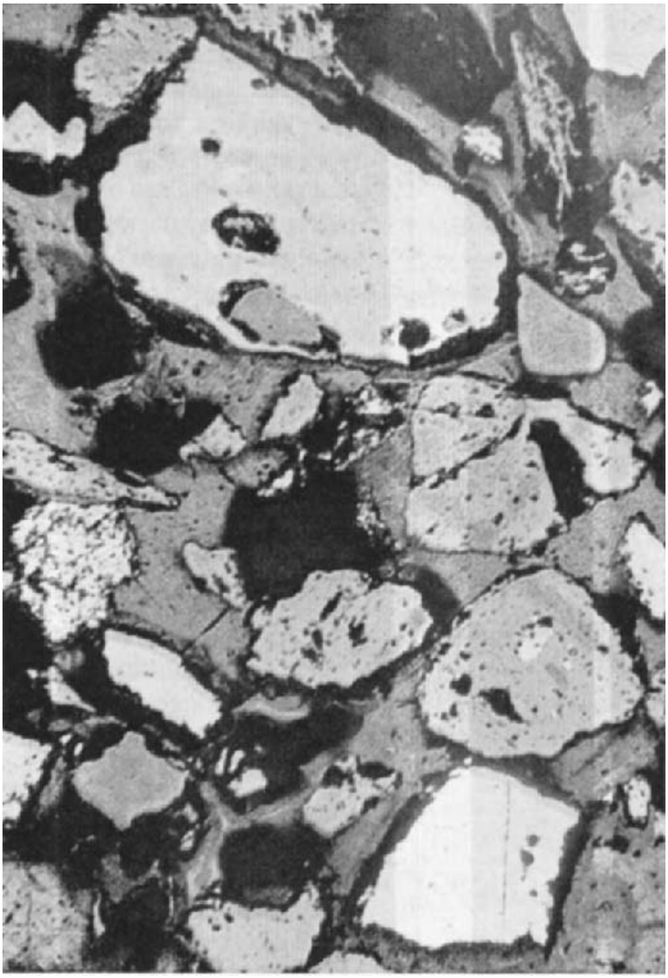


Fig.47. Mineral grains cemented in epoxy-resin; × 200. Photographed on 35 mm film × 40 with opaque illuminator.

Correct exposure should be determined for some standard set of conditions. The author has set up a standard exposure as follows: objective 32 mm; ocular, Leitz No.3; bellows-extension 6 cm; iris diaphragms open; plane-polarized light; no filter; ground-glass in front of illuminator; Kodak Pan X film; exposure about 8 sec. The proper exposure for any other set of conditions may be found by applying the following equation:

$$\frac{\text{new exposure}}{\text{stand. expos.}} = \left(\frac{\text{stand. } NA}{\text{new } NA}\right)^2 \cdot \left(\frac{\text{new mag.}}{\text{stand mag.}}\right)^2 \cdot \left(\frac{\text{stand. iris diam.}}{\text{new iris diam.}}\right)^2$$

where stand. = standard; expos. = exposure; *NA* = numerical aperture of objective; mag. = magnification; iris = upper iris-diaphragm of microscope.

It is best to determine a standard exposure in 35-mm photomicrography by exposing a strip of film to a geometrically series of exposure-times: 1, 2, 4, 8, 16, sec., etc.

Photomicrographs should be developed to a fairly high degree of contrast or the grade of paper should be chosen with that end in view.

A plate-camera can also be adapted for photomicrography, and it may be positioned vertically or horizontally. The advantage over the 35-mm camera is that the negative may be of such size that prints can be made by contact instead of by enlargement, and this usually results in better definition. The cost per negative is, of course, much greater.

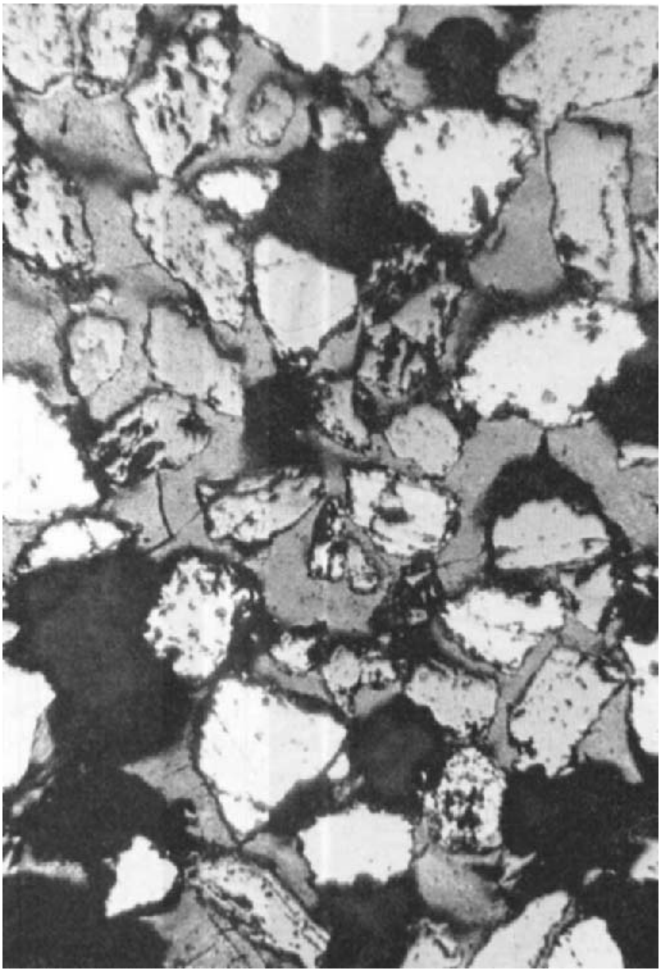


Fig.48. Mineral grains cemented in epoxy-resin; × 200. Photographed on 35 mm film × 40 with opaque illuminator.

The opaque minerals, such as metallic sulphides, may be studied microscopically with a vertical illuminator above the objective lens. Intense and concentrated light in the entrance-port is reflected from the surface of a square of cover-glass, set at 45° to the path of light, and passes down through the objective lens to the polished surface of the specimen. It is thence reflected back up, through the objective and through the cover-glass to the ocular of the microscope. The installation being as indicated above, photographs, made of the polished surface, are given in Fig.47 and 48. SHILLABER (1944) has written one of the best treatises on photomicrography. EASTMAN KODAK COMPANY has booklets on the subject (1957, 1963).

STAINING METHODS

Studies of fine-grained rocks, such as limestones, dolomites and gypsum, sometimes requires staining of the rock surface in order to identify the constituent minerals. The procedure usually requires chemical preparation of the flattened and smoothed rock surface, followed by the application of an organic dye or an inorganic reagent. In this way the presence may be revealed of minerals containing calcium, magnesium, barium, and phosphorous, and compounds of these elements.

FRIEDMAN (1959) has written the most recent and most comprehensive paper on this subject, together with a long list of stains. LEROY (1950) has a short treatment of the subject, as have also TWENHOFEL and TYLER (1941), and MILNER (1962).

FLUORESCENCE OF MINERALS

Many minerals become luminescent when irradiated by a source of ultra-violet light. They are then said to be fluorescent, and this fact may have some significance with respect to the identity of the mineral. The method is of limited application and reliability, however, because minerals of a given species may sometimes be fluorescent, and other times not.

The test is easily applied if one has a quartz mercury-vapor lamp. Hand specimens of minerals are examined, as illuminated by the lamp in a darkened room. The method may also be used with the microscope and mineral grains.

Table XXX gives a list of minerals that have been rated (GRANT, 1962) with respect to their response to ultra-violet illumination. Not all of these occur in fragmental rocks.

FUSIBILITY

A small, sharp splinter of mineral, when held in a certain flame, may reveal its melting-point. The scale of fusibility is given in Table XXXI.

TABLE XXX

RESPONSE OF MINERALS TO ULTRA-VIOLET ILLUMINATION

(After GRANT, 1962)

Mineral	*fluorescent*			
	always (F)	*often (O)*	*sometimes (S)*	*never (N)*
Adamite	+			
Andersonite			+	
Andradite			+	
Anglesite			+	
Autunite	+			
Benitoite			+	
Calcite		+		
Carnotite				+
Curtisite	+			
Diamond		+		
Feldspars		+		
Fluorite			+	
Franklinite	+			
Gibbsite		+		
Gypsum			+	
Halite		+		
Hyalite		+		
Hydrozincite		+		
Metaautunite	+			
Opal			+	
Powellite	+			
Pitchblende				+
Ruby				+
Sapphire		+		
Scheelite	+			
Semi-opal		+		
Stibiconite			+	
Schröckingerite	+			
Tephroite		+		
Tungstite		+		
Uranium arsenates	+			
Uranium carbonates	+			
Uranium micas				+
Uranium phosphates	+			
Uranium silicates				+
Uranium sulphates	+			
Uranospathite	+			
Uranophane	+			
Willemite		+		
Zincite	+			
Zippeite	+			
Zircon			+	

TABLE XXXI

FUSIBILITY SCALE

Fusibility No.	*Mineral*	*Fusing temp. (°C)*	
1	Stibnite	525	(in candle-flame)
2	Chalcopyrite	800	(in Bunsen-flame)
3	Almandite	1,050	(in blow-pipe)
4	Actinolite	1,200	(in blow-pipe)
5	Orthoclase	1,300	(in blow-pipe, with difficulty)
6	Enstatite	1,400	(in blow-pipe almost infusible)
7	Quartz	1,710	(in blow-pipe infusible)

BEAD COLORATION

If a mineral powder can be fused in a platinum-wire loop, after mixing with borax, sodium carbonate, or acid sodium ammonium phosphate, the fused bead may assume a color characteristic of an element that is present.

The reader should consult a mineralogy text (Dana and Hurlbut, 1959; A. N. Winchell, 1929, 1937, 1951), for full information on various color tests.

FLAME COLORATION

Some elements, when present in minerals, reveal their presence when the powder is held in a blow-pipe flame. Lithium and strontium flames are crimson, calcium flame is orange-red, sodium is yellow, potassium is violet, and copper is blue (Dana and Hurlbut, 1959; A. N. Winchell, 1929, 1937, 1951).

SPECTROGRAPHIC EXAMINATION

The spectrograph as an analytical instrument of accuracy and convenience has gained 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 or Ångström unit (Å), which is 10^{-10} m. The familiar "$\mathrm{D_1}$" line of sodium has a wave-length of 5,895.9 Å.

TABLE XXXII

RANGE AND POWER OF SPECTROGRAPHS

Length of spectra (cm) on photographic plate given by various types and sizes of instruments in different regions of the spectrum

ultra violet — 3,900 Å — limits of human vision — 7,600 Å — infra red

2,150 Å — sensitivity of panchromatic plate — 7,000Å

2,150 Å — sensitivity of ordinary photographic plate — 5,600 Å

Wave length (× 1,000 Å)	2	2.5	3	3.5	4	5	8
Quartz prism (small)	3.0	1.5	1.0	0.5	0.7	0.8	
Quartz prism (medium)	10.0	5.0	2.5	2.0	2.0	2.5	
Quartz prism (large)	28.0	14.0	9.0	5.0	5.0	5.6	
Concave grating (Rad. = 3 ft.)	3.0	3.0	3.0	3.0	6.0	18.0	
Concave grating (Rad. = 21 ft.)	19.0	19.0	19.0	19.0	38.0	114.0	

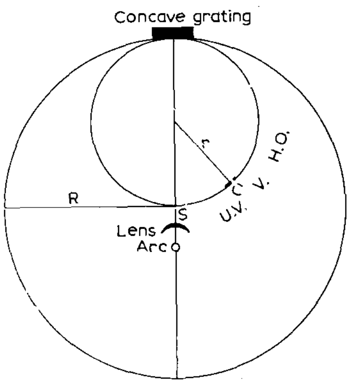


Fig.49. Concave grating spectrograph Paschen-Runge mounting. S = slit; C = plate-holder; R = grating-radius; r = focal-radius; $r = R/2$; $U.V.$ = ultra violet range; V = visible range; $H.O.$ – infra-red and higher orders.

In Table XXXII it is shown that the ordinary photographic plate is sensitive to wave-lengths between 2,150 Å (in the ultra-violet) and 5,600 Å (in the visible), while the limits of human vision lie between 3,900 Å (violet) and 7,600 Å (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.

An instrument for spectral analysis (Fig.49) was installed in the laboratories of the School of Earth Sciences of Stanford University about 1932, and has been very useful and satisfactory. It has been described in detail by CROOK (1935). The 6-inch concave grating has a focal length of 20.71 ft. and is ruled 14,600 lines/inch. It has been used mostly in the ultra-violet and visible range. Some of the spectra are shown in Fig.50, 51.

A recent acquisition is the Ebert Convertible Plane-grating Spectrograph. Advantages of the plane, rotatable grating are versatility and simplicity in operation and adjustment. Two 4 · 10 inch plates (end to end) may be exposed, or 35-mm film may be used.

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 have been called "raies ultimes" (R.U.) but now usually "sensitive lines." These residuary lines (see Table XXXIII) often

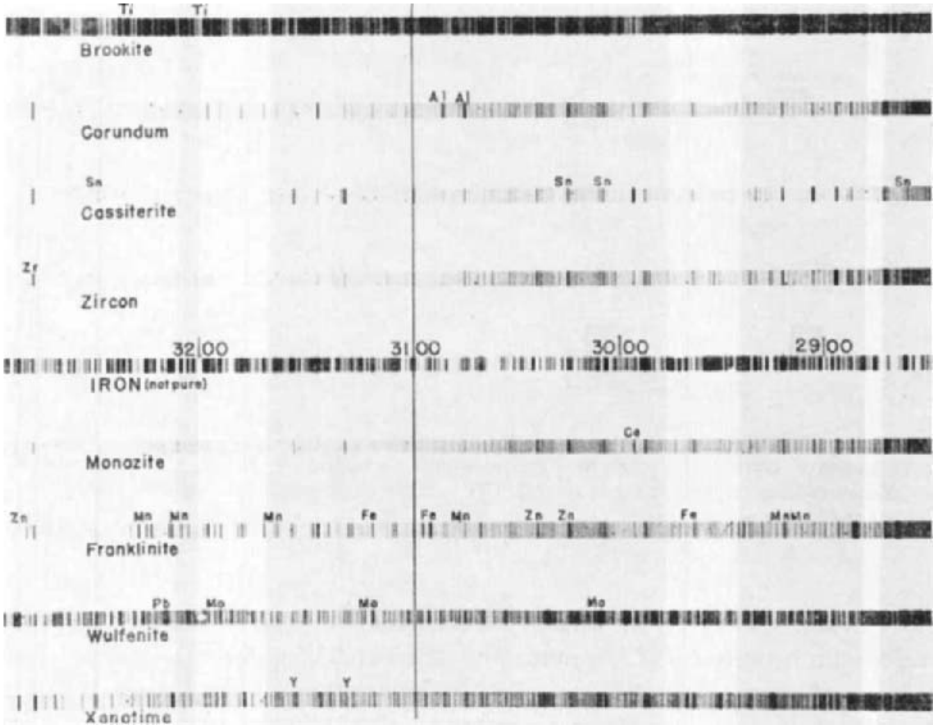


Fig.50. Arc spectra of minerals, made with the Ebert plane-grating spectrograph. The Ebert spectrograph is made by Jarrell–Ash Co.

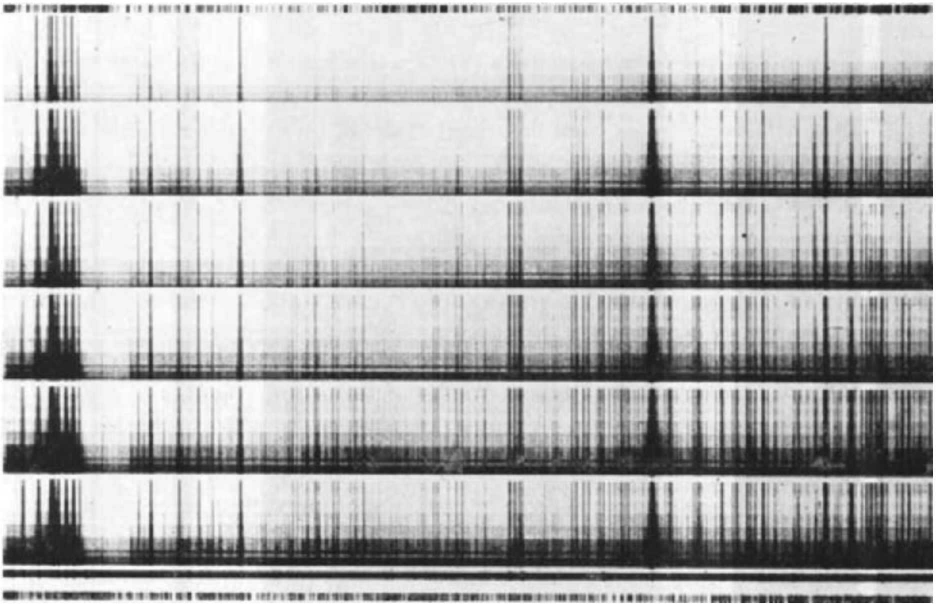


Fig.51. Spectrogram of galena–sphalerite ore to determine content of silver, made with rotating step-sector for quantitative estimation (Iron spectrum top and bottom) made with Ebert plane-grating spectrograph. The Ebert spectrograph is made by Jarrell–Ash Co.

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 HARRISON et al. (1948). 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 powder are placed in the hollowed crater of the lower (positive) carbon electrode of a d.c. arc. This powder 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. At least seven lines of each element will be present.

(*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 film is developed, and it is then a simple matter to compare the lines in

TABLE XXXIII

RAIES ULTIMES OF ELEMENTS

(After TWYMAN, 1923)

Element	*Wave-lenghts of principal raies ultimes*	*Element*	*Wave-lenghts of principal raies ultimes*
Aluminum	3092.7; 3082.2	Molybdenum	3903.0; 3864.1; 3798.3
Antimony	2598.1; 2528.5	Neodymium	4303.6; 4177.3; 3951.2
Arsenic	2780.2; 2349.8	Nickel	3414.83;2416.2;2316.1
Barium	2335.3; 4554.0; 4934.1	Palladium	3634.7; 3609.6; 3404.6
Bismuth	3067.7; 2898.0	Phosphorus	2553.3; 2535.6; 2534.0
Boron	2497.7; 2496.8	Platinum	3966.4; 2929.8; 2659.4
Cadmium	2288.0; 2265.0	Potassium	4047.2; 4044.2; 3446.4
Caesium	4593.2; 4555.3	Rhodium	3434.9
Calcium	4226.7; 3968.5; 3933.7	Rubidium	4215.6; 4201.8
Carbon	2478.6	Ruthenium	3499.0
Cerium	4040.8; 4012.4	Scandium	3630.8; 3613.8
Chromium	4254.3; 3605.3; 3593.5	Silicon	2881.6; 2516.1
Cobalt	3405.1; 2388.9; 2378.6	Silver	3383.0; 3280.2
Copper	3274.0; 3247.5	Sodium	5895.9; 5890.9; 3303.0
Gallium	4172.1	Strontium	4215.5; 4077.7
Germanium	3269.5; 3039.1	Tantalum	3311.2
Gold	2676.0; 2428.0	Tellurium	2385.8; 2383.3
Hydrogen	6562.8	Thallium	5350.5; 3775.7; 2767.9
Iridium	3513.7; 3220.8	Thorium	4019.1; 3601.1; 3539.6
Iron	2755.7; 2395.6; 2382.0	Tin	3262.3; 2863.3
Lanthanum	3949.1	Titanium	3372.8; 3361.2; 3349.4
Lead	4057.8; 3683.5; 2614.2	Tungsten	4302.4; 4294.7; 4008.8
Lithium	6707.9; 4602.2	Vanadium	4408.5; 3102.3; 3093.1
Lutecium	2911.4	Yttrium	3710.3; 3600.7
Magnesium	2852.1; 2802.7; 2795.5	Zinc	4810.5; 4722.2; 3345.0
Manganese	4030.8; 2593.7; 2576.2	Zirconium	3496.2; 3392.0
Mercury	5460.7; 4358.3; 2536.5		

the mineral with the known lines of the 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 all the others. A raie ultime 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.

In Fig.52 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 2,860–3,180 Å. 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 3,130 Å is, in reality, a doublet (3,131 and 3,132) and a raie ultime of beryllium. There should also be noted in the spectrum of beryl the two strong aluminum lines (3,082 and 3,093), 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 (2,882) 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: 2,863 (R.U.), 2,914, 3,009, 3,034, and 3,175 (R.U.). These show more strongly in the spectrum of the mineral than they do in that of the pure salt ($SnCl_2$), 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 1 min in all cases.

Only three titanium lines are marked (3,088, 3,163, and 3,169), 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 (1930) state that, in the range between 2,288 Å and 6,717 Å, the

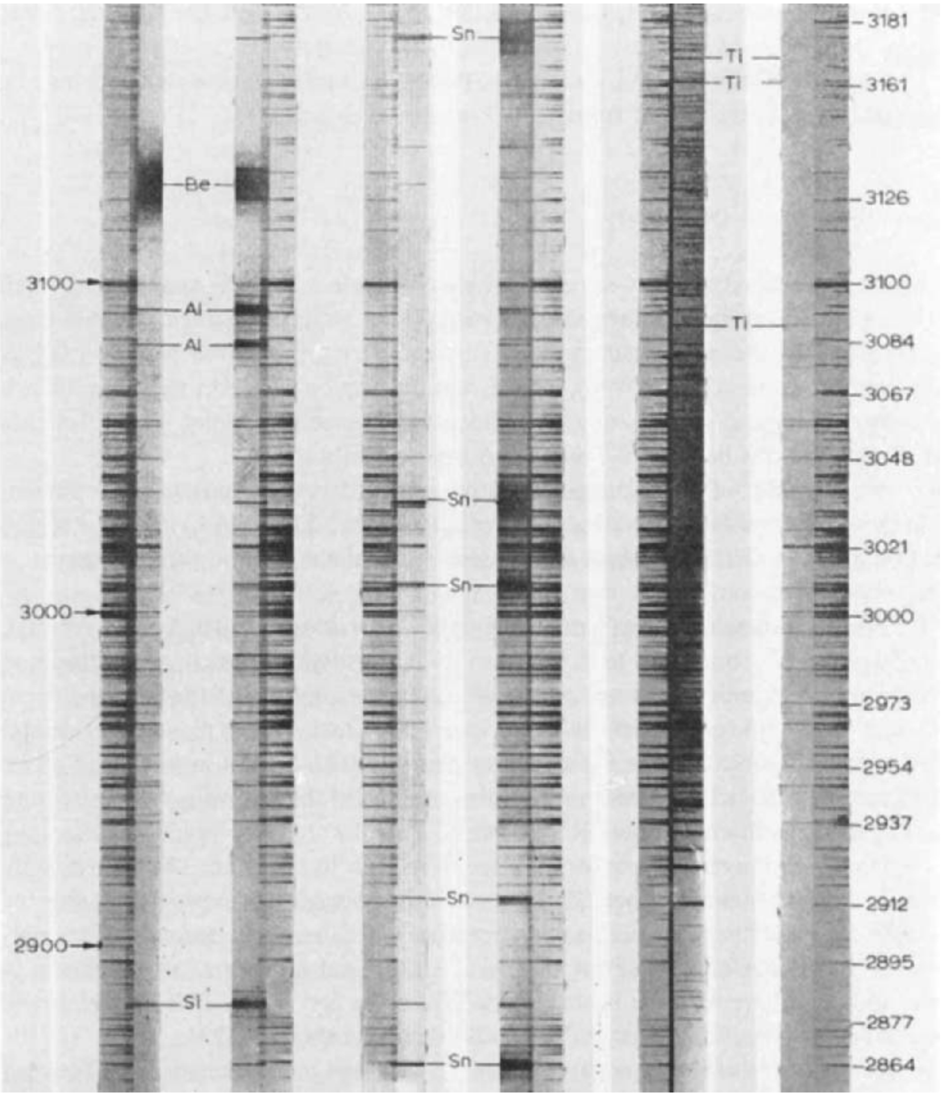


Fig.52. Arc spectra of minerals (same scale as original); made with 21 ft. grating illustrated in Fig.49.

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.

X-RAY DIFFRACTION ANALYSIS

X-rays are produced in an X-ray tube when a suitable voltage is applied and when high-velocity electrons are stopped by a metal target. X-rays are then radiated from the target. They are of very short wave length, covering the region of 0.01–1,000 Å (1 Å being equivalent to 10^{-10} m). The X-rays overlap on the short wave-length side the softer γ-rays and, on the long wave side, the extreme ultraviolet. For diffraction work, wave-lengths between 0.7 and 2.0 Å are generally used.

Wave-lengths of X-radiation are of the same order of magnitude as the dimensions of atoms in mineral crystals. They are, therefore, diffracted by the crystal and the resulting diffraction patterns are characteristic of the atomic arrangement of a given crystal.

When a monochromatic X-ray beam makes contact with the surface of a crystal, parallel planes of atoms react to it, just as in the case of light rays striking a diffraction grating, and the beam is reflected. A maximum in the intensity of the reflected beam can only occur if the component reflected waves from each atomic plane of the crystal reinforce one another, that is, if they are in phase. If they are not in phase the waves interfere with one another so as to reduce the intensity of the beam almost to zero, and also to produce scattered radiation.

The conditions necessary for effective refraction to occur are shown in Fig.53. There it is shown that when theta (θ) is the angle of incidence of the beam and (d) is the spacing of similar parallel planes, the beam reflected from the second plane must travel a distance ABC $= 2d \sin \theta$ in one or an integral number of wave-lengths in order to be in phase with the beam reflected from the first plane. This condition will be satisfied if $n\lambda = 2d_{\mathrm{hkl}} \sin \theta$, as originally stated by BRAGG (1934), where λ is the wave-length of the radiation and n is integer. d_{hkl} designates the spacings between planes in a set with Miller indices hkl.

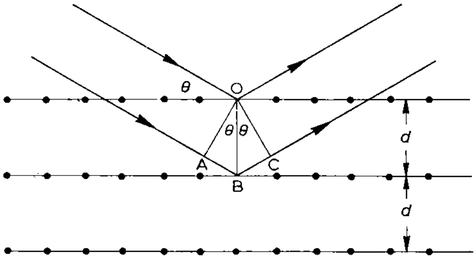


Fig.53. Bragg's law $n = 2\ d_{\mathrm{hkl}} \sin \theta$

TABLE XXXIV

COMMON TARGETS AND FILTERS

Target	*Filter*	*Maximum operating kilovoltage*
Mo	Zr	80
Zn	Cu	50
Cu	Ni	50
Ni	Co	50
Co	Fe	45
Fe	Mn	40
Mn	Cr	40
Cr	Va	35

Of the various X-ray wave-lengths, the strongest group is designated as $K\alpha_1$, $K\alpha_2$, $K\beta_1$, $K\beta_2$. Usually the $K\beta_1$ and $K\beta_2$ are filtered out to attain more nearly monochromatic radiation. If, for example, a copper target is used, the $K\beta$ radiations will be absorbed by a nickel filter. For minerals containing iron, an iron target would be used and a manganese filter, as otherwise, a very dark background on the photographic film would conceal the lines to be observed.

Table XXXIV gives the targets and filters most commonly used in determinative practice.

Crystals are made up of atoms arranged in geometrical *lattices*. Such regularly spaced atomic arrangements will react to X-rays as a ruled diffraction-grating of a spectroscope would to light waves, and such a diffraction-pattern may be photographed.

It is not the purpose here to go into the geometry of this subject or consideration of single-crystal techniques, but merely to indicate how the diffraction of X-rays by crystal planes may be used in a special way (the powder method) for the identification of a mineral species.

If a mineral is finely powdered the crystalline fragments will have random orientation, so that many individuals of the different atomic planes are always in a position to diffract the X-ray beam. A photographic film suitably positioned will, therefore, be exposed to the various wave-lengths of these diffracted rays, and measurements, subsequently made, lead to the evaluation of θ for each ray and to the value of d, by application of Bragg's Law.

The Debye–Scherrer or powder method

The unknown mineral is selected carefully (under the binocular microscope if necessary) as a small grain not necessarily larger than 2–3 mm^3, avoiding other contaminating minerals. The specimen is placed in a small (3-cm diameter) agate mortar, slightly covered with acetone, and ground to a very fine powder. The dried powder is then placed on a piece of glossy-surface paper (black or white as need be). Previously prepared glass filaments have been made by heating 2 mm diameter glass rod in a bunsen flame and quickly pulling it out to arms-length as a hair that will not be greater than 0.1 mm in diameter. This is broken into segments about 1.5 cm in length.

Working with needle-nosed forceps, the end of a glass segment is made to penetrate some vaseline to a depth of about 5 mm. It is then touched to the mineral powder so as to have adhering to it a very thin coating at the end for about 3 mm of its length.

A needle-hole is made in a small cork, the glass filament is inserted into it, and a small vial is stoppered by it. Labelled, and thus preserved, it is ready for the next step.

The sample must be positioned in the exact center of the powder-camera in such a way that it will axially revolve continuously during the exposure to X-rays. A piece of brass rod about 3 mm in diameter and 15 mm long has a shallow hole bored in one end. The hole is filled with plasticine, and the glass filament is inserted, centrally and axially, into the plasticine. This is a delicate procedure and must be done with great care and with the aid of two pairs of good forceps. The rod is then inserted into the place for it in the center of the camera.

Cameras vary in their design, but there must be a way of viewing the sample in such a way as to be able to adjust it so that it stays centered in the camera while rotating.

Powder-camera X-ray film comes in rolls of a standard width. The operator must be provided with a device for cutting the film to the right length for the camera, and of perforating it for the holes that are necessary for the inlet and emergence of the X-ray beam. Some cameras require only one hole in the center of the film. This operation must be done in a safe light.

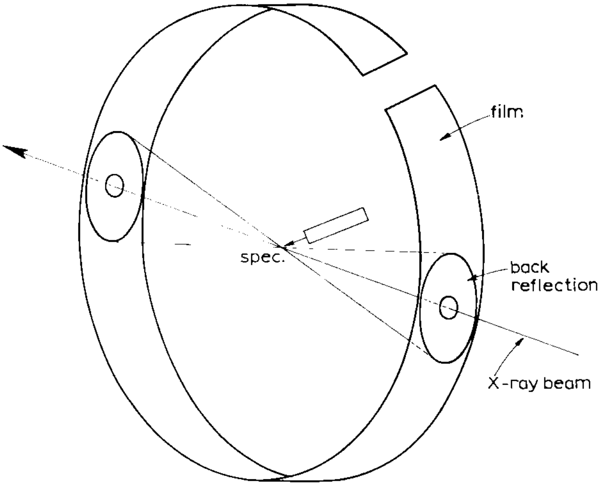


Fig.54. Diagram of a film as mounted in the Debye–Scherrer powder camera.

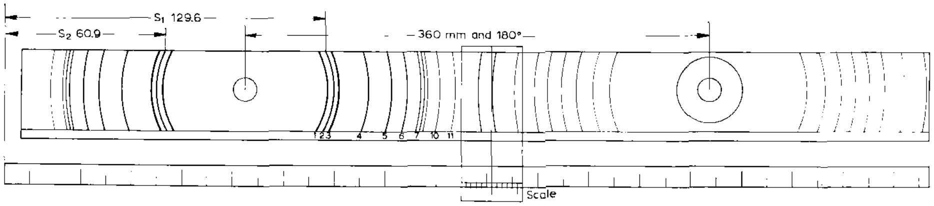
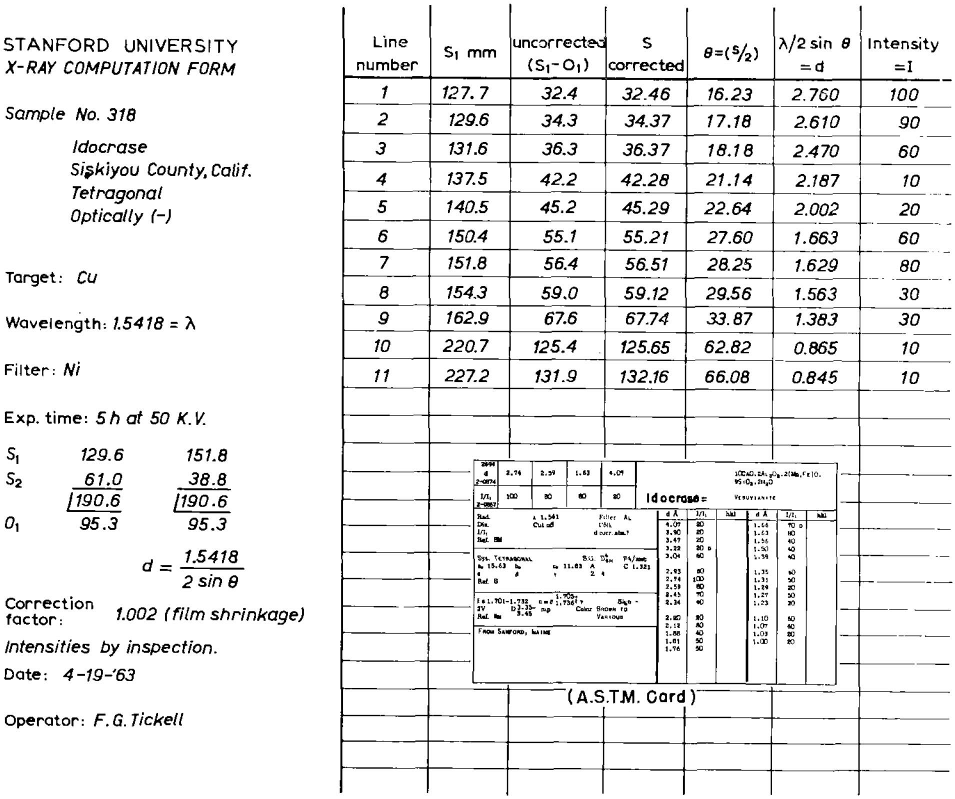


Fig.55. X-ray diffraction. FilmNo.318(Idocrase). Measurement of interplanar spacings.

The covered camera is then placed on the stage of the X-ray instrument in such a way that the rays can enter it. A belted drive is usually provided with a small motor to rotate the specimen during exposure (Fig.54).

The time of exposure will vary from 2–15 h or more, depending upon the sample, target, and voltage.

The film is developed, fixed, washed, and dried. It is then ready for inspection and measurement (Fig.55). The length of the film and the scale of measurement depend upon the internal diameter of the camera. One wishes to measure the distances of the



STANFORD UNIVERSITY
X-RAY COMPUTATION FORM

Sample No. *318*

Idocrase
Siskiyou County, Calif.
Tetragonal
Optically (-)

Target: *Cu*

Wavelength: *1.5418 = λ*

Filter: *Ni*

Exp. time: *5 h at 50 K.V.*

S_1	129.6	151.8
S_2	61.0	38.8
	190.6	190.6
O_1	95.3	95.3

$$d = \frac{1.5418}{2\sin\theta}$$

Correction factor: *1.002 (film shrinkage)*

Intensities by inspection.

Date: *4-19-'63*

Operator: *F. G. Tickell*

Line number	S_1 mm	uncorrected ($S_1 - O_1$)	S corrected	$\theta = (S/2)$	λ/2 sin θ = d	Intensity = I
1	127.7	32.4	32.46	16.23	2.760	100
2	129.6	34.3	34.37	17.18	2.610	90
3	131.6	36.3	36.37	18.18	2.470	60
4	137.5	42.2	42.28	21.14	2.187	10
5	140.5	45.2	45.29	22.64	2.002	20
6	150.4	55.1	55.21	27.60	1.663	60
7	151.8	56.4	56.51	28.25	1.629	80
8	154.3	59.0	59.12	29.56	1.563	30
9	162.9	67.6	67.74	33.87	1.383	30
10	220.7	125.4	125.65	62.82	0.865	10
11	227.2	131.9	132.16	66.08	0.845	10

d	2.74	2.59	1.63	4.07
I/I_1	100	80	80	80

Idocrase = Vesuvianite

$10CaO.2Al_2O_3.2(Mg,Fe)O.9SiO_2.2H_2O$

Rad. λ 1.541 Filter
Dia. Cut off Coll.
I/I_1 d corr. abs.?
Ref.

Sys. Tetragonal S.G. D_{4h}^{4} P4/nnc
a_0 15.63 b_0 c_0 11.83 A C 1.321
α β γ Z 4
Ref. B

εα 1.701-1.732 nωβ 1.705-1.736 εγ Sign -
2V D 3.35-3.45 mp Color Brown to Various
Ref.

From Sanford, Maine

d Å	I/I_1	hkl	d Å	I/I_1	hkl
4.07	80		1.66	70 b	
3.90	20		1.63	80	
3.47	20		1.56	40	
3.22	20 b		1.50	40	
3.04	60		1.39	40	
2.93	60		1.35	40	
2.74	100		1.31	50	
2.59	80		1.29	20	
2.45	70		1.27	50	
2.34	40		1.23	20	
2.20	80		1.10	60	
2.12	80		1.07	60	
1.88	40		1.03	20	
1.81	50		1.00	20	
1.76	50				

(A.S.T.M. Card)

Fig.56. A.S.T.M. card and X-ray computation form made of data taken from Fig.55.

lines from the point of ray-input in such a way as to be able to compute the various *d* values characteristic of the mineral.

When the *d* values have been calculated (see Fig.56), the A.S.T.M. Tables (J. V. SMITH, 1963) and/or card-files are consulted in the effort to find a match. The A.S.T.M. records list a large number of minerals, but are not entirely complete. A new edition is published each year, with revisions and additions.

X-ray diffractometry

This method requires a Geiger–Muller counter with recording equipment in addition to the X-ray instrument. Where numerous and routine determinations are to be made, however, it is a very rapid and convenient method.

The amount of sample, about 10–15 mg, is greater than for the Debeye–Scherrer method. The sample is pulverized under acetone (to which about 1% of a plastic cement has been added) in an agate mortar and, while pasty, it is smeared on a microscope-slide in such a way as to leave a smooth surface on top. It is mounted on the apparatus in such a way that the X-ray beam glances off its surface and thence to the Geiger-counter and recording device.

The operation requires up to several hours to produce a chart from which may be read directly the 2θ values of peaks and from which the *d* values may be computed as in the photographic method. The heights of the peaks represent the intensities of the lines. Part of such a chart is shown in Fig.57.

DIFFERENTIAL THERMAL ANALYSIS

When a clay is heated, dehydration takes place and is accompanied by exothermic or endothermic phenomena. The study of these reactions has been found useful in determining the identity of the clay. The method has also been used in the study of carbonates and other substances.

An electric furnace is required, capable of being heated to a temperature of 1,500°C, and equipped with a recorder and automatic voltage control (T in Fig.58) so that the rate of heating may be maintained at a uniform increase of from 10–15° per min. The clay specimen of about $\frac{1}{2}$ g is placed in one of the holes (S) formed in a nickel or ceramic holding-block. Another, adjoining, hole (A) is filled with dehydrated alumina or some such inert material. Thermocouples are inserted into both holes, with compensating lead-wires (a, b) attached to a differential temperature recorder (D).

During the heating-cycle, when an exothermic reaction occurs in the specimen, its temperature will rise above that of the inert substance, and when an endothermic reaction occurs, there will be the opposite effect. When no reaction is taking place, sample and inert substance will be at the same temperature (see Fig.59). The viscosity and thixotropy of clay–water mixtures is discussed in Chapter III.

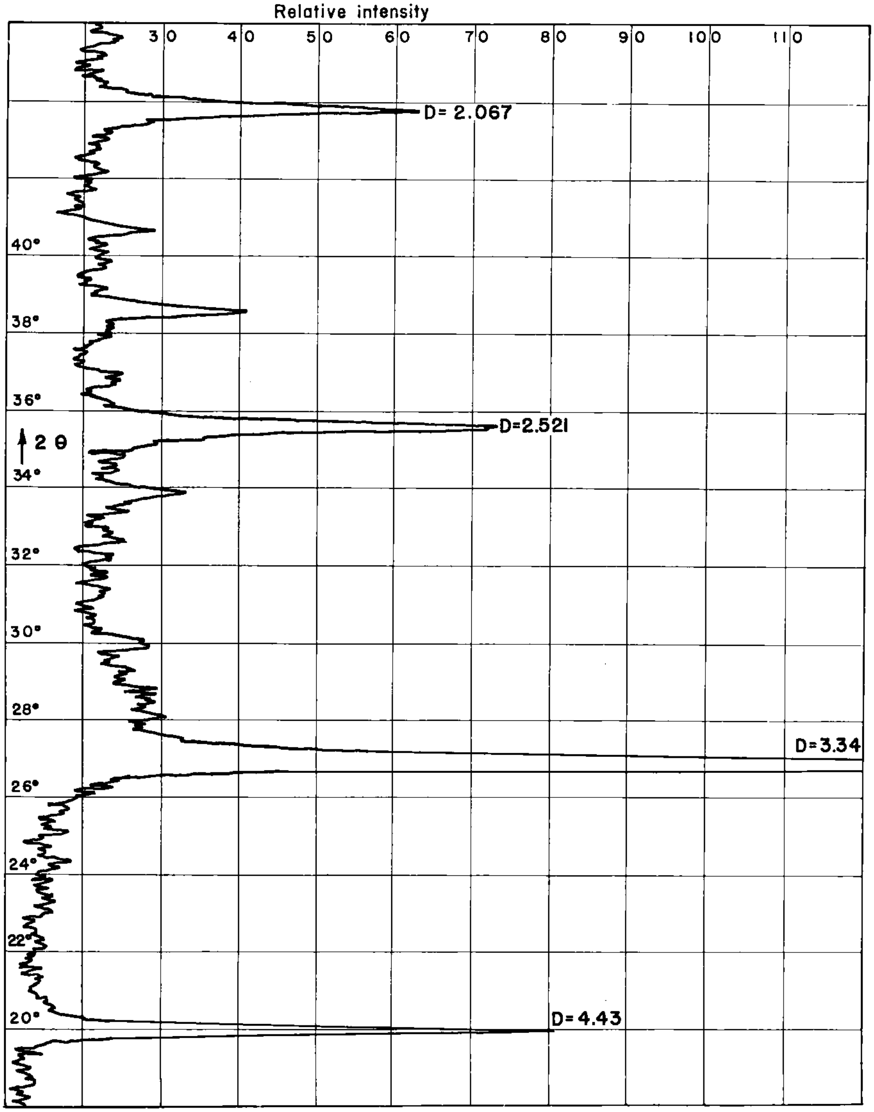


Fig.57. X-ray diffractometer pattern made with Norelco unit.
Mineral: Zircon; locality: Chico, Calif.; target/filter: Cu/Ni; started at 20°; scanned: up; rate 1°/min; divide 1°; multiply: 1.0; operator: F. G. Tickell.

Clays

Clays comprise a class of fragmental rocks that find use in various industrial applications. A clay is a rock that is composed of certain minerals that are very finely divided, so that the size of individual particles is 2μ or less. They may contain water-soluble salts and may exhibit ion-exchange capacity. The particles of a clay are often bound together by electrostatic or intermolecular forces.

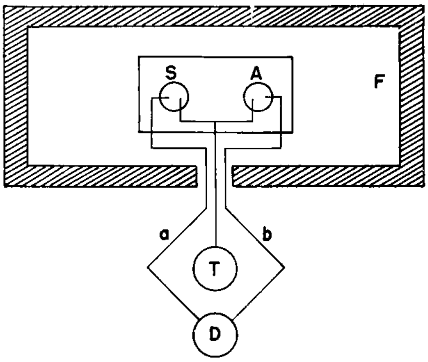


Fig.58. Apparatus for differential thermal analysis. *F*= furnace; *S*= sample; *A*= insert substance; *T*= furnace temperature controller; *D*= temperature-difference recorder: *a* and *b* are thermocouple leads.

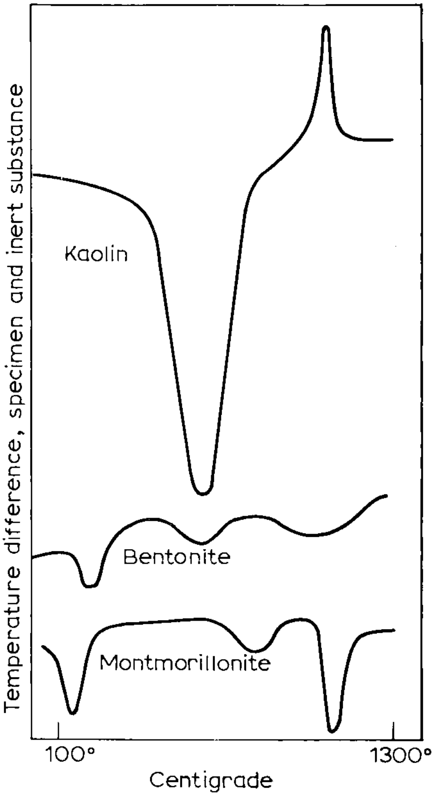


Fig.59. Differential thermal analyses of clays.

X-ray studies of clays have shown that some of the constituents may be amorphous, but that they consist, for the most part, of certain crystalline sheet-structures.

The most commonly occurring mineral species are allophane, kaolinite, halloysite, montmorillonite, illite, chlorite, vermiculite, sepiolite, attapulgite, and palygorskite. Bentonite is a commonly used term for a type of clay that has been proved to be a mixture of clay-minerals with montmorillonite as the chief ingredient.

The clay minerals may be examined and described by the techniques of X-ray diffraction, optical microscopy, electron micrography, ion-exchange, adsorbed water and dehydration studies, and differential thermal analysis. Grim (1953) states that the last named method has yielded many significant results, but that X-ray analysis is the most satisfactory single procedure for evaluating complex mixtures of clay minerals.

Chemical analysis of clay particles

Recent advances in X-ray technology have made possible the chemical analysis of extremely small particles, such as exist in clays. Particles at the surface of a specimen having volumes of one cubic micron ($1\mu^3$) may be analyzed for elements above sodium in the periodic table with a concentration sensitivity of the order of 0.1–0.01% (Long, 1962). The Applied Research Laboratories Inc. (Glendale, California) have developed the A.R.L. Electron Microprobe X-Ray Analyzer (O'Brien, 1963) that makes possible the accurate analysis of such minute areas.

As applied to clay analysis, a dilute, deflocculated suspension is applied to the surface of a highly polished beryllium rod of ¼ inch diameter (White, 1964). The liquid evaporates, leaving individual grains on the surface of the rod. A number of these rods may be processed in the A.R.L. instrument at one time. New development in this field promises to extend the range to lower atomic numbers.

Chapter 6

DESCRIPTION OF MINERALS OCCURRING IN SEDIMENTARY ROCKS

The minerals described in this chapter have been reported as occurring in sedimentary rocks. Some of them are commonly found, while others are more rare. The common minerals are, for the most part, ones that have considerable resistance to erosive agencies or have accumulated in more recent geologic time. Very old sediments are likely to have comparatively few mineral species.

The methods of optical mineralogy serve to identify many of the minerals, herein described, quite readily, but there are other cases where optical tests must be supplemented by specific gravity determination, chemical-tests, dye-tests, flame-tests, fluoroscopy or, in cases where facilities are available, by spectrographic analysis and X-ray diffraction.

It should be realized that the data given herein are generalized and, in some cases, subject to wide variation. This is true, however, to a greater or less degree for most mineralogy texts. For more complete information the reader is advised to consult Deer et al. (1963). Table XXXV (at the end of this chapter) gives some detrital minerals which are characteristic of different rock types.

ACTINOLITE
(Amphibole group)

Composition: $Ca_2(Mg,Fe)_5(OH)_2(Si_4O_{11})_2$
System: monoclinic
Cleavage: 110 perfect
Hardness: 5.0
Specific gravity: 3.0–3.3
Magnet: weakly magnetic
Conductivity: moderate
Optical properties:
  $Nx = 1.614$
  $Ny = 1.630$
  $Nz = 1.641$
Birefringence: 0.027
Biaxial: (—)
2V: 80°
Dispersion: Weak.
  $\varrho < \nu$
Color: Green, grey-green, yellow-green.
Pleochroism:
  x = pale yellow
  y = yellow-green
  z = green
Identification: Usually acicular or fibrous. With decrease of iron grades into tremolite.
Derivation: Metamorphics, crystalline schists.

ALBITE
(Plagioclase group)

Composition: $NaAlSi_3O_8$
System: triclinic
Cleavage: 001 perfect, 010 good, at angle of about 90°
Hardness: 6.0–6.5
Specific gravity: 2.60–2.62
Magnet: non-magnetic
Conductivity: none
Optical properties:
  $Nx = 1.527–1.529$
  $Ny = 1.532–1.533$
  $Nz = 1.534–1.539$
Birefringence: 0.007–0.010
Biaxial: (+)
2V: 45–97°
Dispersion: —

Color: White and various pale tints.
Pleochroism: —
Identification: Stained pink by amaranth, polysynthetic twinning. Special tests. X-rays.
Derivation: Igneous rocks.

ALMANDITE
(Garnet group)

Composition: $Fe_3Al_2(SiO_4)_3$
System: isometric
Cleavage: none
Hardness: 7.0
Specific gravity: 4.1–4.3
Magnet: moderately magnetic
Conductivity: poor
Optical properties:
$n = 1.76$–1.83
Dispersion: —
Color: Red or brownish-red.
Pleochroism: —
Identification: Irregular fractured grains.
Derivation: Igneous and metamorphic rocks.

AMBER

Composition: C : H : O = 40 : 64 : 4
System: amorphous
Cleavage: none
Mariness: 2.0–2.5
Specific gravity: 1.09
Magnet: non-magnetic
Conductivity: good
Optical properties:
$n = 1.53$
Dispersion: —
Color: Yellow, reddish-brown.
Pleochroism: —
Identification: Irregular fragments. Not a mineral, but is here included because it is often found in sediments. Some is fluorescent.
Derivation: Fossil resin from conifers.

ANALCITE
(Zeolite group)

Composition: $NaAlSi_2O_6 \cdot H_2O$
System: isometric
Cleavage: cubic poor
Hardness: 5.0–5.5
Specific gravity: 2.2–2.29
Magnet: non-magnetic
Conductivity: none
Optical properties:
$n = 1.487$
Sometimes anomalously isotropic.
Dispersion: —
Color: White, grey.
Pleochroism: —
Identification: Rare in sediments. Difficult to identify in small grains.
Derivation: Volcanic and other igneous rocks. Diabase and basalt.

ANATASE (Octahedrite)

Composition: TiO_2
System: tetragonal
Cleavage: 001 perfect, 111 perfect
Hardness: 5.5–6.0
Specific gravity: 3.82–3.95
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N\omega = 2.554$
$N\varepsilon = 2.493$
Birefringence: 0.061
Uniaxial: (−)
Dispersion: —
Color: Yellow, brown, blue, black.
Pleochroism: In thick grains only.
ω = pale blue or yellow
ε = dark blue or orange
Identification: Tabular and bevelled grains. Usually of secondary origin. Grains may appear isotropic, but show uniaxial figure.
Derivation: Secondary or igneous and metamorphic rocks. Sometimes decomposed from ilmenite.

ANDALUSITE

Composition: Al_2SiO_5
System: orthorhombic
Cleavage: 110 good, 100 poor
Hardness: 7.5
Specific gravity: 3.2
Magnet: non-magnetic
Conductivity: poor
Optical properties:
$Nx = 1.634$
$Ny = 1.639$
$Nz = 1.643$
Birefringence: 0.009
Biaxial: (−)
$2V$: 85°
Dispersion: —
Color: Rose-red, violet, colorless.
Pleochroism:

x = red
y and z = colorless or green
Identification: Most easily identified by the pleochroism and negative elongation. Prismatic cleavage fragments do not give good interference figures.
Derivation: Igneous and metamorphic rocks.

ANDESINE
(Plagioclase group)

Composition: albite 3, anorthite 2
System: triclinic
Cleavage: 001 perfect, 010 perfect
Hardness: 6.0
Specific gravity: 2.68
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.550$
$Ny = 1.553$
$Nz = 1.557$
Birefringence: 0.007
Biaxial: (+)
2V: 88°
Dispersion: Weak.
$\varrho > v$
Color: Colorless.
Pleochroism: —
Identification: Polysynthetic twinning. Special tests. X-rays.
Derivation: Hypabyssal and volcanic igneous rocks.

ANDRADITE
(Garnet group)

Composition: $3CaO.Fe_2O_3.3SiO_2$
System: isometric
Cleavage: none
Hardness: 7.0
Specific gravity: 3.78
Magnet: moderately magnetic
Conductivity: poor
Optical properties:
$N = 1.865$
Dispersion: —
Color: Yellow, brown, green, black.
Pleochroism: —
Identification: Rare in sediments, sometimes fluorescent.
Derivation: Schists, syenite, contact-metamorphic limestone.

ANHYDRITE

Composition: $CaSO_4$
System: orthorhombic
Cleavage: 001, 010 perfect, 100 good
Hardness: 3.0–3.5
Specific gravity: 2.90–2.98
Magnet: non-magnetic
Conductivity: poor
Optical properties: variable
$Nx = 1.570$
$Ny = 1.575$
$Nz = 1.614$
Birefringence: 0.044
Biaxial: (+)
2V: 42°
Dispersion: —
Color: Colorless, white, grey, pink.
Pleochroism: —
Identification: Variable in form.
Derivation: Metasomatism in limestones.

ANKERITE
(Calcite group)

Composition: $CaCO_3(Mg,Fe,Mn)CO_3$
System: hexagonal (rhombohedral)
Cleavage: $10\bar{1}1$ perfect
Hardness: 3–4
Specific gravity: 3.0–3.12
Magnet: non-magnetic
Conductivity: none
Optical properties:
Similar to calcite, N varies with Fe content.
Birefringence: $\omega - \varepsilon = 0.18–0.19$
Uniaxial: (−)
Dispersion: —
Color: White, yellow, brown.
Pleochroism: —
Identification: In irregular rhombohedral grains.
Derivation: From sedimentary rocks.

ANORTHITE
(Plagioclase group)

Composition: $CaO.Al_2O_3.2SiO_2$
System: triclinic
Cleavage: 001 perfect, 010 imperfect
Hardness: 6.0
Specific gravity: 2.77
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.576$
$Ny = 1.584$

$Nz = 1.588$
Birefringence: 0.012
Biaxial (—)
$2V = 77°$
Dispersion: Weak.
$\varrho > v$
Color: White.
Pleochroism: —
Identification: Polysynthetic twinning. Special tests. X-rays.
Derivation: Basic and ultra-basic igneous rocks.

ANORTHOCLASE
(Feldspar group)

Composition: $(Na,K)AlSi_3O_8$
System: triclinic
Cleavage: 010 perfect, 001 perfect
Hardness: 6.0
Specific gravity: 2.58
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.519$
$Ny = 1.525$
$Nz = 1.527$
Birefringence: 0.008
Biaxial: (—)
$2V$: 45°
Dispersion: Weak.
$\varrho > v$
Color: White.
Pleochroism: —
Identification: Polysynthetic twinning. Special tests. X-rays.
Derivation: Soda-bearing volcanic rocks.

APATITE

Composition: $(CaCl)Ca_4(PO_4)_3$ and $(CaF)Ca_4(PO_4)_3$
System: hexagonal
Cleavage: 0001 poor
Hardness: 5.0
Specific gravity: 3.2
Magnet: non-magnetic
Conductivity: poor
Optical properties:
$N\omega = 1.634–1.648$
$N\varepsilon = 1.630–1.643$
Birefringence: 0.002 + or —
Uniaxial: (—)
$2V$: Sometimes pseudo-biaxial with $2V$ to 20°.
Dispersion: —
Color: Colorless, bluish, greenish.
Pleochroism: Very weak.
Identification: Elongation (—); usually in elongated crystals with rounded ends. Birefringence low.
Derivation: Acidic igneous rocks.

ARAGONITE

Composition: $CaCO_3$
System: orthorhombic
Cleavage: 010 good, 110 fair
Hardness: 3.5–4.0
Specific gravity: 2.9
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.530$
$Ny = 1.682$
$Nz = 1.686$
Birefringence: 0.156
Biaxial: (—)
$2V$: 18°
Dispersion: —
Color: Colorless.
Pleochroism: —
Identification: Shows iridescent colors and twinkling, like calcite. Rare in sediments.
Derivation: Bedded deposits. Associated with limestone and gypsum. Also vesicles in lavas.

ARFVEDSONITE
(Amphibole group)

Composition: $Na_3Fe_3Al(OH)_2Si_8O_{22}$
System: monoclinic
Cleavage: 110 perfect at 124°
Hardness: 6.0
Specific gravity: 3.33–3.45
Magnet: moderately magnetic
Conductivity: poor
Optical properties:
$Nx = 1.670$
$Ny = 1.680$
$Nz = 1.682$
Birefringence: 0.012
Biaxial: (—)
$2V$: Large.
Dispersion: Strong.
$\varrho < v$
Color: Blue, black.
Pleochroism: Strong.
x = dark green
y = pale brown
z = black
Identification: Elongation (—). Extinction often

incomplete, due to strong dispersion.
Derivation: Soda-bearing igneous rocks, such as nepheline syenite.

ARSENOPYRITE

Composition: FeAsS
System: monoclinic
Cleavage: 101 good, 010 poor
Hardness: 5.5–6.0
Specific gravity: 5.9–6.2
Magnet: non-magnetic
Conductivity: good
Optical properties:
Opaque.
Dispersion: —
Color: Silver-white to grey.
Pleochroism: —
Identification: Special tests, chemical or X-ray.
Derivation: Contact-metamorphic rocks and veins.

ASTROPHYLLITE

Composition: $R_4^{I}R_4^{II}Ti(SiO_4)_4$ $R^{I} = H,Na,K$ $R^{II} = Fe,Mn$
System: orthorhombic
Cleavage: 010 perfect, 001 imperfect
Hardness: 3.0
Specific gravity: 5.9–6.2
Magnet: weakly magnetic
Conductivity: —
Optical properties:
$Nx = 1.678$
$Ny = 1.703$
$Nz = 1.733$
Birefringence: 0.055
Biaxial: (+) sometimes (−)
2V: 75°
Dispersion: —
Color: Yellow, gold, bronze.
Pleochroism: Strong.
x = dark yellow
y = orange-yellow
z = lemon-yellow
Identification: Elongated or platy fragments.
Derivation: Nepheline syenite.

AUGITE

(Pyroxene group)

Composition: $CaMgSi_2O_6$ with $(MgFe)(AlFe)_2SiO_6$
System: monoclinic
Cleavage: 110 good
Hardness: 5.0–6.0
Specific gravity: 3.2–3.6
Magnet: moderately magnetic
Conductivity: moderate
Optical properties:
$Nx = 1.698$
$Ny = 1.704$
$Nz = 1.723$
Birefringence: 0.025
Biaxial: (+)
2V: 60°
Dispersion: Weak.
$\varrho > v$
Color: Greenish.
Pleochroism: Very weak.
Identification: Extinction angle usually greater than 45°, and is less for red than for blue light. Similar to diopside.
Derivation: Basic igneous rocks

AUTUNITE

Composition: $Ca(UO_2)_2P_2O_8.8H_2O$
System: tetragonal
Cleavage: 001 perfect, 100 good
Hardness: 2.0–2.5
Specific gravity: 3.1–3.2
Magnet: non-magnetic
Conductivity: —
Optical properties:
$N\omega = 1.577$
$N\varepsilon = 1.553$
Birefringence: 0.024
Uniaxial: (−)
Dispersion: Weak.
Color: Yellow, greenish yellow.
Pleochroism: Weak.
x = colorless
y and z = golden yellow
Identification: Strongly fluorescent. In sediments, as yellow, platy grains. Sometimes abnormally biaxial (−).
Derivation: Veins. Alteration of uraninite.

AXINITE

Composition: $R_7^{II}R_4^{III}B_2(SiO_4)_8$ R^{II} chiefly Ca R^{III} Al
System: triclinic
Cleavage: 010 distinct
Hardness: 6.5–7.0
Specific gravity: 3.25–3.30
Magnet: non-magnetic
Conductivity: poor

Optical properties:
$Nx = 1.678$
$Ny = 1.685$
$Nz = 1.688$
Birefringence: 0.010
Biaxial: (−)
2V: 65–70°
Dispersion: Strong.
$\varrho < v$
Color: Various shades of red, yellow or blue.
Pleochroism: Moderate.
x = pale green
y = blue or violet
z = brown
Identification: Irregular or diamond-shaped grains; frequently pink.
Derivation: Metamorphosed, basic, igneous rocks.

BADDELEYITE

Composition: ZrO_2
System: monoclinic
Cleavage: 001 perfect, 010 imperfect, 110 imperfect
Hardness: 6.5
Specific gravity: 5.4–6.0
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 2.13$
$Ny = 2.19$
$Nz = 2.20$
Birefringence: 0.07
Biaxial: (−)
2V: 30°
Dispersion: Strong.
$\varrho > v$
Color: Yellow, brown, black.
Pleochroism: Distinct.
x = red-brown
y = deep green
z = red-brown
Identification: In sediments, worn, tabular grains.
Derivation: Syenite or pyroxenite.

BARITE

Composition: $BaSO_4$
System: orthorhombic
Cleavage: 001 perfect, 110 perfect, 010 poor
Hardness: 2.5–3.5
Specific gravity: 4.5
Magnet: non-magnetic
Conductivity: poor
Optical properties:
$Nx = 1.636$
$Ny = 1.637$
$Nz = 1.648$
Birefringence: 0.012
Biaxial: (+)
2V: 37.5°
Dispersion: Weak.
$\varrho < v$
Color: Colorless.
Pleochroism: —
Identification: Easily confused with celestite, or anhydrite. Make flame-test for Ba.
Derivation: Veins, sediments and bedded deposits.

BARKEVIKITE

(Amphibole group)

Composition: near arfvedsonite, but more basic
System: monoclinic
Cleavage: 110 perfect
Hardness: 6.0
Specific gravity: 3.43
Magnet: moderately magnetic
Conductivity: moderate
Optical properties:
$Nx = 1.687$
$Ny = 1.707$
$Nz = 1.708$
Birefringence: 0.021
Biaxial: (−)
2V: 54°
Dispersion: Strong.
Color: Green, greenish-brown, black.
Pleochroism: Distinctive.
x = brownish-yellow
y = reddish-brown
z = deep brown
Identification: Prismatic 010 grains.
Derivation: Nepheline syenites.

BENITOITE

Composition: $BaTiSi_3O_9$
System: hexagonal
Cleavage: $10\bar{1}1$ imperfect
Hardness: 6.2–6.5
Specific gravity: 3.6
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N\omega = 1.757$
$N\varepsilon = 1.804$
Birefringence: 0.047

Uniaxial: (+)
Dispersion: —
Color: Blue, purplish blue.
Pleochroism: Strong.
ω = colorless
ε = deep blue
Identification: A rare mineral, except where it occurs with natrolite and neptunite. Often fluorescent. Elongation (+).
Derivation: Veins and schists. In California: sediments of San Benito River.

BERYL

Composition: $Be_3Al_2(SiO_3)_6$
System: hexagonal
Cleavage: 0001 imperfect
Hardness: 7.5–8.0
Specific gravity: 2.63–2.80
Magnet: non-magnetic
Conductivity: poor
Optical properties:
$N\omega = 1.568\text{–}1.602$
$N\varepsilon = 1.564\text{–}1.595$
Birefringence: Low; often anonamously biaxial.
Uniaxial: (−)
Dispersion: —
Color: Green, blue, yellow.
Pleochroism: Weak.
ω = yellowish green
ε = greenish blue
Identification: In sediments, worn, prismatic crystals of green color.
Derivation: Granite, schists, pegmatite veins.

BIOTITE
(Mica group)

Composition: $H_2K(Mg,Fe)_3Al(SiO_4)_3$
System: monoclinic, pseudo-hexagonal
Cleavage: 001 perfect
Hardness: 2.5–3.0
Specific gravity: 2.8–3.4
Magnet: moderately magnetic
Conductivity: moderate
Optical properties:
$Nx = 1.541$
$Ny = 1.574$
$Nz = 1.574$
Birefringence: 0.033
Biaxial: (−)
2V: Usually less than 10°.
Dispersion: Weak.
$\varrho < \nu$
Color: Colorless, yellow, green, brown.
Pleochroism: 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: 5.5–6.0
Specific gravity: 3.8–4.1
Magnet: non-magnetic
Conductivity: moderate
Optical properties:
$Nx = 2.583$
$Ny = 2.586$
$Nz = 2.741$
Birefringence: 0.158
Biaxial: (+)
2V: $2E = 55°$ for red light and
0° for yellow-green light;
dependent on wave-length and
temperature.
Dispersion: Very strong.
Crossed axial plane: 001 for ϱ, 100 for ν.
Color: Brown or yellow.
Pleochroism: Weak.
Identification: Usually as tabular fragments of irregular outline. Extreme dispersion makes the interference figure of unique appearance.
Derivation: Acid, igneous and metamorphic rocks.

BYTOWNITE
(Plagioclase group)

Composition: albite 30–10%, anorthite 70–90%
System: triclinic
Cleavage: 100 perfect, 010 distinct
Hardness: 6.0
Specific gravity: 2.73
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.566$
$Ny = 1.572$
$Nz = 1.576$
Birefringence: 0.010
Biaxial: (−)
2V: 82°

Dispersion:
$\varrho > v$
Color: Colorless, grey, green, white.
Pleochroism: —
Identification: Rare in sediments.
Derivation: Basic, plutonic and volcanic rocks.

CALCITE
(Carbonate group)

Composition: $CaCO_3$
System: hexagonal (rhombohedral)
Cleavage: $10\bar{1}1$ perfect
Hardness: 3.0
Specific gravity: 2.7
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N\omega = 1.658$
$N\varepsilon = 1.486$
Birefringence: 0.172
Unaxial: (−)
Dispersion: —
Color: Pale tints or colorless. Exhibits "twinkling" in plane-polarized light on rotation of the polarizer.
Pleochroism: Cleavage striae parallel to long diagonals of the rhombohedral cleavage.
Identification: If aragonite is immersed in 1. bromonaphthalene ($n = 1.658$), its index is greater for both directions; not so for calcite.
Derivation: Various sources, mostly sedimentary. Also from alteration of lime silicates of igneous rocks.

CARBORUNDUM
(artificial)

Composition: SiC
System: hexagonal
Cleavage: $10\bar{1}1$ rare, 0001 poor
Hardness: 9.5
Specific gravity: 3.2
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N\omega = 2.654$
$N\varepsilon = 2.697$
Birefringence: 0.043
Uniaxial: (+)
Dispersion: Very strong.
Color: Usually bluish-grey.
Pleochroism: Apparent: $\varepsilon > \omega$.
Identification: The Delft-blue color and pleochroism usually distinguish this substance.
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
(Rutile group)

Composition: SnO_2
System: tetragonal
Cleavage: 100 poor, 111 poor
Hardness: 6.0–7.0
Specific gravity: 6.8–7.1
Magnet: non-magnetic
Conductivity: moderate
Optical properties:
$N\omega = 1.997$
$N\varepsilon = 2.093$
Birefringence: 0.096
Uniaxial: (+)
Dispersion: —
Color: Brown, black, reddish brown, grey.
Pleochroism: Absorption: $\omega < \varepsilon$.
Identification: Usually in prismatic grains. Distinguished from rutile by the lower birefringence.
Derivation: Acid igneous rocks or pegmatite veins.

CELESTINE
(Barite group)

Composition: $SrSO_4$
System: orthorhombic
Cleavage: 001 perfect, 110 good, 010 imperfect
Hardness: 3.0–3.5
Specific gravity: 3.95–3.97
Magnet: non-magnetic
Conductivity: none
Opcital properties:
$Nx = 1.622$
$Ny = 1.624$
$Nz = 1.631$
Birefringence: 0.009
Biaxial: (+)
2V: 51°
Dispersion:
$\varrho < v$
Color: Colorless, white, pale blue.
Pleochroism: Faintly pleochroic if blue.
Identification: Flame test for strontium. X-rays.
Derivation: Associated with limestones, or sandstones as cementing material. Also from geodes and veins.

CEYLONITE
(Spinel group)

Composition: $(MgFe)O.Al_2O_3$
System: isometric
Cleavage: 111 imperfect
Hardness: 8.0
Specific gravity: 3.5–3.6
Magnet: weakly magnetic
Conductivity: none
Optical properties:
$N = 1.75\text{–}1.79$
Dispersion: —
Color: Green, blue-green.
Pleochroism: —
Identification: Octahedral habit.
Derivation: Basic igneous rocks, metamorphic rocks.

CHALCEDONY

Composition: SiO_2
System: cryptocrystalline
Cleavage: none, conchoidal fracture
Hardness: 6.5
Specific gravity: 2.57–2.64
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N = 1.53\text{–}1.54$
Birefringence: Sometimes about 0.006.
Dispersion: —
Color: White, blue, green, yellow, pink.
Pleochroism: —
Identification: Usually exhibits fibrous texture, spherulites, or aggregate polarization.
Derivation: Hydrothermal action, producing crusts, veins and cavity fillings.

CHALCOPYRITE

Composition: $CuFeS_2$
System: tetragonal
Cleavage: 011 distinct
Hardness: 3.5–4.0
Specific gravity: 4.1–4.3
Magnet: non-magnetic
Conductivity: moderate
Optical properties:
Opaque.
Dispersion: —
Color: Brass-yellow or iridescent.
Pleochroism: —
Identification: In sediments: irregular yellow grains, sometimes striated. Metallic luster.
Derivation: Veins in contact-metamorphic rocks.

CHLORITE GROUP
(Mica division)

Composition: $H_8(Mg,Fe)_5Al_2Si_3O_{18}$
System: monoclinic
Cleavage: 001 perfect
Hardness: 2.0–2.5
Specific gravity: 2.6–3.0
Magnet: moderately magnetic
Conductivity: poor
Optical properties:
$N = 1.56\text{-}1.60$ (mean)
Birefringence: 0.004–0.025
Biaxial: (+) or (−)
Dispersion: Weak.
$\varrho < v$
Color: Usually green.
Pleochroism: Sometimes green to yellowish green.
Identification: Irregular flakes with pale green color, weak birefringence, and strong dispersion. Sometimes deep blue with anomalous interference colors. It is said (C.O. Hutton, personal communication) that there are only two kinds of chlorite, the 7 Å spacing and the 14 Å spacing, the spacing indicating the amount of Si and Mg.
Derivation: Metamorphic rocks.

CHLORITOID
(Clintonite group)

Composition: $H_2(FeMg)Al_2SiO_7$
System: probably triclinic
Cleavage: 001 perfect
Hardness: 7.0
Specific gravity: 3.3
Magnet: weakly magnetic
Conductivity: none
Optical properties:
$Ny = 1.73$
Birefringence: 0.010
Biaxial: (+)
2V: 36–60°
Dispersion: Moderate.
$\varrho > v$
Color: Grey, green.
Pleochroism: Strong.
x = olive green
y = blue
z = yellow green
Identification: Rare in sediments.
Derivation: Schists and phyllites. Altered clays.

CHROMITE
(Spinel group)

Composition: $FeCr_2O_4$
System: isometric
Cleavage: none
Hardness: 5.5
Specific gravity: 4.5
Magnet: moderately magnetic
Conductivity: good
Optical properties:
Opaque, except in very thin flakes.
$N = 2.07$
Dispersion: —
Color: Black, purplish or brownish black.
Pleochroism: —
Identification: Use borax-bead test for Cr. Bead is green in both oxidizing and reducing flames.
Derivation: Basic igneous rocks. Peridotites, serpentines and schists.

CHRYSOBERYL

Composition: $BeAl_2O_4$
System: orthorhombic
Cleavage: 110 good, 010 imperfect, 001 poor
Hardness: 8.5
Specific gravity: 3.75
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.747$
$Ny = 1.748$
$Nz = 1.756$
Birefringence: 0.009
Biaxial: (+)
2V: 45°
Dispersion:
$\varrho > v$
Color: Green, yellowish green.
Pleochroism:
x = red
y = orange
z = emerald green
Identification: Rolled and flattened pebbles and grains.
Derivation: In gem-gravels, from pegmatites. Also from mica-schists.

CHRYSOTILE
(Serpentine and talc division)

Composition: $3MgO.2SiO_2.2H_2O$
System: monoclinic
Cleavage: fibrous
Hardness: 2.5–4.0
Specific gravity: 2.22
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.508$
$Ny = 1.512$
$Nz = 1.522$
Birefringence: 0.014
Biaxial: (+)
2V: 30–35°
Dispersion: —
Color: Green, yellow.
Pleochroism: Faint.
Identification: Fibrous habit, elongation (+). Often asbestiform.
Derivation: Serpentine rocks.

CINNABAR

Composition: HgS
System: hexagonal
Cleavage: $10\bar{1}0$ perfect
Hardness: 2.0–2.5
Specific gravity: 8.1
Magnet: non-magnetic
Conductivity: none
Optical properties:
Opaque to translucent.
$N\omega = 2.913$
$N\varepsilon = 3.272$
Birefringence: 0.359
Uniaxial: (+)
Dispersion: —
Color: Red.
Pleochroism: —
Identification: Irregular detrital grains. Circular polarization extreme.
Derivation: Veins in or near volcanic rocks.

CLINOZOISITE
(Epidote group)

Composition: $Ca_2(AlOH)Al_2(SiO_4)_3$
System: monoclinic
Cleavage: 001 perfect, 100 imperfect
Hardness: 6.5
Specific gravity: 3.35–3.38
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.715$
$Ny = 1.720$
$Nz = 1.725$
Birefringence: 0.010

Biaxial: (+) occasionally (−)
2V: 66°
Dispersion: Strong.
$\varrho < v$
Color: Colorless, yellow.
Pleochroism:
x = green
y = pink or green
z = deep red or green
Identification: Rare in sediments.
Derivation: Schists and from altered feldspars.

COLUMBITE–TANTALITE

Composition: niobate and tantalate of Fe and Mn
System: orthorhombic
Cleavage: 100 distinct, 010 poor
Hardness: 6.0
Specific gravity: 5.3–7.3
Magnet: weakly magnetic
Conductivity: good
Optical properties:
Opaque in some.
$Nx = 2.26$
$Ny = 2.29$
$Nz = 2.34$
Birefringence: 0.08
Biaxial: (+) columbite may be (−)
2V: 73–75°
Dispersion: Strong.
$\varrho < v$
Color: Black, grey.
Pleochroism: —
Identification: Water-worn crystalline grains.
Derivation: Granites, pegmatites and veins.

CORDIERITE

Composition: $Mg_2Al_4Si_5O_{18}$
System: orthorhombic
Cleavage: 010 good, 100 poor, 001 poor
Hardness: 7.0–7.5
Specific gravity: 2.57–2.66
Magnet: moderately magnetic
Conductivity: poor
Optical properties:
$Nx = 1.534$
$Ny = 1.538$
$Nz = 1.540$
Birefringence: 0.006
Biaxial: (−)
2V: 40–84°
Dispersion: Weak.
$\varrho < v$
Color: Blue, yellow, brown.
Pleochroism:
x = yellow to white
y = dark blue
z = light blue
Identification: Small, sub-angular grains.
Derivation: Gneisses and crystalline schists.

CORUNDUM

Composition: Al_2O_3
System: hexagonal (rhombohedral)
Cleavage: none, sometimes parting on 0001
Hardness: 9.0
Specific gravity: 3.95–4.10
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N\omega = 1.768$
$N\varepsilon = 1.760$
Birefringence: 0.008
Uniaxial: (−)
2V: Anomalous 2E = 11–58°.
Dispersion: —
Color: Colorless, blue, red, yellow, brown.
Pleochroism: Colored varieties.
Identification: Irregular fragments.
Derivation: Volcanic and metamorphic rocks.

DIAMOND

Composition: carbon
System: isometric, isotropic
Cleavage: 111 perfect
Hardness: 10.0
Specific gravity: 3.52
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N = 2.419$
Dispersion: Strong.
Color: Various.
Pleochroism: —
Identification: In sediments: clear, colorless, octahedral grains; inclusions common. Often fluorescent. Luster, adamantine.
Derivation: Ultra-basic rocks. Pegmatite veins.

DIASPORE

Composition: $Al_2O_3.H_2O$
System: orthorhombic
Cleavage: 010 perfect, 210 distinct
Hardness: 6.5–7.0
Specific gravity: 3.4–3.5

Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.702$
$Ny = 1.722$
$Nz = 1.750$
Birefringence: 0.048
Biaxial: (+)
2V: 84°
Dispersion: Weak.
$\varrho < v$
Color: White, grey, pink, red.
Pleochroism: In some cases.
x and y are colorless
z = blue
Identification: Uncommon in sediments.
Derivation: Volcanics and schists. Bauxite deposits.

DIOPSIDE
(Pyroxene group)

Composition: $CaMgSi_2O_6$
System: monoclinic
Cleavage: 110 good, 100 parting
Hardness: 5.0–6.0
Specific gravity: 3.3
Magnet: weakly magnetic
Conductivity: moderate
Optical properties:
$Nx = 1.673$
$Ny = 1.680$
$Nz = 1.702$
Birefringence: 0.029
Biaxial: (+)
2V: 59°
Dispersion: Weak.
$\varrho > v$
Color: Pale green or grey.
Pleochroism: Very weak or lacking.
Identification: Easily confused with augite, but birefringence is greater and dispersion less. It gives more complete extinction in white light.
Derivation: Basic igneous and metamorphic rocks.

DUMORTIERITE

Composition: $HBAl_8Si_4O_{20}$
System: orthorhombic
Cleavage: 100 good, 110 poor, 001 parting
Hardness: 7.0
Specific gravity: 3.3
Magnet: non-magnetic
Conductivity: poor
Optical properties:
$Nx = 1.670$
$Ny = 1.691$
$Nz = 1.692$
Birefringence: 0.022
Biaxial: (−)
2V: 20–52°
Dispersion: Strong.
$\varrho > v$ or
$\varrho < v$
Color: Blue, violet.
Pleochroism: Strong.
x = blue
y = colorless or violet
z = colorless or blue
Identification: Strong pleochroism. Resembles tourmaline.
Derivation: Pegmatites and gneisses. Metamorphic rocks.

ENIGMATITE
(Amphibole group)

Composition: titano-silicate of Fe^{2+}, Al, Na and Fe^{3+}
System: triclinic
Cleavage: 110 distinct, $1\bar{1}0$ distinct
Hardness: 5.5
Specific gravity: 3.74–3.85
Magnet: moderately magnetic
Conductivity: moderate
Optical properties:
$Ny = 1.80$
Birefringence: 0.006
Biaxial: (+)
2V: 32°
Dispersion:
$\varrho < v$
Color: Black.
Pleochroism: Intense.
x = reddish brown
y = dark brown
z = very dark brown
Identification: Oblique extinction 4° to prismatic cleavage.
Derivation: Nepheline syenites.

ENSTATITE
(Pyroxene group)

Composition: $MgSiO_3$
System: orthorhombic
Cleavage: 110 good, 010 parting
Hardness: 5.5
Specific gravity: 3.2

Magnet: non-magnetic
Conductivity: poor
Optical properties:
$Nx = 1.650$
$Ny = 1.653$
$Nz = 1.658$
Birefringence: 0.008
Biaxial: (+)
2V: 30–70°
Dispersion: Weak.
$\varrho > v$
Polor: Grey, yellow, green.
Cleochroism: Weak.
x = yellow
z = green
Identification: Distinguished from hypersthene by weak pleochroism. Grains usually lie on 110 face and have ragged terminations.
Derivation: Metamorphic rocks. Basic igneous rocks.

EPIDOTE

Composition: $HCa_2(Al,Fe)_3Si_3O_{13}$
System: monoclinic
Cleavage: 001 perfect, 100 poor
Hardness: 6.0–7.0
Specific gravity: 3.4–3.5
Magnet: weakly magnetic
Conductivity: poor
Optical properties:
$Nx = 1.729$
$Ny = 1.754$
$Nz = 1.768$
Birefringence: 0.039
Biaxial: (−)
2V: 90° (+) or (−)
Dispersion: Strong.
$\varrho > v$
Color: Pale green to yellowish green.
Pleochroism: Weak.
x = colorless
y = greenish yellow
z = colorless
Identification: Grains are usually clear and transparent, and show a centered optic-axis figure. Clinozoisite is similar but colorless.
Derivation: Metamorphic rocks. Altered limestones.

EUCLASE
(Datolite group)

Composition: $HBeAlSiO_5$
System: monoclinic
Cleavage: 010 perfect, 100 imperfect, 010 imperfect
Hardness: 7.5
Specific gravity: 3.0–3.1
Magnet: non-magnetic
Conductivity: moderate
Optical properties:
$Nx = 1.652$
$Ny = 1.655$
$Nz = 1.671$
Birefringence: 0.019
Biaxial: (+)
2V: 50° (+) or (−)
Dispersion: Moderate.
$\varrho > v$
Color: Pale green, blue, light brown, sometimes colorless.
Pleochroism: Usually lacking.
Identification: Green or blue water-worn grains.
Derivation: Chlorite schist, metamorphics and pegmatites.

EUDIALITE

Composition: $(Na,Ca,Fe)_6Zr(OH,Cl)(SiO_3)_6$
System: hexagonal
Cleavage: 0001 distinct, $10\bar{2}0$ poor
Hardness: 5.0–6.0
Specific gravity: 2.8–3.1
Magnet: non-magnetic
Conductivity: —
Optical properties:
$N\omega = 1.610$
$N\varepsilon = 1.611$
Birefringence: 0.001
Uniaxial: (+)
Dispersion: —
Color: Pink, red, brown.
Pleochroism: Weak.
Identification: Pink to red, flattened grains.
Derivation: Nepheline syenite. Soda-granites.

FAYALITE
(Olivine group)

Composition: Fe_2SiO_4
System: orthorhombic
Cleavage: 010 distinct, 100 poor
Hardness: 6.5
Specific gravity: 4.3
Magnet: weakly magnetic
Conductivity: none
Optical properties:
$Nx = 1.835$
$Ny = 1.877$

$Nz = 1.886$
Birefringence: 0.051
Biaxial: (−)
2V: 47–50°
Dispersion: Strong.
$\varrho > v$
Color: Pale greenish yellow.
Pleochroism: Weak.
Identification: Rare in sediments.
Derivation: Volcanics and pegmatites.

FLUORITE

Composition: CaF_2
System: isometric
Cleavage: 111 perfect
Hardness: 4.0
Specific gravity: 3.2
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N = 1.434$
Dispersion: —
Color: Colorless and various tints of green, blue, yellow, lavender, pink.
Pleochroism: —
Identification: Often as triangular grains with bevelled edges. May show anomalous polarization due to strains. Sometimes fluorescent.
Derivation: Acidic igneous rocks, metamorphic rocks and veins. Limestones.

FUCHSITE
(Mica group)

Composition: $H_2KAl_3(SiO_4)_3 + Cr$
System: monoclinic
Cleavage: 001 perfect
Hardness: 2.5
Specific gravity: 2.86
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Ny = 1.594$
Birefringence: 0.04
Biaxial: (−)
2V: 40°
Dispersion: Strong.
$\varrho > v$
Color: Green, translucent.
Pleochroism: In thick grains.
x = colorless
y = yellowish green
z = dark bluish green
Identification: Basal plates give good figure.
Derivation: Mica schist, micaceous quartzite.

GADOLINITE
(Datolite group)

Composition: $Be_2FeY_2Si_2O_{10}$
System: monoclinic
Cleavage: none
Hardness: 6.5–7.0
Specific gravity: 4.0–4.5
Magnet: slightly magnetic
Conductivity: poor
Optical properties:
$Nx = 1.78$
$Ny = 1.78$
$Nz = 1.785$
Birefringence: 0.005
Biaxial: (+)
2V: 85°
Dispersion: Strong.
$\varrho > v$
Color: Greenish black, translucent to opaque.
Pleochroism: Weak.
Identification: Very rare in sediments.
Derivation: Granites and pegmatites.

GALENA

Composition: PbS
System: isometric
Cleavage: 100 perfect
Hardness: 2.5
Specific gravity: 7.4–7.6
Magnet: non-magnetic
Conductivity: good
Optical properties:
Opaque.
Dispersion: —
Color: Bluish grey or lead-grey.
Pleochroism: —
Identification: The cubical cleavage and color are distinctive. Metallic luster.
Derivation: Veins and ore-deposits. Pegmatites.

GARNET GROUP

Composition: $R_3^{II}R_2^{III}(SiO_4)_3$ R^{II} = Ca,Mg,Fe,Mn R^{III} = Al,Fe,Cr,Ti
System: isotropic
Cleavage: 110 poor
Hardness: 7.0
Specific gravity: 3.8
Magnet: moderately magnetic
Conductivity: poor

Optical properties:
$N = 1.71–1.89$
Dispersion: —
Color: Various.
Pleochroism: —
Identification: Irregular, transparent, and isotropic grains. Rarely anomalously biaxial (—) with strong dispersion. Compare with spinel.
Derivation: Metamorphic rocks. Common species are: pyrope, grossularite, andradite, spessartite, almandine and uvarovite.

GLAUCONITE

Composition: hydrous K,Fe,Al silicate.
System: monoclinic
Cleavage: 001 perfect
Hardness: 2.0
Specific gravity: 2.2–2.8
Magnet: moderately magnetic
Conductivity: none
Optical properties:
$Nx = 1.590–1.612$
$Ny = 1.609–1.643$
$Nz = 1.610–1.644$
Birefringence: 0.020–0.032
Biaxial: (—)
2V: 0–20°
Dispersion:
$\varrho > v$
Color: Shades of green.
Pleochroism:
x = straw-yellow or pale yellow-green
y = yellow
z = yellow
Identification: Rounded or irregular grains or aggregates. Decomposes readily to limonite.
Derivation: Sediments and lavas.

GLAUCOPHANE
(Amphibole group)

Composition: $Na(Al,Fe)(SiO_3)_2$
System: monoclinic
Cleavage: 110 perfect
Hardness: 6.0–6.5
Specific gravity: 3.0–3.5
Magnet: moderately magnetic
Conductivity: moderate
Optical properties:
$Nx = 1.621$
$Ny = 1.638$
$Nz = 1.639$
Birefringence: 0.018
Biaxial: (—)
2V: 45°
Dispersion: Strong.
$\varrho > v$
Color: Blue-violet to bluish black.
Pleochroism: Marked.
x = colorless or yellowish
y = blue-violet
z = dark blue
Identification: By pleochroism and positive elongation.
Derivation: Metamorphic rocks. Crystalline limestones.

GOLD

Composition: Au
System: isometric
Cleavage: none
Hardness: 2.5–3.0
Specific gravity: 19.3
Magnet: non-magnetic
Conductivity: good
Optical properties:
Opaque or translucent in very thin flakes.
Dispersion: —
Color: Yellow.
Pleochroism: —
Identification: Rounded, flattened grains. Metallic luster.
Derivation: Veins, quartzite.

GRAPHITE

Composition: carbon
System: hexagonal
Cleavage: 0001 perfect, $10\bar{1}1$ poor
Hardness: 1.0–2.0
Specific gravity: 2.25
Magnet: non-magnetic
Conductivity: none
Optical properties:
Opaque, translucent in thin flakes.
$N = 2.0$ (+) or (—)
Birefringence: —
Uniaxial: (—) for very thin flakes.
Dispersion: —
Color: Steel grey, black.
Pleochroism: Strong in very thin flakes. In polished section, pleochroism and birefringence are extreme.
Identification: In sediments, rounded, platy grains. Luster metallic to dull.
Derivation: Metamorphic rocks.

GROSSULARITE
(Garnet group)

Composition: $Ca_3Al_2(SiO_4)_3$
System: isometric, isotropic
Cleavage: none
Hardness: 6.0
Specific gravity: 3.4–3.6
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N = 1.735$
Dispersion: —
Color: Yellow, brown, green.
Pleochroism: —
Identification: Rounded or sub-angular grains.
Derivation: Metamorphic rocks.

GYPSUM

Composition: $CaSO_4.2H_2O$
System: monoclinic
Cleavage: 010 perfect, 100 poor, $\bar{1}11$ poor
Hardness: 2.0
Specific gravity: 2.32
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.521$
$Ny = 1.523$
$Nz = 1.530$
Birefringence: 0.009
Biaxial: (+)
$2V$: 58°
Dispersion: Inclined, strong.
$\varrho > \nu$
Color: Colorless.
Pleochroism: —
Identification: Low refringence and birefringence with strong dispersion. Sometimes fluorescent.
Derivation: Sedimentary rocks and bedded deposits. Veins.

HEMATITE

Composition: Fe_2O_3
System: hexagonal (rhombohedral)
Cleavage: none
Hardness: 5.0
Specific gravity: 5.2
Magnet: moderately magnetic
Conductivity: good
Optical properties:
Opaque except in thin flakes.
$N\omega = 3.22$
$N\varepsilon = 2.94$
Birefringence: 0.28
Uniaxial: (−)
Dispersion: Strong.
$\omega > \varepsilon$
Color: Steel grey to iron black, earthy varieties are red.
Pleochroism: In very thin scales.
ω = brownish red
ε = yellowish red
Identification: Red in streak or powder.
Derivation: Many sources. Igneous and metamorphic rocks, veins and limestones.

HERCYNITE
(Spinel group)

Composition: $FeAlO_4$
System: isotropic
Cleavage: 110 poor
Hardness: 3.5–4.0
Specific gravity: 2.18–2.22
Magnet: weakly magnetic
Conductivity: poor
Optical properties:
Opaque to translucent.
$N = 1.80$
Dispersion: —
Color: Black.
Pleochroism: —
Identification: Difficult, may require X-rays.
Derivation: Contact metamorphic rocks.

HEULANDITE
(Zeolite group)

Composition: $(CaNa_2)O.Al_2O_3.6SiO_2.5H_2O$
System: monoclinic
Cleavage: 010 perfect
Hardness: 3.5–4.0
Specific gravity: 2.18–2.22
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.498$
$Ny = 1.499$
$Nz = 1.505$
Birefringence: 0.007
Biaxial: (+)
$2V$: Variable usually near 34°.
Dispersion: —
Color: White, brown, grey, red.
Pleochroism: —
Identification: Rare in sediments.

Derivation: Basic volcanics.

HORNBLENDE
(Amphibole group)

Composition: Na,Al,Ca,Mg,Fe silicate
$Ca(Mg,Fe)_3Si_4O_{12}$;$CaMg_2(Al,Fe)_2Si_3O_{12}$
$NaAl(SiO_3)_2$
System: monoclinic
Cleavage: 110 perfect, 010 good
Hardness: 5.5
Specific gravity: 3.0–3.47
Magnet: moderately magnetic
Conductivity: moderate
Optical properties:
$\left.\begin{array}{l} Nx = \\ Ny = \\ Nz = \end{array}\right\}$ Indices variable with amount of iron, average about 1.67.
Birefringence: about 0.02
Biaxial: (−)
2V: Variable.
Dispersion: Weak.
$\varrho < v$
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.

HUMITE
(Humite group)

Composition: $3Mg_2SiO_4.Mg(F,OH)_2$
System: orthorhombic
Cleavage: 001 perfect
Hardness: 6.0
Specific gravity: 3.1–3.3
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.622$
$Ny = 1.632$
$Nz = 1.652$
Birefringence: 0.030
Biaxial: (+)
2V: 67–70°
Dispersion: Weak.
$\varrho > v$
Color: Colorless, white, yellow, brown.
Pleochroism: Weak.
x = golden yellow
y = pale yellow
z = pale yellow
Identification: Rare in sediments.
Derivation: Veins and contact altered limestone.

HYPERSTHENE
(Pyroxene group)

Composition: $(Mg,Fe)SiO_3$
System: orthorhombic
Cleavage: 110 good
Hardness: 5.0–6.0
Specific gravity: 3.3–3.5
Magnet: somewhat magnetic
Conductivity: moderate
Optical properties:
$Nx = 1.692$
$Ny = 1.702$
$Nz = 1.705$
Birefringence: 0.013
Biaxial: (−)
2V: About 75° (variable).
Dispersion: Weak.
$\varrho > v$
Color: Yellowish brown, brown, brownish green.
Pleochroism: Strong.
x = pink
y = yellow
z = green
Identification: Prismatic grains usually have ragged terminations and strong pleochroism. Enstatite is similar, but is weakly pleochroic.
Derivation: Basic igneous rocks.

IDDINGSITE
(Talc group)

Composition: $MgO.Fe_2O_3.3SiO_2.4H_2O$
System: orthorhombic
Cleavage: 100 perfect, 001 perfect, 010 perfect
Hardness: 3.0
Specific gravity: 2.5–2.84
Magnet: moderately magnetic
Conductivity: weak
Optical properties:
$Nx = 1.674$
$Ny = 1.715$
$Nz = 1.718$
Birefringence: 0.044
Biaxial: (−) rarely (+)
2V: 35°
Dispersion: Strong.
$\varrho > v$
Color: Red, reddish brown.
Pleochroism: $x < y < z$, in reddish brown grains.
Identification: Irregular grains in sediments.

Derivation: Basic igneous rocks. Gabbros and basalts.

IDOCRASE (Vesuvianite)

Composition: $Ca_6[Al(OH,F)]Al_2(SiO_4)_5$ probably a basic Ca,Al silicate
System: tetragonal
Cleavage: 110 poor, conchoidal fracture
Hardness: 6.5
Specific gravity: 3.35–3.45
Magnet: non-magnetic
Conductivity: poor
Optical properties:
$N\omega = 1.705\text{–}1.736$
$N\varepsilon = 1.701\text{–}1.732$
Birefringence: 0.001–0.006
Uniaxial: (−) Sometimes biaxial.
2V: Anomalously 17–33°.
Dispersion: Weak.
Color: Red, brown, yellowish green.
Pleochroism: Weak and variable, $\omega > \varepsilon$.
Identification: Interference colors often anomalously purple, grey, or green.
Derivation: Metamorphic rocks. Schists, pegmatites, gneiss.

ILMENITE
(Hematite group)

Composition: $FeTiO_3$
System: hexagonal (rhombohedral)
Cleavage: 0001 parting
Hardness: 5.5
Specific gravity: 4.6–4.9
Magnet: moderately magnetic
Conductivity: good
Optical properties:
Opaque.
Dispersion: —
Color: Black, purplish black.
Pleochroism: —
Identification: Crush a grain and dissolve in HCl; add one drop to a H_2SO_4 solution of phenol, brick red color proves Ti. Ilmenite often has white borders of leucoxene. Submetallic luster.
Derivation: Basic igneous rocks.

JADEITE
(Pyroxene group)

Composition: $NaAlSi_2O_6$
System: monoclinic
Cleavage: splintery fracture
Hardness: 6.5–7.0
Specific gravity: 3.335
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.655$
$Ny = 1.659$
$Nz = 1.667$
Birefringence: 0.012
Biaxial: (+)
2V: 68–72°
Dispersion:
$\varrho < v$
Color: Translucent, apple-green, emerald green, greenish white.
Pleochroism: Very rare in sediments.
Identification: Very rare in sediments.
Derivation: Pegmatites.

KAOLINITE
(Kaolin division)

Composition: $H_4Al_2Si_2O_9$
System: monoclinic
Cleavage: 001 perfect
Hardness: 2.0–2.5
Specific gravity: 2.6–2.63
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.561$
$Ny = 1.565$
$Nz = 1.567$
Birefringence: 0.006
Biaxial: (−)
2V: 60°
Dispersion: Weak.
$\varrho > v$
Color: Colorless or tinted.
Pleochroism: —
Identification: Usually very finely comminuted, sometimes pseudo-hexagonal plates are seen. Distinguished from sericite and talc by low birefringence. X-rays.
Derivation: Clay, alteration products from acidic igneous rocks.

KYANITE
(Topaz group)

Composition: Al_2SiO_5
System: triclinic
Cleavage: 100 perfect, 010 good, 001 parting
Hardness: 4.5 on 100

7.0 on 010
Specific gravity: 3.6
Magnet: non-magnetic
Conductivity: poor
Optical properties:
Nx = 1.712
Ny = 1.720
Nz = 1.728
Birefringence: 0.016
Biaxial: (−)
2V: 82°
Dispersion: Weak.
$\varrho > v$
Color: Blue to colorless.
Pleochroism: Faint.
x = colorless
y = violet
z = blue
Identification: Has many cleavage lines. Elongated 100 grains are common, with extinction of 30°, high relief. Acute bisectrix is nearly normal to 100. Pleochroism not often seen.
Derivation: Metamorphic rocks. Schists and gneisses.

LABRADORITE
(Plagioclase group)

Composition: albite 20, anorthite 30
System: triclinic
Cleavage: 001 perfect, 010 perfect, 110 imperfect
Hardness: 6.0
Specific gravity: 2.69–2.72
Magnet: non-magnetic
Conductivity: none
Optical properties:
Nx = 1.559
Ny = 1.563
Nz = 1.568
Birefringence: 0.009
Biaxial: (+)
2V: 77°
Dispersion: Weak.
$\varrho > v$
Color: Colorless, grey, green.
Pleochroism: —
Identification: Extinction angle from twin-lamellae 30–40°. X-rays.
Derivation: Basic igneous rocks.

LAWSONITE

Composition: $H_4CaAl_2Si_2O_{10}$
System: orthorhombic
Cleavage: 010 perfect, 001 perfect, 110 good
Hardness: 8.0
Specific gravity: 3.1
Magnet: non-magnetic
Conductivity: none
Optical properties:
Nx = 1.665
Ny = 1.674
Nz = 1.699
Birefringence: 0.034
Biaxial: (+)
2V: 84°
Dispersion: Strong.
$\varrho > v$
Color: Colorless, blue, grey.
Pleochroism: In thick grains.
x = blue
y = yellow
z = colorless
Identification: Cleavage and high relief.
Derivation: Schists.

LEPIDOLITE
(Mica group)

Composition: $(OH,F)_2KLiAl_2Si_3O_{10}$
System: monoclinic
Cleavage: 001 perfect
Hardness: 2.5–4.0
Specific gravity: 2.8–2.9
Magnet: non-magnetic
Conductivity: none
Optical properties:
Nx = 1.532
Ny = 1.555
Nz = 1.555
Birefringence: 0.023
Biaxial: (−)
2V: 0–50°
Dispersion:
$\varrho > v$
Color: Lilac, white, yellow, pink.
Pleochroism: Sometimes.
x = colorless
y = lilac or pink
z = lilac or pink
Identification: Irregular cleavage flakes, similar to muscovite.
Derivation: Granites, pegmatites.

LEPIDOMELANE
(Mica group)

Composition: near biotite, but rich in Fe and Ti
System: monoclinic
Cleavage: 001 perfect

Hardness: 3.0
Specific gravity: 3.1
Magnet: moderately magnetic
Conductivity: moderate
Optical properties:
$Nx = 1.615$
$Ny = 1.726$
$Nz = 1.733$
Birefringence: 0.118
Uniaxial: (−) Sometimes.
Biaxial: (−)
$2V$: 31°
Dispersion: Weak.
$\varrho < v$
Color: Dark brown, black.
Pleochroism: Strong.
x = light brown
y = dark brown
z = dark brown
Identification: Like biotite, but darker color.
Derivation: Syenites and metamorphics.

LEUCOXENE

Composition: mostly TiO_2
System: amorphous
Cleavage: —
Hardness: —
Specific gravity: 3.5–4.5
Magnet: non-magnetic
Conductivity: moderate
Optical properties:
Opaque, or translucent.
N = high
Dispersion: —
Color: White, yellow, brown, in reflected light.
Pleochroism: —
Identification: Rounded grains, having unglazed-porcelain appearance, and rough, pitted surface.
Derivation: A decomposition product of ilmenite.

MAGNESITE
(Carbonate group)

Composition: $MgCO_3$
System: hexagonal (rhombohedral)
Cleavage: $10\bar{1}1$ perfect
Hardness: 3.5–4.0
Specific gravity: 2.96
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N\omega = 1.700$
$N\varepsilon = 1.509$
Birefringence: 0.191
Uniaxial: (−)
Dispersion: —
Color: Colorless, white, yellow, brown.
Pleochroism: —
Identification: Irregular grains. Dye-test. X-rays.
Derivation: Magnesite deposits, schists, ultra basic rocks.

MAGNETITE
(Spinel group)

Composition: Fe_3O_4
System: isometric
Cleavage: none, 111 parting
Hardness: 6.0
Specific gravity: 5.17
Magnet: strongly magnetic
Conductivity: good
Optical properties:
Opaque.
Dispersion: —
Color: Black, bluish black.
Pleochroism: —
Identification: Octahedra and irregular grains. Lifted by bar-magnet. Luster metallic to dull.
Derivation: Basic igneous and metamorphic rocks.

MARCASITE
(Marcasite group)

Composition: FeS_2
System: orthorhombic
Cleavage: 110 poor, 011 imperfect
Hardness: 6.0–6.5
Specific gravity: 4.8
Magnet: weakly magnetic
Conductivity: good
Optical properties:
Opaque.
Dispersion: —
Color: Brass-yellow to greyish yellow.
Pleochroism: —
Identification: Small ragged grains in sediments. Metallic luster, often tarnished.
Derivation: Veins; sedimentary rocks.

MELANITE
(Garnet group)

Composition: variety of andradite
System: isometric
Cleavage: none

Hardness: 7.0
Specific gravity: 3.7
Magnet: moderately magnetic
Conductivity: poor
Optical properties:
$N = 1.94$
Dispersion: —
Color: Black.
Pleochroism: —
Identification: Sub-angular grains with 110 striations.
Derivation: Metamorphics, syenites. Altered limestones.

MICROCLINE
(Feldspar group)

Composition: $KAlSi_3O_8$
System: triclinic
Cleavage: 001 perfect, 010 good, intersecting at 90°
Hardness: 6.0–6.5
Specific gravity: 2.55
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.522$
$Ny = 1.526$
$Nz = 1.530$
Birefringence: 0.007
Biaxial: (−)
2V: 65–80°
Dispersion: Weak.
$\varrho > v$
Color: Colorless, pale green, green, pink.
Pleochroism: —
Identification: 001 flakes show grating structure due to crossed, polysynthetic twinning.
Derivation: Acidic igneous rocks. Metamorphics.

MOLYBDENITE

Composition: MoS_2
System: hexagonal
Cleavage: 0001 perfect
Hardness: 1.0–1.5
Specific gravity: 4.62–4.73
Magnet: non-magnetic (diamagnetic)
Conductivity: poor
Optical properties:
Opaque.
Dispersion: —
Color: Lead-grey.
Pleochroism: —
Identification: Flattened grains. X-rays. Metallic luster.
Derivation: Granitic rocks, Metamorphics. Pegmatites, crystalline limestones.

MONAZITE

Composition: $(CeLaDi)\ PO_4$
System: monoclinic
Cleavage: 001 perfect, 100 good
Hardness: 5.0
Specific gravity: 5.1
Magnet: weakly magnetic
Conductivity: poor
Optical properties:
$Nx = 1.786$
$Ny = 1.788$
$Nz = 1.837$
Birefringence: 0.051
Biaxial: (+)
2V: 14°
Dispersion: Weak.
$\varrho > v$ or
$\varrho < v$
Color: Yellow, reddish brown.
Pleochroism: Very weak.
x = yellow
z = greenish yellow
Identification: Commonly in honey-yellow, rounded grains or crystals with weak dispersion and small axial angle.
Derivation: Acidic igneous rocks. Granites.

MUSCOVITE
(Mica group)

Composition: $H_2KAl_3(SiO_4)_3$
System: monoclinic
Cleavage: 001 perfect
Hardness: 2.5–3.0
Specific gravity: 2.76–3.00
Magnet: slightly magnetic
Conductivity: none
Optical properties:
$Nx = 1.558$
$Ny = 1.595$
$Nz = 1.601$
Birefringence: 0.043
Biaxial: (−)
2V: 40° (+) or (−)
Dispersion: Moderate.
$\varrho < v$
Color: Colorless to yellow.
Pleochroism: —
Identification: Colorless grains have pale bluish interference color.
Derivation: Igneous and metamorphic rocks.

NEPHELINE

(Nepheline group)

Composition: $(NaK)AlSiO_4$
System: hexagonal
Cleavage: $10\bar{1}0$ poor, 0001 poor
Hardness: 5.5–6.0
Specific gravity: 2.55–2.65
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N\omega = 1.536\text{–}1.549$
$N\varepsilon = 1.532\text{–}1.544$
Birefringence: 0.004–0.005
Uniaxial: (−)
Dispersion: —
Color: Colorless.
Pleochroism: —
Identification: Irregular grains.
Derivation: Nepheline syenite. Phonolite.

OLIGOCLASE

(Plagioclase group)

Composition: albite 40, anorthite 60
System: triclinic
Cleavage: 001 perfect, 010 distinct
Hardness: 6.0
Specific gravity: 2.64
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.539$
$Ny = 1.543$
$Nz = 1.547$
Birefringence: 0.008
Biaxial: (−)
2V: 86°
Dispersion: Weak.
$\varrho < v$
Color: White, grey, green.
Pleochroism: —
Identification: Commonest plagioclase in sediments.
Derivation: Acidic igneous rocks; gneisses and schists. Occurs both of low and high temperature origin.

OLIVINE SERIES

Composition: $(MgFe,Ca,Mn)_2SiO_4$
System: orthorhombic
Cleavage: 010 poor, 110 poor
Hardness: 6.5–7.0
Specific gravity: 3.27–3.37
Magnet: weakly magnetic
Conductivity: none
Optical properties:
$Nx = 1.635\text{–}1.824$
$Ny = 1.651\text{–}1.864$
$Nz = 1.670\text{–}1.875$
Birefringence: 0.035–0.051
Biaxial: (+) or (−)
2V: 47–90°
Dispersion:
$\varrho < v$
Color: Colorless, green, brown.
Pleochroism: —
Identification: Olivine grains are commonly rimmed or criss-crossed by alteration or reaction minerals.
Derivation: Ultra-basic rocks and metamorphosed limestone.
Classification (mol.% $FeSiO_4$)

forsterite	0–10
chrysolite	10–30
hyalosiderite	30–50
hortonolite	50–70
ferrohortonolite	70–90
fayalite	90–190

Forsterite is $MgSiO_4$, fayalite is Fe_2SiO_4

OPAL

Composition: $SiO_2.nH_2O$
System: amorphous
Cleavage: none, conchoidal fracture
Hardness: 5.5–6.5
Specific gravity: 2.01–2.16
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N = 1.435\text{–}1.455$
Dispersion: —
Color: White, yellow, red, brown, green, grey, blue. Sometimes shows a rich play of colors.
Pleochroism: —
Identification: Uncommon in sediments. Shapeless grains, often porcelain-white. Sometimes shows interference colors, due to strain. Not regarded as a mineral species, but as a variety of cristobalite.
Derivation: Decomposed igneous rocks. Sediments.

ORTHOCLASE

(Feldspar group)

Composition: $KAlSi_3O_8$
System: monoclinic

Cleavage: 001 perfect, 010 good
Hardness: 6.0
Specific gravity: 2.55
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.518$
$Ny = 1.524$
$Nz = 1.526$
Birefringence: 0.008
Biaxial: (−)
2V: Var. adularia 70°.
Var. sanidine 0–40°.
Dispersion: Weak.
$\varrho > v$
Color: Colorless, grey, reddish.
Pleochroism: —
Identification: Irregular grains, flattened parallel to 001. Cobalt nitrate stains orthoclase yellow.
Derivation: Acidic igneous rocks, pegmatites.

OXYHORNBLENDE (Basaltic hornblende)

Composition: similar to hornblende, with high content of iron
System: monoclinic
Cleavage: 110 perfect, 010 good
Hardness: 5.5
Specific gravity: 3.4
Magnet: moderately magnetic
Conductivity: moderate
Optical properties:
$Nx = 1.692$
$Ny = 1.730$
$Nz = 1.760$
Birefringence: 0.068
Biaxial: (—)
2V: 80°
Dispersion:
$\varrho < v$
Color: Reddish brown, brown, black.
Pleochroism: Rather strong, $x < y < z$.
Identification: Higher relief than hornblende and stronger pleochroism. $z \wedge c$ is small (0–15°).
Derivation: Diorites and other igneous rocks.

PARGASITE
(Amphibole group)

Composition: see hornblende
System: monoclinic
Cleavage: 110 perfect, 010 good
Hardness: 5.5
Specific gravity: 3.0–3.47
Magnet: moderately magnetic
Conductivity: moderate
Optical properties:
$Nx = 1.613$
$Ny = 1.618$
$Nz = 1.633$
Birefringence: 0.020
Biaxial: (+)
2V: 63°
Dispersion:
$\varrho > v$
Color: Green.
Pleochroism: Not strong.
x = greenish yellow
y = green
z = greenish blue
Identification: A green (optically +) variety of hornblende. $z \wedge c = 30°$.
Derivation: Igneous and metamorphic rocks.

PENNINE (Penninite)
(Chlorite group)

Composition: $H_8(Mg,Fe)_5Al_2Si_3O_{18}$
System: monoclinic
Cleavage: 001 perfect
Hardness: 2.5
Specific gravity: 2.6–2.85
Magnet: weakly magnetic
Conductivity: none
Optical properties:
$Nx = 1.576$
$Ny = 1.576$
$Nz = 1.579$
Birefringence: 0.003
Biaxial: (+) also (−)
2V: $2E = 36°$
Dispersion: Strong.
$\varrho < v$
Color: Green, translucent.
Pleochroism:
x = green
y = green
z = yellow
Identification: Rare in sediments.
Derivation: Decomposed igneous rocks.

PERICLASE
(Periclase group)

Composition: MgO
System: isometric, isotropic
Cleavage: 100 perfect, 111 poor
Hardness: 5.0
Specific gravity: 3.6
Magnet: non-magnetic

Conductivity: none
Optical properties:
$N = 1.736$
Dispersion: —
Color: Colorless, yellow, green, transparent to translucent.
Pleochroism: —
Identification: Rare in sediments.
Derivation: Dolomitic limestones.

PEROVSKITE

Composition: $CaTiO_3$
System: isometric or orthorhombic, pseudo-isometric
Cleavage: 001 imperfect, 100 poor
Hardness: 5.5
Specific gravity: 4.01
Magnet: non-magnetic
Conductivity: none
Optical properties:
Opaque, sometimes.
$N = 2.30–2.37$
Birefringence: see below.
Dispersion: —
Color: Black, brown.
Pleochroism: Weak, $z > x$.
Identification: Black, square-shaped grains. Isotropic or, when birefringent, biaxial (+).
Derivation: Basic igneous rocks, schists. Altered limestones.

PHENAKITE
(Phenakite group)

Composition: Ba_2SiO_4
System: hexagonal (tri-rhombohedral)
Cleavage: $11\bar{2}0$ poor, $10\bar{1}1$ poor
Hardness: 7.5–8.0
Specific gravity: 2.97–3.0
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N\omega = 1.654$
$N\varepsilon = 1.670$
Birefringence: 0.016
Uniaxial: (+)
Dispersion: —
Color: Colorless, yellow, rose-red, brown.
Pleochroism: Faint.
x = colorless
z = yellow
Identification: Rare in sediments.
Derivation: Pegmatites, schists, veins.

PHLOGOPITE
(Mica group)

Composition: near biotite (Iron poor)
System: monoclinic
Cleavage: 001 perfect
Hardness: 3.0–4.0
Specific gravity: 2.8–3.3
Magnet: moderately magnetic
Conductivity: moderate
Optical properties:
$Nx = 1.551$
$Ny = 1.598$
$Nz = 1.598$
Birefringence: 0.047
Biaxial: (−)
2V: 0–3°
Dispersion: Weak.
$\varrho < v$
Color: Brown.
Pleochroism:
x = colorless
y = brownish yellow
z = brown
Identification: Shapeless grains or flakes.
Derivation: Contact metamorphosed limestone. Rarely in igneous rocks.

PICOTITE
(Spinel group)

Composition: $(Mg,Fe)O.(AlCr)_2O_3$
System: isometric; isotropic
Cleavage: 111 imperfect, conchoidal fracture
Hardness: 8.0
Specific gravity: 4.08
Magnet: moderately magnetic
Conductivity: good
Optical properties:
Opaque or translucent.
$N = 2.05$
Dispersion: —
Color: Brown, greenish brown.
Pleochroism: —
Identification: Rolled, octahedral grains.
Derivation: Serpentine, schists, basic igneous rocks.

PIEDMONTITE
(Epidote group)

Composition: $HCa_2(Al,Mn)_3Si_3O_{13}$
System: monoclinic
Cleavage: 001 perfect
Hardness: 6.5

Specific gravity: 3.45–3.50
Magnet: weakly magnetic
Conductivity: moderate
Optical properties:
  $Nx = 1.750$
  $Ny = 1.782$
  $Nz = 1.832$
Birefringence: 0.082
Biaxial: (+)
2V: 55–80°
Dispersion: Strong.
  $\varrho > v$
Color: Reddish brown, black, translucent.
Pleochroism:
  x = yellow
  y = violet or pink
  z = red
Identification: Irregular grains, similar to epidote but optically (+).
Derivation: Metamorphics, acidic volcanics. Schists and gneisses.

PLAGIOCLASE SERIES

(Feldspar group)

Composition: $NaAlSi_3O_8$ (albite), $CaAl_2Si_2O_8$ (anorthite)
System: triclinic
Cleavage: 001 perfect, 010 good, at angles of about 94°
Hardness: 6.0–6.5
Specific gravity: 2.6–2.8
Magnet: non-magnetic
Conductivity: none
Optical properties:
  $Nx = 1.535\text{–}1.576$
  $Ny = 1.529\text{–}1.583$
  $Nz = 1.536\text{–}1.589$
Birefringence: 0.011–0.013
Biaxial: (+) or (−)
2V: Variable, see species.
Dispersion: —
Color: Colorless, grey.
Pleochroism: —
Identification: Amaranth stains plagioclases pink. Grains often turbid and show polysynthetic twinning. Distinction between the various members: (*1*) immerse in index liquids and determine one index, (*2*) measure extinction angle on section normal to either bisectrix.
Derivation: Igneous rocks.

PLATINUM

Composition: Pt
System: isometric
Cleavage: none
Hardness: 4.0–4.5
Specific gravity: 14.0–19.0
Magnet: non-magnetic
Conductivity: good
Optical properties:
  Opaque.
Dispersion —
Color: Whitish steel-grey.
Pleochroism: —
Identification: Worn, flattened plates with rough texture. Metallic luster.
Derivation: Basic and ultra-basic igneous rocks, dunite, serpentine, etc.

PSEUDOBROOKITE

Composition: Fe_2TiO_5
System: orthorhombic
Cleavage: 010 distinct
Hardness: 6.0
Specific gravity: 4.3–4.4
Magnet: weakly magnetic
Conductivity: —
Optical properties:
  $Nx = 2.38$
  $Ny = 2.39$
  $Nz = 2.42$
Birefringence: 0.04
Biaxial: (+)
2V: 50° (+) or (−)
Dispersion:
  $\varrho < v$
Color: Reddish brown, brownish black.
Pleochroism: Weak.
Identification: Flattened, prismatic grains.
Derivation: Volcanics.

PSILOMELANE

Composition: hydrous MnO_2
System: amorphous
Cleavage: none
Hardness: 5.0–6.0
Specific gravity: 4.2
Magnet: non-magnetic
Conductivity: none
Optical properties:
  Opaque.
Dispersion: –
Color: Grey, black.
Pleochroism: —
Identification: Irregular steel-grey grains with smooth surface and dull metallic luster.

Derivation: Sedimentary rocks, lode minerals.

PUMPELLYITE

(Zeolite group)

Composition: $6CaO.3Al_2O_3.7SiO_2.4H_2O$
System: monoclinic
Cleavage: 100 perfect, 001 good
Hardness: 5.5
Specific gravity: 3.18–3.20
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.698$
$Ny = 1.706$
$Nz = 1.720$
Birefringence: 0.022
Biaxial: (+)
2V: 30–80°
Dispersion: Strong.
$\varrho < \nu$
Color: Bluish green, brown.
Pleochroism:
x = colorless
y = bluish green or yellow
z = colorless
Identification: Aggregates or fibrous.
Derivation: Metamorphics, iron ores.

PYRITE

Composition: FeS_2
System: isometric
Cleavage: poor
Hardness: 6.0–6.5
Specific gravity: 5.0
Magnet: non-magnetic
Conductivity: good
Optical properties:
Opaque.
Dispersion: —
Color: Brass yellow.
Pleochroism: —
Identification: Often in octahedra or dodecahedra with striated faces, also nodules and aggregates that may appear greenish yellow. Soluble in HNO_3 but not in HCl.
Derivation: Igneous rocks, veins, and as a secondary mineral in sediments.

PYROLUSITE

Composition: MnO_2
System: orthorhombic, but pseudomorphous after manganite
Cleavage: none
Hardness: 2.0–2.5
Specific gravity: 4.75
Magnet: weakly magnetic
Conductivity: moderate
Optical properties:
Opaque.
Dispersion: —
Color: Purplish black.
Pleochroism: —
Identification: Irregular grains.
Derivation: Of secondary origin, veins.

PYROPE

(Garnet group)

Composition: $Mg_3Al_2(SiO_4)_3$
System: isometric, isotropic
Cleavage: none
Hardness: 7.0
Specific gravity: 3.51
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N = 1.705$
Dispersion: —
Color: Red, purplish red.
Pleochroism: —
Identification: Rolled or shapeless grains.
Derivation: Ultra basic igneous rocks, serpentine, or peridotite.

PYRRHOTITE

(Niccolite group)

Composition: $Fe_5S_6 \longrightarrow Fe_{16}S_{17}$
System: hexagonal
Cleavage: 0001 fair, $11\bar{2}0$ poor
Hardness: 3.5–4.5
Specific gravity: 4.53–4.77
Magnet: strongly magnetic
Conductivity: good
Optical properties:
Opaque.
Dispersion: —
Color: Bronze yellow.
Pleochroism: —
Identification: Irregular fragments. Metallic luster.
Derivation: Metamorphic rocks. Basic igneous rocks. Sometimes from pegmatites.

QUARTZ

Composition: SiO_2
System: hexagonal
Cleavage: none
Hardness: 7.0
Specific gravity: 2.65
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N\omega = 1.544$
$N\varepsilon = 1.553$
Birefringence: 0.009
Unaxial: (+)
Dispersion: —
Color: Colorless or tinted.
Pleochroism: —
Identification: Irregular grains with no cleavage, and low index and birefringence. Most grains will give uniaxial figure. Sometimes anomalously biaxial. Piezoelectric.
Derivation: Various: very resistant to decomposition. Mostly from acidic-type rocks.

RIEBECKITE
(Amphibole group)

Composition: $NaFe^{III}(SiO_3)$ with a varying amount of $FeSiO_3$
System: monoclinic
Cleavage: 110 perfect, at 124°
Hardness: 4.0
Specific gravity: 3.44
Magnet: weakly magnetic
Conductivity: weak
Optical properties:
$Nx = 1.697$
$Ny = 1.700$
$Nz = 1.703$
Birefringence: 0.006
Biaxial: (+) or (−)
2V: 68°
Dispersion: Strong.
$\varrho > \nu$
Color: Dark blue to black.
Pleochroism: Strong.
x = blue
y = brownish yellow
z = grey, yellow
Identification: Shapeless grains. Rare in sediments.
Derivation: Metamorphics. Sodium-rich rocks.

ROMEITE

Composition: $Ca_5Sb_6O_{20}$
System: isometric, isotropic
Cleavage: 111 imperfect
Hardness: 5.5–6.5
Specific gravity: 4.7–5.4
Magnet: weakly magnetic
Conductivity: none
Optical properties:
$N = 1.81–1.87$
Dispersion: —
Color: Yellow, yellowish brown.
Pleochroism: —
Identification: Rounded, octahedral grains. Rare in sediments.
Derivation: Mineral veins.

RUTILE
(Rutile group)

Composition: TiO_2
System: tetragonal
Cleavage: 110 good, 100 good
Hardness: 6.0–6.5
Specific gravity: 4.18–4.25
Magnet: non-magnetic
Conductivity: moderate
Optical properties:
$N\omega = 2.61$
$N\varepsilon = 2.90$
Birefringence: 0.286
Uniaxial: (+)
Dispersion: —
Color: Yellow, reddish brown, black.
Pleochroism: Weak, brown to yellow.
Identification: Rounded, prismatic grains, sometimes knee-twinned with prismatic cleavages. Parallel extinction. Elongation (+).
Derivation: Acidic, igneous and metamorphic rocks. Often from decomposition of ilmenite.

SCHEELITE
(Scheelite group)

Composition: $CaWO_4$
System: tetragonal
Cleavage: 101 good
Hardhess: 4.5–5.0
Specific gravity: 6.1
Magnet: weakly magnetic
Conductivity: poor
Optical properties:
$N\omega = 1.919$
$N\varepsilon = 1.935$
Birefringence: 0.016
Uniaxial: (+)

Dispersion: —
Color: Colorless, white, yellow, brown.
Pleochroism: —
Identification: Sub-angular, octahedral grains. Strongly fluorescent.
Derivation: Pegmatite veins. Altered limestones, mineral veins.

SIDERITE

(Carbonate group)

Composition: $FeCO_3$
System: hexagonal (rhombohedral)
Cleavage: $10\bar{1}1$ perfect
Hardness: 3.5–4.0
Specific gravity: 3.78–3.89
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N\omega = 1.875$
$N\varepsilon = 1.633$
Birefringence: 0.242
Uniaxial: (—)
Dispersion: —
Color: Shades of brown or grey.
Pleochroism: —
Identification: Rounded rhombohedral grains.
Derivation: Stratified rocks and veins.

SILLIMANITE

(Topaz group)

Composition: Al_2SiO_5
System: orthorhombic
Cleavage: 010 perfect
Hardness: 6.5
Specific gravity: 3.25
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.660$
$Ny = 1.661$
$Nz = 1.681$
Birefringence: 0.021
Biaxial: (+)
2V: 20°
Dispersion: Strong.
$\varrho > v$
Color: Colorless or tinted.
Pleochroism: Weak, $x < y < z$.
Identification: Slender prisms or fibres with strong birefringence and (+) elongation.
Derivation: Metamorphics.

SODALITE

(Sodalite group)

Composition: $3NaAlSiO_4.NaCl$
System: isometric, isotropic
Cleavage: 110 poor
Hardness: 5.5–6.0
Specific gravity: 2.14–2.40
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N = 1.48–1.51$
Dispersion: —
Color: Colorless, pale blue, yellow.
Pleochroism: —
Identification: Irregular grains. Rare in sediments.
Derivation: Alkaline igneous rocks. Sometimes altered from nepheline.

SPESSARTITE

(Garnet group)

Composition: $Mn_3Al_2(SiO_4)_3$
System: isometric, isotropic
Cleavage: none
Hardness: 7.0
Specific gravity: 3.80–4.25
Magnet: weakly magnetic
Conductivity: poor
Optical properties:
$N = 1.805$
Dispersion: —
Color: Pink, yellow, brown.
Pleochroism: —
Identification: Rare in sediments.
Derivation: Acidic igneous rocks. Altered sediments.

SPHALERITE

Composition: ZnS
System: isometric
Cleavage: dodecahedral perfect
Hardness: 3.5–4.0
Specific gravity: 4.1
Magnet: moderately magnetic
Conductivity: good
Optical properties:
Opaque to translucent.
$N = 2.4$
Dispersion: —
Color: Yellow, brown, black.
Pleochroism: —
Identification: Use blow-pipe; gives sublimate

on charcoal that is yellow when hot and white when cold. Resinous luster.
Derivation: Veins and ore-bodies. Clays.

SPHENE (Titanite)

Composition: $CaTiSiO_5$
System: monoclinic
Cleavage: 110 good, 100 imperfect
Hardness: 5.0–5.5
Specific gravity: 3.40–3.56
Magnet: non-magnetic
Conductivity: moderate
Optical properties:
$Nx = 1.900$
$Ny = 1.905$
$Nz = 2.034$
Birefringence: 0.134
Biaxial: (+)
$2V$: 23–55°
Dispersion: Extreme.
$\varrho > v$
Color: Brown, orange, green.
Pleochroism: Sometimes.
x = colorless or yellow
y = pink or yellow
z = pink or yellow
Identification: Irregular grains with extreme index, birefringence and dispersion. Some grains give good acute bisectrix figure.
Derivation: Igneous and metamorphic rocks.

SPINEL
(Spinel group)

Composition: $MgAl_2O_4$
System: isometric, isotropic
Cleavage: 111 poor
Hardness: 8.0
Specific gravity: 3.6
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N = 1.78–2.05$
Dispersion: —
Color: Red, yellow, blue, green.
Pleochroism: —
Identification: Well rounded, octahedral grains, pitted. Important species are: ceylonite, gahnite, magnetite, franklinite and chromite.
Derivation: Schists, limestone.

SPODUMENE
(Pyroxene group)

Composition: $LiAlSi_2O_6$
System: monoclinic
Cleavage: 110 good at 87°, parting on 010
Hardness: 6.0–7.0
Specific gravity: 3.1–3.2
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.651$
$Ny = 1.669$
$Nz = 1.677$
Birefringence: 0.026
Biaxial: (+)
$2V$: 54–60°
Dispersion: Weak.
$\varrho < v$
Color: Yellow, green, pink.
Pleochroism: Weak.
Identification: Fragments on 010 parting, showing traces of 110 cleavage, will have extinction angle of $z \wedge c = 24°$.
Derivation: Acidic plutonic rocks and metamorphics.

STAUROLITE

Composition: $HFeAl_5Si_2O_{13}$
System: orthorhombic
Cleavage: 010 good
Hardness: 7.0–7.5
Specific gravity: 3.65–3.77
Magnet: weakly magnetic
Conductivity: poor
Optical properties:
$Nx = 1.736$
$Ny = 1.741$
$Nz = 1.746$
Birefringence: 0.010
Biaxial: (+)
$2V$: 88° (approx.)
Dispersion: Weak.
$\varrho > v$
Color: Reddish brown, yellow.
Pleochroism: Moderate, $x < y$ and z.
Identification: Flat, irregular grains with weak birefringence and pleochroic in yellow tints. Rarely biaxial (−).
Derivation: Metamorphic rocks.

STILPNOMELANE
(Chlorite group)

Composition: Iron silicate
System: uncertain
Cleavage: 001 perfect

Hardness: 1.5 + or −
Specific gravity: 2.7–3.0
Magnet: moderately magnetic
Conductivity: none
Optical properties:
Nx = 1.546–1.625
Ny = 1.576–1.735
Nz = 1.576–1.735
Birefringence: 0.030–0.110
Biaxial: (−)
2V: Nearly 0°.
Dispersion: —
Color: Yellow, green, brown.
Pleochroism: Strong.
x = yellow
y = dark brown or green
z = dark brown or green
Identification: Resembles biotite.
Derivation: Iron ores.

STRONTIANITE
(Carbonate group)

Composition: $SrCO_3$
System: orthorhombic
Cleavage: 110 perfect, 010 poor
Hardness: 4.0
Specific gravity: 3.7
Magnet: non-magnetic
Conductivity: none
Optical properties:
Nx = 1.520
Ny = 1.667
Nz = 1.667
Birefringence: 0.147
Biaxial: (−)
2V: 7°
Dispersion: Weak.
$\varrho < v$
Color: Colorless, white, green, yellow.
Pleochroism: None.
Identification: Acicular in habit. Flame test for Sr.
Derivation: Veins, limestone.

SULPHUR

Composition: S
System: orthorhombic
Cleavage: 001 imperfect, 110 imperfect, 111 imperfect
Hardness: 2.0
Specific gravity: 2.06
Magnet: non-magnetic
Conductivity: none
Optical properties:
Nx = 1.957
Ny = 2.037
Nz = 2.245
Birefringence: 0.288
Biaxial: (+)
2V: 69°
Dispersion: Weak.
$\varrho < v$
Color: Yellow, translucent.
Pleochroism: —
Identification: Rare in sediments.
Derivation: Volcanics, veins, hot-springs.

THORIANITE
(Uranite group)

Composition: $(Th,U)\,O_2$
System: isometric
Cleavage: 001 poor
Hardness: 6.5
Specific gravity: 9.7
Magnet: non-magnetic
Conductivity: none
Optical properties:
Opaque or translucent in thin grains.
N = 2.20
Dispersion: —
Color: Grey, black.
Pleochroism: —
Identification: Radioactive, water-worn, cubic grains or pebbles.
Derivation: Pegmatites.

THURINGITE
(Chlorite group)

Composition: $8FeO.4(Al,Fe_2)O_3.6SiO_2.9H_2O$ silicate
System: monoclinic
Cleavage: 010 distinct
Hardness: 2.5
Specific gravity: 2.6–3.0
Magnet: weakly magnetic
Conductivity: none
Optical properties:
Ny = 1.65–1.68
Birefringence: 0.004–0.010
Biaxial: (−)
2V: Small.
Dispersion: Weak.
Color: Olive green, dark green.
Pleochroism:
x = colorless
y = dark green

z = dark green

Identification: Scaly, green grains or aggregates, like mica. Uncommon in sediments.

Derivation: Metamorphics and ores.

TOPAZ

(Topaz group)

Composition: $[Al(F,OH)_2]AlSiO_4$

System: orthorhombic

Cleavage: 001 perfect

Hardness: 8.0

Specific gravity: 3.52–3.57

Magnet: non-magnetic

Conductivity: poor

Optical properties:

$Nx = 1.619$

$Ny = 1.620$

$Nz = 1.627$

Birefringence: 0.008

Biaxial: (+)

2V: 48–67°

Dispersion: Moderate.

$\varrho > v$

Color: Colorless, yellow, blue, red, green.

Pleochroism: Very weak.

Identification: Irregular grains that usually give good acute bisectrix figure.

Derivation: Acidic plutonics and metamorphics.

TORBERNITE

(Uranite group)

Composition: $Cu(UO_2)_2P_2O_8.12\,H_2O$

System: tetragonal

Cleavage: 001 perfect, 100 good

Hardness: 2.0–2.5

Specific gravity: 3.2

Magnet: non-magnetic

Conductivity: none

Optical properties:

$N\omega = 1.592$

$N\varepsilon = 1.582$

Birefringence: 0.010

Uniaxial: (−)

2V: Very small.

Dispersion: —

Color: Shades of green.

Pleochroism: In thick grains.

ω = skyblue

ε = green

Identification: Tabular grains.

Derivation: Veins in granite.

TOURMALINE

Composition: $HgAl_3(B,OH)_2Si_4O_{19}$

System: hexagonal (rhombohedral)

Cleavage: poor

Hardness: 7.0–7.5

Specific gravity: 2.9–3.2

Magnet: weakly magnetic

Conductivity: moderate

Optical properties:

$N\omega = 1.642$

$N\varepsilon = 1.622$

Birefringence: 0.020

Uniaxial: (−)

Dispersion: —

Color: Brown, bluish-black, green, red, colorless.

Pleochroism: Strong. $\omega > \varepsilon$.

Identification: Absorption is greater when crystallographic axis is normal to vibration direction in lower nicol.

Derivation: Acidic plutonics and metamorphics.

TREMOLITE

(Amphibole group)

Composition: $CaMg_3Si_4O_{12}$

System: monoclinic

Cleavage: 110 good, 100 rarely, 010 rarely

Hardness: 5.0–6.0

Specific gravity: 3.0–3.3

Magnet: non-magnetic

Conductivity: none

Optical properties:

$Nx = 1.600$

$Ny = 1.616$

$Nz = 1.627$

Birefringence: 0.027

Biaxial: (−)

2V: 80°

Dispersion: Weak.

$\varrho < v$

Color: Colorless, white, grey.

Pleochroism:

x = pale yellow

y = greenish yellow

z = green

Identification: Ragged grains. Similar to hornblende. Piezoelectric.

Derivation: Metamorphics. Sometimes altered from serpentine.

URANINITE

(Uranate group)

Composition: UO_2

System: isometric
Cleavage: none
Hardness: 5.0–6.0
Specific gravity: 8.0–10.0
Magnet: non-magnetic
Conductivity: —
Optical properties:
Opaque or translucent in thin flakes when color is green, brown or yellow.
Dispersion: —
Color: Green, brown, yellow, black.
Pleochroism: —
Identification: Irregular grains. Strongly radioactive. Non-fluorescent.
Derivation: Granites, pegatites, veins.

URANOTHORITE

Composition: variety of thorite ($ThSiO_4$) containing uranium oxide
System: tetragonal
Cleavage: —
Hardness: 4.5–5.0
Specific gravity: 6.7
Magnet: moderately magnetic
Conductivity: —
Optical properties:
$N\omega = 1.818\text{–}1.825$
$N\varepsilon = 1.839\text{–}1.840$
Birefringence: 0.015–0.021
Uniaxial: (+)
Dispersion: —
Color: Brown, yellow-olive, green.
Pleochroism:
x = pale lime-green
z = green
Identification: Occurs in sediments as well-rounded and worn grains and euhedral crystals.
Derivation: Syenites.

UVAROVITE
(Garnet group)

Composition: $Ca_3Cr_2(SiO_4)_3$
System: isometric, isotropic
Cleavage: none
Hardness: 7.5
Specific gravity: 3.4
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N = 1.838$
Dispersion: —
Color: Emerald green, transparent to translucent.
Pleochroism: —
Identification: Sub-angular and rounded, dodecahedral grains.
Derivation: Gneiss, serpentine. Altered limestone.

WOLFRAMITE
(Wolframite group)

Composition: $(Fe,Mn)WO_4$
System: monoclinic
Cleavage: 010 perfect
Hardness: 5.0–5.5
Specific gravity: 7.2–7.5
Magnet: moderately magnetic
Conductivity: moderate
Optical properties:
$Nx = 2.26$
$Ny = 2.32$
$Nz = 2.42$
Birefringence: 0.16
Biaxial: (+)
2V: 60–70°
Dispersion: —
Color: Brown, black.
Pleochroism: Variable.
x = yellow-green
y = pale green
z = grass-green or red
Identification: Irregular, bladed metallic grains, translucent on thin edges.
Derivation: Mineral veins.

WOLLASTONITE

Composition: $CaSiO_3$
System: monoclinic
Cleavage: 100 perfect, 001 good
Hardness: 5.0
Specific gravity: 2.9
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.620$
$Ny = 1.632$
$Nz = 1.634$
Birefringence: 0.014
Biaxial: (—)
2V: 35–60°
Dispersion: Weak.
Color: Colorless, white, grey, yellow.
Pleochroism: —
Identification: Tablets or fibers elongate parallel to b axis yield an extinction angle of 4° or less.
Derivation: Metamorphosed limestone.

XENOTIME

Composition: YPO_4
System: tetragonal
Cleavage: 110 perfect
Hardness: 4.0–5.0
Specific gravity: 4.4–4.6
Magnet: moderately magnetic
Conductivity: none
Optical properties:
$N\omega = 1.721$
$N\varepsilon = 1.816$
Birefringence: 0.095
Uniaxial: (+)
Dispersion: —
Color: Shades of brown, red, yellow.
Pleochroism: Weak.
ω = pale yellow
ε = yellow or green
Identification: Double terminated prisms, or sub-angular flakes. To distinguish from zircon, immerse in methylene iodide: ($n = 1.735$).
Derivation: Granites, pegmatites.

ZIRCON
(Zircon group)

Composition: $ZrSiO_4$
System: tetragonal
Cleavage: 110 imperfect, 111 poor
Hardness: 7.5
Specific gravity: 4.5–4.7
Magnet: non-magnetic
Conductivity: none
Optical properties:
$N\omega = 1.923–1.960$
$N\varepsilon = 1.968–2.015$
Birefringence: 0.045–0.058
Uniaxial: (+)
Dispersion: —
Color: Colorless, yellow, brown, purple.
Pleochroism: In thick, strongly colored grains.
Identification: Usually as slightly rounded prismatic crystals, with extreme index and moderate birefringence (see xenotime).
Derivation: All kinds of rocks.

ZOISITE
(Epidote group)

Composition: $HCa_2Al_3Si_3O_{13}$
System: orthorhombic
Cleavage: 010 perfect
Hardness: 6.0
Specific gravity: 3.25–3.36
Magnet: non-magnetic
Conductivity: none
Optical properties:
$Nx = 1.696–1.700$
$Ny = 1.696–1.702$
$Nz = 1.702–1.706$
Birefringence: 0.005–0.009
Biaxial: (+)
2V: If iron-free, 30° (+) or (−). With 5% Fe_2O_3, 60°.
Dispersion: Moderate.
$\varrho > v$ with 5% Fe_2O_3
$\varrho < v$ if iron-free
Color: Grey, green, brown, pink, colorless.
Pleochroism:
In variety thulite:
x = pink or red
y = light pink
z = yellow
Identification: Prismatic grains. High index and moderate birefringence. Inclusions are common.
Derivation: Basic igneous rocks and metamorphics.

TABLE XXXV

DETRITAL MINERALS CHARACTERISTIC OF DIFFERENT ROCK TYPES

Veins	*Acid igneous*	*Basic igneous*	*Pegmatite*
Arsenopyrite	Albite	Analcite	Beryl
Autunite	Anatase	Anorthite	Cassiterite
Barite	Andalusite	Anorthoclase	Chrysoberyl
Benitoite	Andesine	Arfvedsonite	Columbite
Calcite	Apatite	Astrophyllite	Diamond
Chalcedony	Beryl	Augite	Dumortierite
Chalcopyrite	Biotite	Axinite	Euclase
Cinnabar	Brookite	Barkevikite	Fayalite
Fluorite	Cassiterite	Benitoite	Gadolinite
Gold	Corundum	Bytownite	Jadeite
Hematite	Fayalite	Ceylonite	Lepidolite
Humite	Fluorite	Chromite	Orthoclase
Marcasite	Gadolinite	Diamond	Phenakite
Phenakite	Hornblende	Diopside	Pyrrhotite
Psilomelane	Lepidolite	Enigmatite	Quartz
Pyrite	Lepidomelane	Eudialite	Scheelite
Pyrolusite	Melanite	Glauconite	Thorianite
Quartz	Microcline	Hematite	Uraninite
Romeite	Molybdenite	Heulandite	Xenotime
Siderite	Monazite	Hypersthene	
Sphalerite	Muscovite	Iddingsite	
Strontianite	Oligoclase	Ilmenite	
Sulphur	Opal	Labradorite	
Torbernite	Orthoclase	Magnesite	
Wolframite	Pargasite	Nepheline	
	Piedmontite	Olivine	
	Pseudobrookite	Oxyhornblende	
	Pyrite	Pennine	
	Quartz	Perovskite	
	Rutile	Picotite	
	Spessartite	Plagioclase	
	Sphene	Platinum	
	Spodumene	Pyrope	
	Topaz	Pyrrhotite	
	Tourmaline	Sodalite	
	Uraninite	Sphene	
	Xenotime	Sulphur	
	Zircon	Zircon	
		Zoisite	

Metamorphic	*Metamorphic*	*Sediments*
Actinolite	Kaolinite	Amber
Almandite	Kyanite	Anhydrite
Anatase	Lawsonite	Ankerite
Andalusite	Lepidomelane	Aragonite
Andradite	Magnesite	Barite
Axinite	Melanite	Calcite
Beryl	Molybdenite	Celestine
Biotite	Muscovite	Chalcedony
Brookite	Olivine	Glauconite
Ceylonite	Perovskite	Gypsum
Chlorite	Phenakite	Hematite
Chloritoid	Phlogopite	Kaolinite
Chrysotile	Picotite	Leucoxene
Clinozoisite	Piedmontite	Marcasite
Cordierite	Platinum	Opal
Corundum	Pumpellyite	Periclase
Diopside	Pyrope	Psilomelane
Dumortierite	Pyrrhotite	Pyrite
Enstatite	Quartz	Quartz
Epidote	Riebeckite	Siderite
Euclase	Rutile	Spinel
Fluorite	Sillimanite	Stilpnomelane
Fuchsite	Sphene	Strontianite
Garnet	Spinel	Zircon
Glaucophane	Spodumene	
Gold	Staurolite	
Graphite	Thuringite	
Grossular	Topaz	
Hematite	Tourmaline	
Hercynite	Tremolite	
Hornblende	Uvarovite	
Humite	Wollastonite	
Idocrase	Zoisite	

APPENDIX I

DETRITAL MINERALS; MICROSCOPIC IDENTIFICATION OF NON-OPAQUE MINERALS OCCURRING IN SEDIMENTARY ROCKS

Key

	group no.
Isotropic	
index < balsam	
colorless	1
colored	2
index > balsam	
colorless	3
colored	4
Anisotropic	
Extinction parallel	
colorless	
index < balsam	
uniaxial +	5
uniaxial −	6
biaxial +	7
biaxial −	8
index > balsam	
uniaxial +	9
uniaxial −	10
biaxial +	11
biaxial −	12
colored	
non-pleochroic	
index < balsam	
uniaxial +	13
uniaxial −	14
biaxial +	15
biaxial −	16
index > balsam	
uniaxial +	17
uniaxial −	18
biaxial +	19
biaxial −	20

colored pleochroic	group no.
index < balsam	
uniaxial +	21
uniaxial −	22
biaxial +	23
biaxial −	24
index > balsam	
uniaxial +	25
uniaxial −	26
biaxial +	27
biaxial −	28
Extinction inclined	
colorless	
index < balsam	
biaxial +	29
biaxial −	30
index > balsam	
biaxial +	31
biaxial −	32
colored	
non-pleochroic	
index < balsam	
biaxial +	33
biaxial −	34
index > balsam	
biaxial +	35
biaxial −	36
colored	
pleochroic	
index < balsam	
biaxial +	37
biaxial −	38
index > balsam	
biaxial +	39
biaxial −	40

INDEX TO APPENDIX I

	Group
Barite	11,19
Barkevikite	28
Benitoite	9
Beryl	10,12,18,20
Biotite	30,34
Brookite	11,19,27
Bytownite	36
Calcite	10,14,18
Carpholite	24
Cassiterite	9,17
Celsian	31
Celestine	11
Chlorite group	3,4
Chloritoid	39
Chrysoberyl	27
Clinochlore	35,36,37,39
Clinozoisite	31
Cordierite	24
Corundum	12,26
Crossite	28
Diamond	3,4
Diaspore	11
Diopside–Hedenbergite	39
Dolomite	10
Dumortierite	12
Enigmatite	39
Enstatite	11,27
Epidote	12,28,32,36,40
Epistilbite	8
Eudialite	17
Fayalite	28
Fluorite	1,2
Fuchsite	40
Garnet group	3,4
Glauconite	40
Glaucophane	28
Gypsum	29
Harmotome	29
Heulandite	7
Hornblende	40
Hyalophane	30
Hypersthene	12,28
Iddingsite	27,28
Idocrase	10,18
Jadeite	35
Kyanite	32,36,40

	Group
Labradorite	31
Laumontite	30
Lawsonite	11
Lepidolite	12
	Group
Microcline	8,30,34
Monazite	11,19,31,35,39
Muscovite	32,36
Natrolite	7
Nepheline	10
Oligoclase	8,12,30
Opal	1,2,5
Orthoclase	8,30
Oxyhornblende	28
Pargasite	39
Pennine	25,26,27
Phillipsite	29,30
Piedmontite	11,12,39,40
Pigeonite	35
Quartz	9,15,17
Rhodonite	35,36
Riebeckite	39,40
Rutile	17,25
Sanidine	8
Scheelite	9
Siderite	10,14,18
Sillimanite	11,19,27
Sphene	11,27,31,35,39
Spinel	3,4
Spodumene	31
Staurolite	27
Stilbite	8
Sulphur	19
Thomsonite	7
Thorite	9,17
Topaz	11,19
Torbernite	18
Tourmaline	26
Wollastonite	32
Xenotime	17
Zircon	9,17
Zoisite	11

Abbreviations and symbols

elong.: elongated
flat.: flattened
grs: grains
irreg.: irregular
mod.: moderate
par.: parallel
var.: various

System

A: amorphous
H: hexagonal
M: monoclinic
O: orthorhombic
Te: tetragonal
Tr: triclinic

Habit

oct.: octahedral
triang.: triangular
Xls: crystals
vert.: vertical

Cleavage

I: imperfect
G: good
P: perfect
prism.: prismatic

Color

Bk: black
Bl: blue
Br: brown
C: colorless
Dk: dark
Gn: green
Gy: gray
Lt: light
Pk: pink
R: red
var.: various
Vi: violet
W: white
Y: yellow

Pleochroism

x: fast ray
y: intermediate ray
z: slow ray
ω: ordinary ray
ε: extraordinary ray

Dispersion

$\varrho > \nu$: red greater than violet
$\varrho < \nu$: red less than violet

Relief

		N
VL:	very low	< 1.49
L:	low	1.50–1.59
M:	medium	1.60–1.69
H:	high	1.70–1.74
VH:	very high	1.75–1.99
XH:	extreme	2.00–2.60

Special character

anom.: anomalous
transp.: transparent

Note: Some minerals are listed in more than one group. Calcite (10) is also in (14) and (18) because it may be anomalously biaxial.

Group	*Mineral*	*System*	*Habit*	*Cleavage*	*Color*	*Max. bi-refrigence*
1	Acid glass	A	irreg. fregments	none	var., pale	
	Fluorite	I	triang. or oct. oct. plates	111 P	var.	
	Opal	A	layers	none	C, pale	
2	Fluorite	I	triang. or oct. plates	111 P	var.	
	Opal	A	layers	none	C, pale	
3	Garnet group	I	fractured grs	none	var.	
	Spinel	I	oct.	111 I	var.	
	Diamond	I	oct.	111 P	var., pale	
	Chlorite group	M	irreg. flakes	001 P	Gn, Y-Gn	0.004–0.015
4	Garnet group	I	fractured grs	none	var.	
	Spinel	I	oct.	111 I	var.	
	Diamond	I	oct.	111 P	var., pale	
	Chlorite group	M	irreg. flakes	001 P	Gn, Y-Gn	0.004–0.015
5	Chalcedony	H spherulitic	fibrous or	none	W, var.	0.020–0.027
	Opal	A	layers	none	C, pale	
6	Chalcedony	H	fibrous or spherulitic	none	W, var.	0.020–0.027
7	Heulandite	M		010 P	var.	0.01
	Natrolite	0	acicular	110 P	var.	0.01
	Thomsonite	0	prismatic	010 P	var.	0.01
8	Stilbite	M		010 P	var.	0.010
	Epistilbite	M		010 P	W	0.010
	Sanidine	M	prismatic	001 P 010 G	C	0.006
	Orthoclase	M	prismatic	001 P 010 G	W, Y, Pk	0.006

Pleochroism	*Dispersion*	*Relief*	*2V*	*Special characters*
		L		Conchoidal fracture. Gas inclusions common.
		L		Rounded grs rare. $N_D = 1.43$
		L		Anom. polarization common if stained. N_D = variable. Conchoidal fracture.
		L		Rounded grs rare. $N_D = 1.43$
		L		Anom. polarization common if stained. N_D = variable. Conchoidal fracture.
		VH		Sometimes anom. anisotropic. Inclusions common.
		H		Usually well-rounded grs; pitted. Conchoidal fracture.
		VH		Irreg. fragments with conchoidal fracture. White glimmer between crossed nicols.
sometimes Gn–Y-Gn		VL		Interference color sometimes the so-called "ultra blue".
		VH		Sometimes anom. anisotropic. Inclusions common.
		H		Usually well-rounded grs; pitted. Conchoidal fracture.
		XH		Irreg. fragments with conchoidal fracture. White glimmer between crossed nicols.
sometimes Gn–Y-Gn		VL		Interference color sometimes the so-called "ultra blue".
none		L		Fiber elong. mostly(+); some(−). $N_D = 1.70\pm$
		L		Anom. polarization common if stained. N_D = variable. Conchoidal fracture.
none		L		Fiber elong. mostly(+); some(−). $N_D = 1.70\pm$
none		L	34°	Ext. angle 3°±. (A zeolite)
none		L	63°	Sometimes fibrous. (A zeolite)
none		L	54°	Sometimes radiate and fibrous. (A zeolite)
none		L	33°	Globular, radiate, or lamellar. (Zeolite)
none	strong $\varrho < \nu$	L	44°	Radiated, spherical aggregates. (Zeolite)
none		L	70°	Glassy var. of Orthoclase.
none		L	70°	Usually irreg. grs, flat. par. to 001 Inclusions common.

Group	*Mineral*	*System*	*Habit*	*Cleavage*	*Color*	*Max. bi-refrigence*
	Oligoclase	Tr	prismatic	001 P 010 G	W, Gy, Gn	0.006
	Microcline	Tr	prismatic	001 G 010 I	Gn, W, Y, R	0.008
9	Quartz	H	prismatic	none	C	0.009
	Zircon	Te	prismatic	110 I	C, Y, Vi	0.058–0.062
	Cassiterite	Te	prismatic	100 I	var.	0.096
	Thorite	Te	rounded grs	prism. distinct	Gn, Y-Gn	
	Benitoite	H	tabular	$10\bar{1}1$ poor	C, Bl	0.044
	Scheelite	Te	oct. or tabular	101 G 112 I	C, W, Y, Br	0.016
10	Beryl	H	prismatic	0001 I	Gn, Bl, W	low
	Apatite	H	prismatic	0001 poor	C, Bl, Gn	low
	Corundum	H	platy	0001 parting	var.	0.008
	Idocrase	Te		001 I 110 I	Gn, var.	0.008
	Calcite	H	rhombs	$10\bar{1}1$ P	C, Bl, var.	0.172
	Siderite	H	rhombs	$10\bar{1}1$ P	Gy, Br	0.242
	Dolomite	H	rhombs	$10\bar{1}1$ P	C, var.	0.181
	Nepheline	H	tabular	$10\bar{1}0$ I 0001 I	C, Gy, Gn	0.004
11	Brookite	O	prismatic	110 I 001 I	Y, Br	0.158
	Enstatite	O	prismatic	110 G	Gy, Y, Gn	0.008
	Topaz	O	prismatic	001 P	C, Y, var.	0.008
	Barite	O	prismatic	001 P 110 P	C, Y	0.012
	Sphene	M	prismatic	110 G 100 I	Br, Y-Br	0.134
	Lawsonite	O	prismatic, tabular	001 P 010 P	C, Bl	0.034
	Diaspore	O	prismatic, flat. par. to 010	010 P	pale	0.048

Pleochroism	*Dispersion*	*Relief*	*2V*	*Special characters*
none		L	86°	Irreg. grs.
none	weak $\varrho > v$	L	83°	001 plates show grating-structure.
none		L		Irreg. grs, with no cleavage, and low birefrigence and Index. $N_D = 1.547$
none		VH		Prisms with pyramidal ends.
none		VH		Prismatic and pyramidal grs with adamantine luster. FeO inclusions common.
		M		Smooth, polished grs. Urano-thorite is similar. $N_D = 1.7$
strong $\omega = C; \varepsilon = Bl$	strong $\omega = C; \varepsilon = Bl$	VH		Rare in sediments.
none		H		Sub-angular oct. grs Sometimes tabular or striated.
weak		L		Often striated vertically. Sometimes abnormally biaxial.
none		L		Elong. Xls with rounded ends.
pleochroic if colored		H		Sometimes anom. biaxial.
pleochroic if colored		L		Rounded grs.
none		VH		Twin striations par. to $10\bar{1}1$. Exhibits twinkling.
none		VH		Translucent grs. Exhibits twinkling.
none		VH		Rhombohedral grs common. Exhibits twinkling.
none		L		Rare in sediments.
001 grs are pleochroic	strong $\varrho > v$	VH	30°	Pseudo-uniaxial figure for Gn-Y light. Some grs do not extinguish in any position.
in thick grs Y-Gn	weak $\varrho < v$	M	70°	$2V$ varies with amount of iron.
in thick grs Y-Pk	distinct $\varrho > v$	H	60°	Basal grs show good figures.
none	weak $\varrho < v$	H	37°	Angular grs common. Cleavage frag. may show obtuse bisectrix.
weak x = Y; z = Pk	mod. $\varrho > v$	VH	27°	Slightly rounded or ragged grs.
in thick grs x = Bl, y = Y, z = C	strong $\varrho > v$	H	84°	A secondary mineral.
weak x = Vi, z = Y	weak $\varrho < v$	H	84°	Rarely optically (—).

Group	*Mineral*	*System*	*Habit*	*Cleavage*	*Color*	*Max. bi-refrigence*
	Monazite	M	flat. Xls	001 P 100 G	Y-Br, Y, R	0.049
	Sillimanite	O	prismatic, fibrous	010 G	C, Y, Br	0.021
	Zoisite	O	prismatic	010 P	C	var. 0–60°
	Celestine	O	prismatic, tabular	001 P 110 G	W, Bl	0.009
	Piedmontite	M	prismatic	001 P	R-Br, Bk	0.082
12	Hypersthene	O	prismatic, tabular	110 G 100 I	Br-Gn, Gy, Gn	0.013
	Andalusite	M	prismatic, acicular	110 P 100 I	C, var.	0.009
	Epidote	M	prismatic, striated	001 P 100 I	Gn-Y, Gn, Br	0.028
	Dumortierite	O	prismatic	100 G 110 1	C, var.	0.011
	Piedmontite	M	prismatic	001 P	R-Br, Bk	0.082
	Lepidolite	M	tabular, micaceous	001 P	W, Y, Vi	0.023
	Oligoclase	Tr	lamellar	001 P 010 G	W, Gy, Gn	0.008
	Beryl	H	prismatic	0001 I	W, Gn, Bl	0.004
13						
14	Calcite	H	rhombic var.	$10\bar{1}1$ P	C, Bl, var.	0.172
	Siderite	H	rhomb, often curved	$10\bar{1}1$ P	Gy, Br	0.242
15	Quartz	H	prismatic	none	C, var.	0.008
16						
17	Cassiterite	Te	euhedral pyramids	100 I	Br, R-Br, Bk	0.096
	Quartz	H	irreg. or rounded grs	none	C, var.	0.008
	Rutile	Te	prismatic, twinned	110 G 100 G	R, Y, R-Br	0.287
	Xenotime	Te	prismatic	110 P	R-Br, Y	0.107

Pleochroism	*Dispersion*	*Relief*	*2V*	*Special characters*
in thick grs Y-Gn-Y	weak $\varrho < v$	VH	14°	Well-rounded grs with dark borders or blotches. Flat. par. to 100
if strong Y-Br	strong $\varrho > v$	H	20°	Thin prisms or fibers, show good biax. figure.
sometimes Y-Pk	strong var.	M	var.	Dispersion $\varrho < v$ if iron-free and $2V = 0$–30° Otherwise $\varrho > v$, and $2V = 30$–60°
faint C-Bl	distinct $\varrho < v$	H	51°	Variably shaped fragments.
$x = Y, y = Pk,$ $z = R$	strong $\varrho > v$	VH	55° 80°	Irreg. grs of deep R-Br color. Sometimes optically (−) with $2V = 90°$
marked, $x = Pk,$ $y = Y, z = Gn$	weak $\varrho > v$	H	75° ±	Grs often have jagged ends. Inclusions common.
strong $x = R, z = C$	weak $\varrho > v$	H	85°	Glassy grs with pinkish tinge. Sometimes turbid from inclusions.
weak $x = C,$ $y = Gn\text{-}Y, z = C$	strong $\varrho > v$	H	92° ±	Very transp. grs show brilliant interference colors.
strong $x = Bl,$ $y = Y, z = C$	strong $\varrho > v$	H	30° 40°	Prismatic grs resemble Tourmaline.
$x = Y, y = Pk,$ $z = R$	strong $\varrho > v$	VH	55° 80°	Irreg. grs of deep R-Br color. Usually biaxial (+). If (−) $2V = 90°$
mod. $x = C$, y and z are Pk	$\varrho > v$	L	0° 50°	Micaceous flakes of Vi color.
none	weak $\varrho < v$	L	86°	Irreg. grs with twin lamellae.
none		M		Abnormally biaxial. Often striated vertically.
none		VH		Sometimes abnormally biaxial with $2V = 30°$ Exhibits twinkling. Striations par. to $10\bar{1}1$
none		VH		Translucent grs. Shows twinkling.
none		L		Abnormally biaxial in some cases. Extinction commonly undulatory.
rare		VH		Knee-twins, but rarely seen in small grs. Inclusions common.
		L		Extinction commonly undulatory. Sometimes anom. biaxial.
weak Br-Y		VH		Anom. biaxial in twinned Xls. Knee-twins common 65° angle.
weak, ω = pale Y		VH		Short prisms, doubly terminated, or rounded grs. Resembles Zircon.

Group	*Mineral*	*System*	*Habit*	*Cleavage*	*Color*	*Max. bi-refrigence*
	Zircon	Te	euhedral, prismatic	110 I	C, Y, Vi	0.058–0.062
	Thorite	Te	prismatic	110 G	Y-Gn, Gn	0.010
	Eudialite	H	tabular	0001 G $10\bar{2}0$ I	Pk, R, Br	0.001
18	Anatase	Te	oct., tabular	001 P 111 P	Y, Br, Bl, Bk	0.061
	Apatite	H	prismatic	0001 I	W, Gn	0.005
	Beryl	H	prismatic	0001 I	W, Gn, Bl	0.004
	Calcite	H	rhombs	$10\bar{1}1$ P	C, Bl, var.	0.172
	Siderite	H	rhombs	$10\bar{1}1$ P	Gy, Br	0.242
	Idocrase	Te	prismatic	110 poor	var.	0.008
	Torbernite	Te	tabular	001 P 100 G	Gn	0.010
	Ankerite	H	rhombic	$10\bar{1}1$ P	W, Y, R-Br	0.185
19	Barite	O	prismatic	001 P 110 P	C, Y	0.012
	Brookite	O	prismatic	110 I 011 I	Y, Br	0.158
	Monazite	M	flat. Xls	001 P 100 G	Y, Y-Br, R	0.050
	Sillimanite	O	prismatic, rectangular	010 G	C, Y, Br	0.021
	Topaz	O	striated prisms	001 P	C, Y, var.	0.008
	Sulphur	O	prismatic, tabular	imperfect	Y	0.288
20	Beryl	H	prismatic	0001 I	Gn, Bl, W	0.004
21						
22						
23						
24	Cordierite	O	short prisms	010 G	Bl, Y, Br	0.006
	Carpholite	O	fibrous, radiate	010 P	pale Y	0.019

Pleochroism	*Dispersion*	*Relief*	*2V*	*Special characters*
ε = Y or Gn in thick Xls		VH		Colorless prisms with pyramidal terminations.
		M		Smooth, polished grs. Sometimes isotropic. Urano-Thorite is similar.
very weak		H		Flat. grs.
in thick grs Br-Y		VH		Tabular 001 grs common.
weak		L		Sometimes pseudo-biaxial.
none		M		Abnormally biaxial. Often striated vertically.
none		VH		Sometimes abnormally biaxial. $2V = 30°$ Usually twin striae par. to major diagonal.
none		VH		Translucent grs. Shows twinkling.
none unless colored		H		Rounded grs. Sometimes abnormally biaxial.
weak ω = Bl, ε = Gn		L		Tabular Gn grs, somewhat like mica. Pleochroic only in thick grs.
none		M		N_D varies with $FeCO_3$ content. Curvilinear grs. Shows twinkling.
	weak $\varrho < v$	H	37°	Angular grs common. Cleavage grs may show acute bisectrix.
001 grs may be pleochroic	strong $\varrho > v$	VH		Pseudo-uniaxial figure for Gn-Y light. Some grs do not extinguish in any position.
in thick grs Y–Gn-Y	weak $\varrho < v$	VH	14°	Well-rounded pale Y grs with dark borders of blotches.
if strong x and y are Y, z = Br	strong $\varrho > v$	H	20°	Thin prisms or flat. fibers. May show good biaxial figure.
in thick grs Y-Pk	distinct $\varrho > v$	H	60° ±	Basal grs show good interference figures.
none	weak $\varrho < v$	VH	69°	Rare in sediments.
none		M		Abnormally biaxial. Often striated vertically.
common, x = Y, y = Dk Bl, z = Lt Bl	weak $\varrho < v$	L	40–84	Inclusions common.
x = C, y = Y, z = C	strong $\varrho > v$	H	60°	Rare in sediments. Has tourmaline-like pleochroism, but in Y hues.

Group	*Mineral*	*System*	*Habit*	*Cleavage*	*Color*	*Max. bi-refrigence*
25	Rutile	Te	prismatic, acicular	110 G 100 G	R, R-Br, Y	0.287
	Pennine	M	lamellar	001 P	Gn	0.003
26	Anatase	Te	oct., tabular	001 P 111 P	Y, Br, var.	0.061
	Apatite	H	prismatic	0001 I	W, Gn	0.005
	Corundum	H	hexagonal, bipyramidal	0001 parting	var.	0.008
	Pennine	M	lamellar, platy	001 P	Gn	0.003
	Tourmaline	H	prismatic vert. striae	$11\bar{2}0$ I	Br, Bl, Gn, Bk	0.040
	Autunite	Te	scaly aggregates	001 P 100 I	Y, Gn-Y	0.024
27	Brookite	O	prismatic, tabular	110 I 001 I	Y, Br	0.158
	Enstatite	O	prismatic, pyramidal	110 G at 88°	Gy, Y, Gn	0.008
	Sillimanite	O	prismatic, rectangular	010 G	C, Y, Br	0.021
	Sphene	M	euhedral, prismatic	110 G 100 I	Br, Y-Br	0.134
	Staurolite	O	prismatic	010 G	R-Br, Br-Y, Y	0.010
	Iddingsite	O	lamellar	100 P 001 P 010 P	R, R-Br	0.044
	Anthophyllite	O	prismatic, lamellar	110 P 010 G	Br, Gn	0.013
	Chrysoberyl	O	tabular, prismatic	011 G 010 I	Gn, Y, var.	0.010
	Pennine	M	lamellar, platy	001 P	Gn	0.003
28	Barkevikite	M	prismatic	110 G 010 G	Dk Br	0.020
	Crossite	M	prismatic	110 P 010 P	Dk Bl	0.01
	Epidote	M	prismatic	001 P 100 I	Gn-Y, Gn, Br	0.028
	Fayalite	O	prismatic, tabular	010 G 100 I	Gn-Y	0.051
	Glaucophane	M	prismatic, short Xls	110 P	C, Bl, Bl-Bk	0.017

Pleochroism	*Dispersion*	*Relief*	*2V*	*Special characters*
weak Br-Y		VH		Anom. biaxial in twinned Xls. Knee-twins common. 65° angle.
x = Y-Gn, y = Gn, z = Gn	strong $\varrho < \nu$	L	0° ±	Usually biaxial (+). Most grs show abnormal "ultra-blue" interference tints.
weak		VH		Tabular grs show interference figures.
weak for colored grs		M		Inclusions common.
pleochroic if colored		H		Anomalously biaxial.
x = Gn, y = Gn z = Y-Gn	strong $\varrho < \nu$	L	0° ±	Usually biaxial (+).
varies with color		H		Color absorption much greater when crystal axis is normal to vibration direction in lower nicol.
weak, x = C, z = Y		L		Mica-like, platy grs, transp. to translucent.
001 grs may be pleochroic	strong $\varrho > \nu$	VH		Pseudo-uniaxial figure for Gn-Y light. Some grs do not extinguish in any position.
faint–med., x = Y, y = Br-Y, z = Gn	weak $\varrho < \nu$	M	70°	Grayish grs. Inclusions common.
if strong Y-Br	strong $\varrho > \nu$	H	20°	Thin prisms or flat. fibers. Flat. grs show good biaxial figure.
weak, x = Y, z = Pk	mod. $\varrho > \nu$	VH	27°	Irreg. shaped, slightly rounded grs.
mod., x = C, y = Y, z = Y	weak $\varrho > \nu$	H	88° ±	Irreg. or platy grs with hackly fracture. Rarely (−).
x < y < z	strong $\varrho > \nu$	H	35° ±	Nearly always optically (−). Pseudomorphous.
some is pleochroic, x and y are Br, z = pale Y-Gn	$\varrho < \nu$	M	90° near	Often lamellar or fibrous.
in thick grs x = R, y = Y, z = Gn		H	10° 70°	*2V* is variable with iron content.
x = Gn, y = Gn, z = Y-Gn	strong $\varrho < \nu$	L	0° ±	Sometimes uniaxial (−).
marked Br	$\varrho > \nu$	H	31° 52°	A basic amphibole.
strong, x = Y, y = Bl, z = Vi	strong $\varrho > \nu$	H	var.	A soda amphibole.
weak, x = C, y = Gn-Y, z = C	strong $\varrho > \nu$	H	92° ±	Irreg. and angular grs. Very transp. grs show brilliant interference colors.
weak, x = C, y = Vi, z = Bl	strong $\varrho > \nu$	VH	47° 50°	Olivine group.
marked, x = C, y = Vi, z = Bl	strong $\varrho > \nu$	H	45° ±	Inclusions common.

Group	*Mineral*	*System*	*Habit*	*Cleavage*	*Color*	*Max. bi-refrigence*
	Hypersthene	O	prismatic, tabular	110 G 100 I	Br-Gn, Gy, Gn	0.013
	Iddingsite	O	lamellar	100 P 001 P 010 P	R, R-Br	0.044
	Andalusite	O	prismatic	110 P 100 I	C, var.	0.009
	Oxyhornblende	M	prismatic	110 P	Br	0.023
	Allanite	M	tabular, elong.	001 P 100 I	Br, Bk	0.024
29	Gypsum	M	tabular or prismatic	010 P 100 I 111 1	W	0.010
	Harmotome	M		010 G 001 I	W, var.	0.005
	Albite	Tr	tabular, prismatic	010 P 001 P	C, Gy	0.011
	Phillipsite	O		001 G 010 G	C	0.005
30	Anorthoclase	Tr	prismatic	010 P 001 P	W	0.008
	Hyalophane	M		001 P 010 G	C	0.005
	Laumontite	M		010 P 110 P	W, Y, Gy	0.012
	Microcline	Tr	prismatic	010 I 001 G	W, Y, Gn, R	0.008
	Orthoclase	M	prismatic	001 P 010 G	W, Y, Pk	0.006
	Biotite	M	flakes with jagged edges	001 P	Y, Gn, Br	0.064
	Phillipsite	O		001 G 010 G	C	0.005
	Oligoclase	Tr	prismatic	001 P 010 G	W, Gy, Gn	0.008
31	Andesine	Tr	tabular, prismatic	001 P 010 P	C	0.007
	Augite	M	prismatic	110 G	Y-Gn, Gn	0.043
	Celsian	M	short, prismatic	001 P 010 G	C	0.010

Pleochroism	*Dispersion*	*Relief*	*2V*	*Special characters*
marked, x = Pk y = Y, z = Gn	weak $\varrho > \nu$	H	75° ±	Grs often have jagged ends. Inclusions common.
x < y < z Br grs	strong $\varrho > \nu$	H	35° ±	Sometimes optically (+).
strong x = R, y and z are C	weak $\varrho > \nu$	H	85°	Glassy, irreg. grs. Inclusions common.
variable, x = Y, y = Br, z = Gn or Br	weak $\varrho > \nu$	H	83°	Also called Basaltic Hornblende.
x = Y or Br, y = Dk Br, z = Dk R-Br	strong $\varrho > \nu$	H	70° 90°	Epidote group.
	strong $\varrho > \nu$	L	58°	Often as colorless Xls, somewhat rounded.
		VL	43°	A zeolite.
		VL	74°	Polysynthetically twinned. Inclusions common.
		VL	var.	A zeolite.
	weak $\varrho > \nu$	L	45°	Grs often show cross-hatched twinning.
	$\varrho > \nu$	L	74° 79°	A barium bearing orthoclase.
	large $\varrho < \nu$	L	25°	A zeolite.
	weak $\varrho > \nu$	L	83°	001 plates show grating-structure.
		L	70°	Usually irreg. grs, flat. par. to 010 Inclusions common.
x = C, y and z are Br-Y	weak $\varrho < \nu$	M	0° 35°	Almost uniaxial figure is usual.
	weak $\varrho < \nu$	L	60° 80°	A zeolite.
	weak $\varrho < \nu$	L	86°	Irreg. shaped grs.
		L	88°	A plagioclase. Irreg. clear grs. Twinned.
weak Gn-Vi	$\varrho > \nu$	VH	65°	A pyroxene. Rounded or irreg. grs.
		M	86°	A barium feldspar, similar to Anorthite.

Group	*Mineral*	*System*	*Habit*	*Cleavage*	*Color*	*Max. bi-refrigence*
	Clinozoisite	M	tabular	001 P 100 I		0.010
	Labradorite	Tr	tabular	001 P 010 P	C, Gy, Gn	0.009
	Monazite	M	grs flat. par. to 100	001 P 100 G	Y, Y-Br, R	0.049
	Sphene	M	rounded or ragged grs	110 G 100 I	Br, Y-Br	0.134
	Spodumene	M	prismatic	110 P	Gn, Y, Pk	0.016
32	Anorthite	Tr	prismatic	001 P 010 I	W	0.012
	Axinite	Tr	diamond- or wedge Xls	010 G	var.	0.010
	Epidote	M	prismatic	001 P 100 I	Gn-Y, Gn, Br	0.028
	Kyanite	Tr	prismatic, bladed	100 P 010 G	C, W, Gn, Gy, Bl	0.016
	Muscovite	M	pseudo-hexagonal flakes	001 P	C, Y, Gy	0.043
	Wollastonite	M	tabular	100 P 001 G	C, W, Y, Gy	0.014
33	Albite	Tr	tabular, prismatic	010 P 001 P	C, Gy	0.011
34	Microcline	Tr	prismatic	010 I 001 G	W, Y, Gn, R	0.008
	Biotite	M	flakes with jagged edges	001 P	Y, Gn, Br	0.064
35	Augite	M	prismatic	110 G	Y-Gn, Gn	0.043
	Clinochlore	M	pseudo-hexagonal plates	001 P	Gn, Y, W	0.005
	Monazite	M	grs flat. par. to 100	001 P 100 G	Y, R, Y-Br	0.049
	Sphene	M	rounded or ragged grs	110 G 100 I	Br, Y-Br	0.134
	Jadeite	M	prismatic		Gn, W	0.013
	Rhodonite	Tr	tabular	110 P 001 G	Lt R, Gn, Y	0.010
	Pigeonite	M	prismatic	110 G 100 G	pale Gn	0.026
36	Actinolite	M	slender prisms	110 P	Gn-Y, Gy, Gn	0.027
	Bytownite	Tr	broad twin-bands	100 P 010 G	C, W, Gy, Gn	0.010

Pleochroism	*Dispersion*	*Relief*	*2V*	*Special characters*
x = Gn, y = Pk or Gn, z = R or Gn	strong $\varrho < v$	H	66°	Epidote group. "Ultra blue", anom. interference colors sometimes seen.
	weak $\varrho > v$	L	79°	A plagioclase feldspar, always polysynthetic twinned. Iridescence on 010
	weak $\varrho < v$	VH	14°	Well-rounded pale Y grs with dark border or blotches.
weak x = Y, z = Pk	mod. $\varrho > v$	VH	27°	Slightly rounded or ragged grs.
weak, x = Vi, y = Pk, z = C	weak $\varrho < v$	H	54° 60°	A pyroxene.
	weak $\varrho > v$	L	77°	A plagioclase, rare in sediments.
mod., x = Gn, y = Bl, z = Br	mod. $\varrho < v$	H	65° 70°	In irreg. or diamond-shaped grs. Grs sometimes fail to extinguish in any position.
weak, x = C, y = Gn-Y, z = C	strong $\varrho > v$	H	92° ±	Very transp. grs show brilliant interference colors.
weak, x = C, y = Bl, z = Dk Bl	weak $\varrho > v$	H	82° 84°	Ragged grs. On 100 $z/c = 30°$
	distinct $\varrho < v$	L	40° ±	Usually thin, colorless, plates with Bl-Gy interference color and good figure. Inclusions common.
none	distinct $\varrho > v$	H	39°	Nx = 1.620, Ny = 1.632, Nz = 1.634
none		VL	74°	Polysynthetically twinned. Inclusions common.
	weak $\varrho > v$	L	83°	001 plates show grating-structure.
x = C, y and z are Br-Y	weak $\varrho < v$	M	0° 35°	Almost uniaxial figure is usual.
weak, Gn-Vi	$\varrho > v$	VH	65°	A pyroxene. Rounded or irreg. grs.
x and y are pale Gn, z = pale Y	weak $\varrho < v$	L	0° ±	Chlorite group. Seldom in sediments.
in thick grs Y-Gn-Y	weak $\varrho < v$	VH	14°	Well-rounded pale Y grs with dark border or blotches.
weak x = Y, z = Pk	mod. $\varrho > v$	VH	27°	Slightly rounded or ragged grs.
		M	70°	A polyaugite of rare occurrence in sediments.
	weak $\varrho < v$	H	61° 76°	Also optically (—).
weak	weak	H	0° 30°	A pyroxene.
weak, x = pale Y, y and z are Gn	weak $\varrho < v$	H	80°	Fibrous aggregates or single grs. Extinction angle usually low. Nephrite is related.
	$\varrho > v$	L	82°	Rarely found in sediments.

Group	*Mineral*	*System*	*Habit*	*Cleavage*	*Color*	*Max. birefrigence*
	Epidote	M	prismatic, striated	001 P 100 I	Gn-Y, Gn, Br	0.028
	Kyanite	Tr	prismatic bladed	100 P 010 G	C, W, Gn, Gy, Bl	0.016
	Muscovite	M	pseudo-hexagonal flakes	001 P	C, Y, Gy	0.043
	Clinochlore	M	pseudo-hexagonal plates	001 P	Gn, Y, W	0.005
	Rhodonite	Tr	tabular	110 P 001 G	Lt R, Gn-Y	0.010
37	Clinochlore	M	pseudo-hexagonal plates	001 P	Gn, Y, W	0.005
38						
39	Diopside–Hedenbergite	M	prismatic	110 G 100 G	W, Gy-Gn	0.030
	Sphene	M	prismatic	110 G 100 I	Br, Y-Br	0.134
	Riebeckite	M	prismatic	110 P at 24°	Dk Bl, Bk	0.006
	Pargasite	M	prismatic elong. par. to c	110 P 100 G 010 G	Gn, Bl-Gn	0.019
	Monazite	M	grs flat. par. to 100	001 P 100 G	Y, R, Y-Br	0.049
	Clinochlore	M	pseudo-hexagonal plates	001 P	Gn, Y, W	0.005
	Enigmatite	Tr	prismatic	010 G 100 G	R-Br, Bk	0.006
	Piedmontite	M	elong. par. to b	001 P	R-Br, Bk	0.082
	Chloritoid	M Tr?	pseudo-hexagonal plates	001 P	Dk Gn, Gn-Bk	0.007 0.016
40	Aegirine	M	prismatic	110 P	Gn, Dk Gn	0.045
	Epidote	M	elong. par. to b	001 P 100 I	Gn-Y, Gn, Br	0.028

leochroism	Dispersion	Relief	2V	Special characters
eak, x = C, = Gn-Y, z = C	strong $\varrho > \nu$	H	92° ±	Very transp. grs show brilliant interference colors.
eak, x = C, = Bl, z = Dk Bl	weak $\varrho > \nu$	H	82° 84°	Ragged grs. On 100, $z/c = 30°$
	distinct $\varrho < \nu$	L	40° ±	Usually thin, colorless plates with Bl-Gy interference colors and good figure. Inclusions common.
= pale Gn, = pale Gn, = pale Y-Gn	weak $\varrho < \nu$	L	0° ±	Chlorite group.
	weak $\varrho < \nu$	H	61° 76°	Also optically (+).
= pale Gn, = pale Gn, = pale Y-Gn	weak $\varrho < \nu$	L	0° ±	Chlorite group.
ne	$\varrho > \nu$	H	56° 63°	A pyroxene. Tabular grs par. to 110 give parallel extinction.
ak = Y, z = Pk	mod. $\varrho > \nu$	VH	27°	Slightly rounded or ragged grs.
ong, x = Bl, = Br-Y, = Gn or Y	strong $\varrho > \nu$ $\varrho < \nu$	H	80° 90°	An amphibole. Usually optically (—). Prisms are long. Striated. Sometimes fibrous.
= Gn-Y, y = Gn, = Gn-Bl	$\varrho > \nu$	H	52° 65°	An amphibole. Extinction angle 26° Similar to Hornblende, but optically (+).
thick grs -Gn-Y	weak $\varrho < \nu$	VH	14°	Well-rounded pale Y grs with dark borders or blotches.
= pale Gn, = pale Gn, = pale Y-Gn	weak $\varrho < \nu$	L	0° ±	Chlorite group.
ong, x = R-Br, = Br, z = Dk	$\varrho < \nu$	VH	32°	Strong Br color. Extinction 4° to prismatic cleavage.
= Y, y = Vi Pk, z = R	strong $\varrho > \nu$	VH	85°	Epidote group.
= olive Gn = Gn-Bl, = Y-Gn	strong $\varrho > \nu$	H	36° 63°	Not common in sediments. Biaxial figure common. Pleochroism is distinctive.
= olive Gn, = Gn = Y-Gn	$\varrho > \nu$	H	81°	A pyroxene. Rare in sediments.
ak, x = C, = Gn-Y, z = C	strong $\varrho > \nu$	H	92° ±	Very transparent grs show brilliant interference colors.

Group	*Mineral*	*System*	*Habit*	*Cleavage*	*Color*	*Max. bi-refrigence*
	Hornblende	M	prismatic, elong. par. to c	110 P 100 G 010 G	Dk Gn, Br, Bk	0.016
	Riebeckite	M	prismatic	110 P at 124°	Dk Bl, Bk	0.006
	Kyanite	Tr	prismatic	100 P 010 G	C, W, Bl, Gn-Gy	0.016
	Piedmontite	M	elong. par. to b	001 P	R-Br, Bk	0.082
	Glauconite	M	platy	001 P	Gn, Dk Gn	0.018–0.032
	Fuchsite	M	platy	001 P	Gn	0.040
	Baddeleyite	M	tabular	001 P	Y, Br, Bk	0.07

Pleochroism	*Dispersion*	*Relief*	*2V*	*Special characters*
x = Y or pale Gn y = Y or Y-Gn z = Br or Dk Gn	weak $\varrho < \nu$	H	84° ±	An amphibole. Extinction angle usually 10–15°
strong, x = Bl, y = Br-Y, z = Gn or Y	strong $\varrho > \nu$ $\varrho < \nu$	H	80° 90°	An amphibole. Usually optically (−). Prisms are long. Striated. Sometimes fibrous.
weak, x = C, y = Bl, z = Dk Bl	weak $\varrho > \nu$	H	82° 84°	Ragged grs. On 100 $z/c = 30°$
x = Y, y = Vi or Pk, z = R	strong $\varrho > \nu$	VH	85°	Epidote group.
x = Y or Y-Gn, y = Gn, z = Y	$\varrho > \nu$	H	0° 20°	Rounded or irreg. grs.
weak, x = C, y = Y-Gn, z = Bl-Gn	strong $\varrho > \nu$	L	40°	The chromium mica. Rare in sediments.
mod., y = Gn, x and y are R-Br	strong $\varrho > \nu$	VH	30°	Worn, tabular grs but rare in sediments.

APPENDIX II

ORIENTATION-CLEAVAGE CRYSTAL DRAWINGS

(After TRÖGER, 1959)

Abbreviations and symbols

Color

Bk: black
Bl: blue
Br: brown
C: colorless
Dk: dark
Gn: green
Gy: gray
Lt: light
Ol: olive
Or: orange
Pk: pink
R: red
Vi: violet
Y: yellow

Pleochroism

x: fast ray
y: intermediate ray
z: extraordinary ray

Dispersion

$\varrho > \nu$ red greater than violet
$\varrho < \nu$ red less than violet

AP: axial plane

Colors indicated in Fig.60–158 that do not conform to those given in Appendix I, are given in brackets.

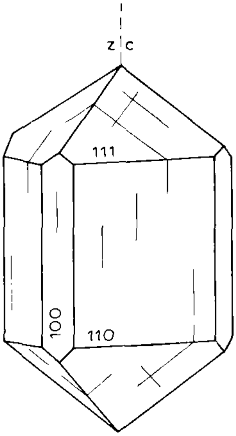


Fig.60. Cassiterite.

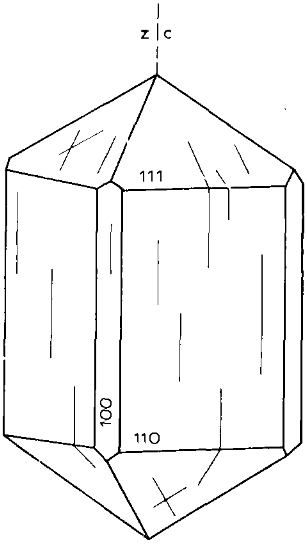


Fig.61. Rutile.

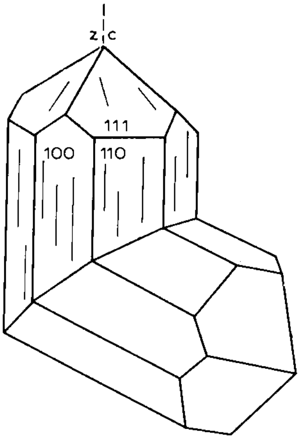


Fig.62. Rutile.

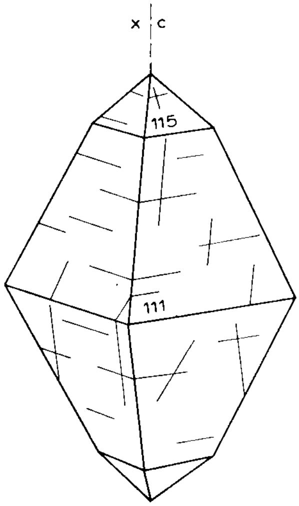


Fig.63. Anatase.

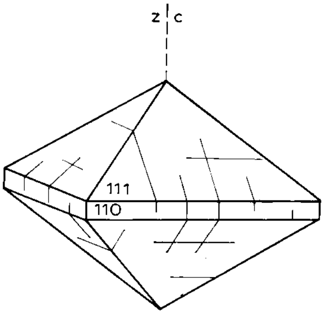


Fig.64. Xenotime.

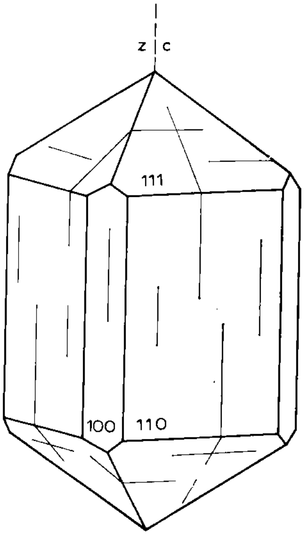


Fig.65. Zircon.

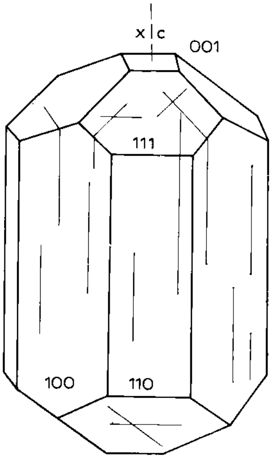


Fig.66. Idocrase.

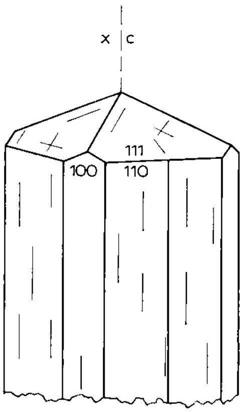


Fig.67. Scapolite.

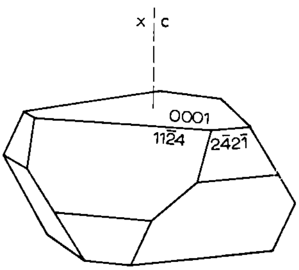


Fig.68. Ilmenite.

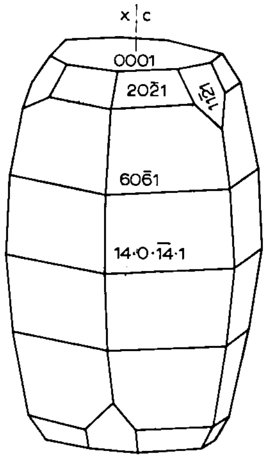


Fig.69. Corundum.

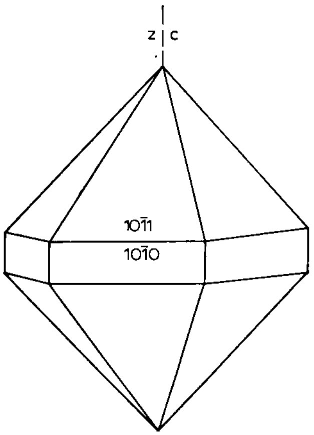


Fig.70. α Quartz.

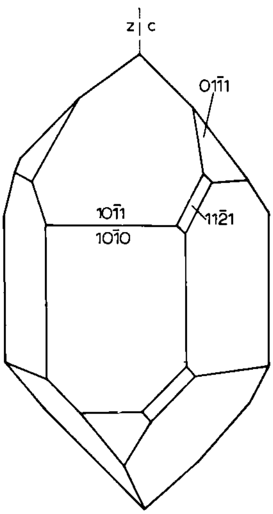


Fig.71. β Quartz.

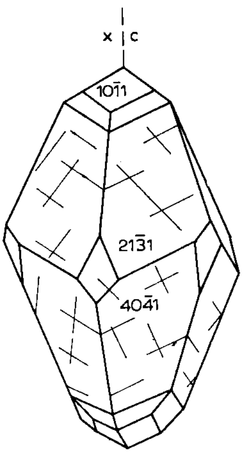


Fig.72. Calcite.

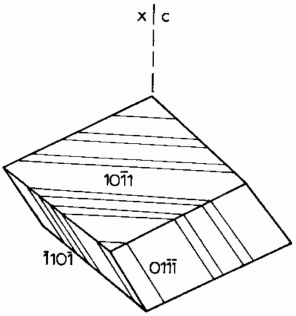


Fig.73. Calcite (cleaved).

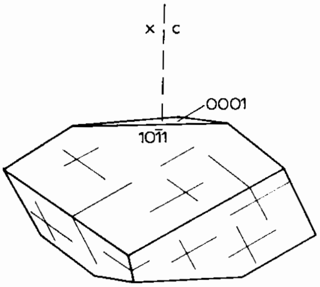


Fig.74. Siderite.

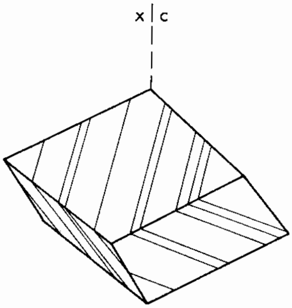


Fig.75. Dolomite.

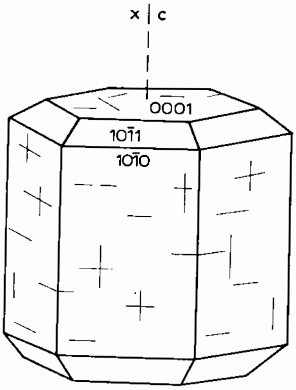


Fig.76. Apatite.

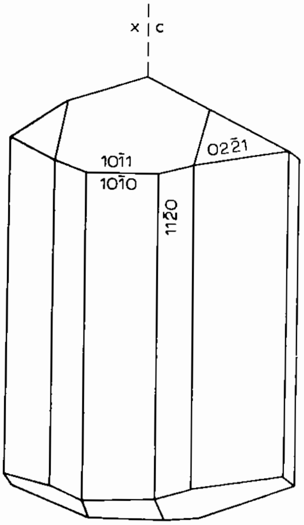


Fig.77. Tourmaline.

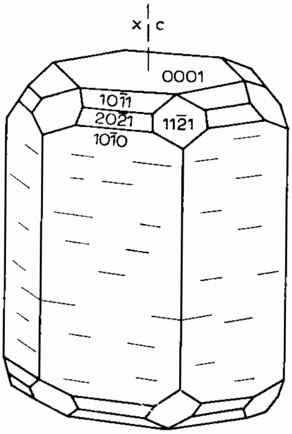


Fig.78. Beryl.

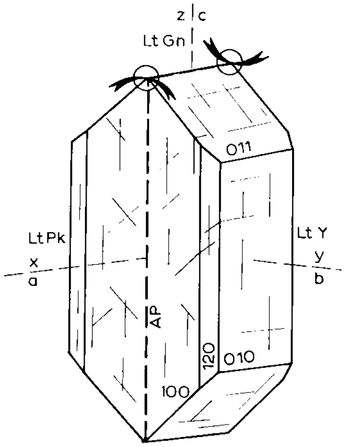


Fig.79. Chrysoberyl.

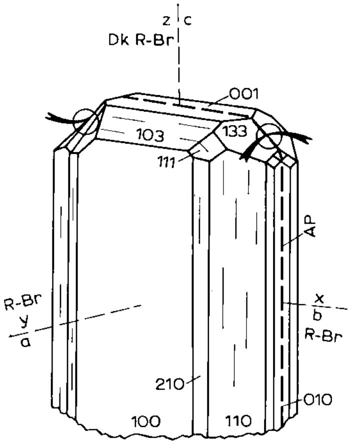


Fig.80. Columbite–Tantalite series.

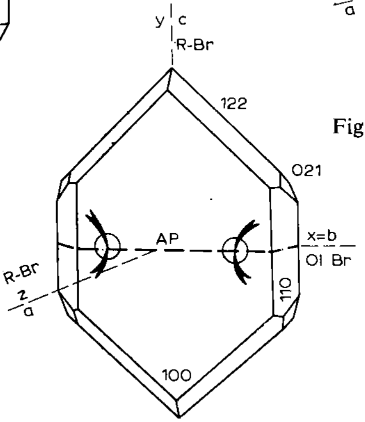


Fig.81. Brookite, λ=red.

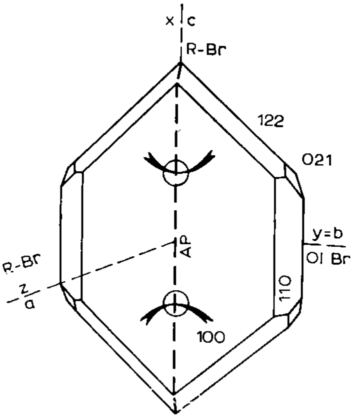


Fig.82. Brookite, λ=blue.

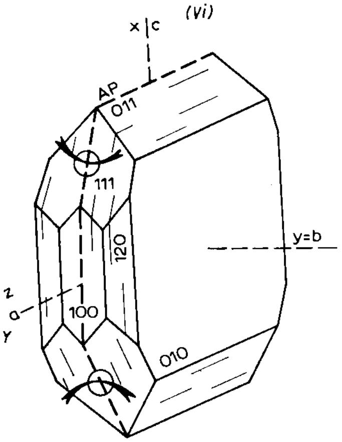


Fig.83. Diaspore.

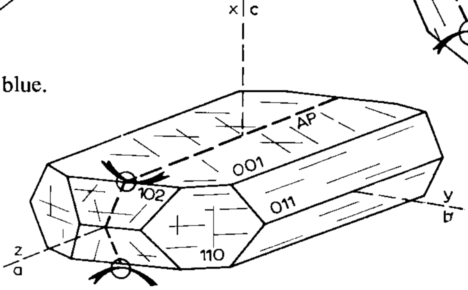


Fig.84. Barite.

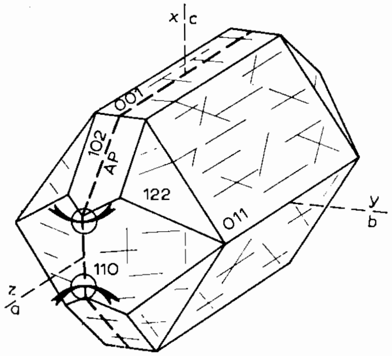


Fig.85. Celestine.

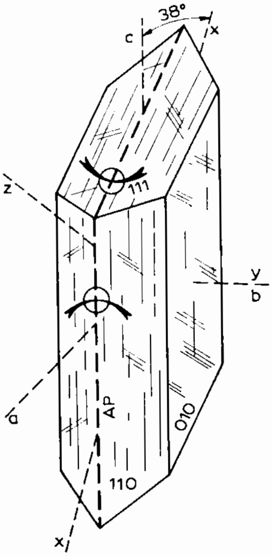


Fig.86. Gypsum.

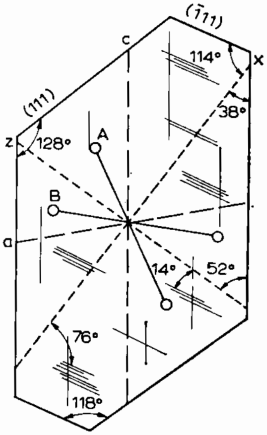


Fig.87. Cypsum (cleaved // 010).

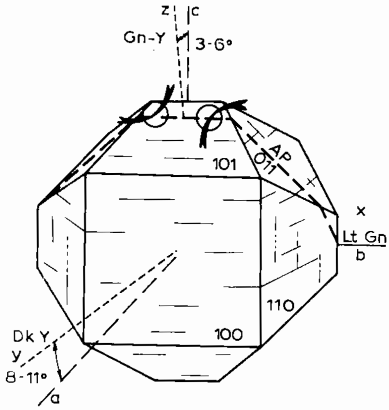


Fig.88. Monazite.

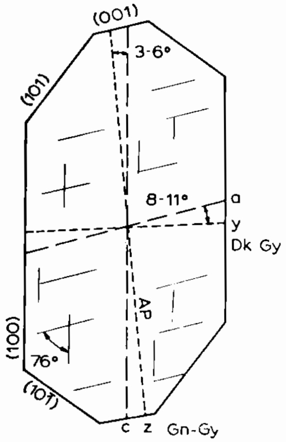


Fig.89. Monazite (cleaved // 010).

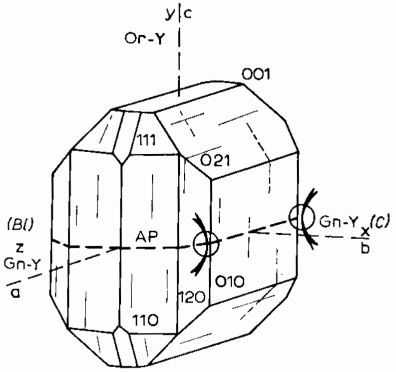


Fig.90. Fayalite.

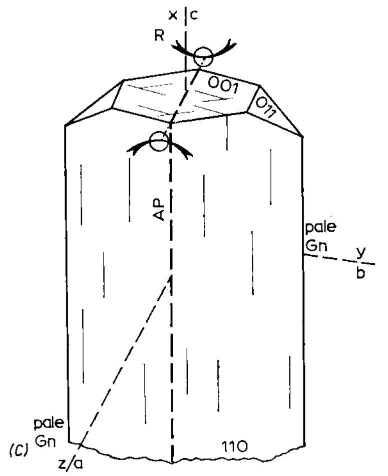


Fig.91. Andalusite.

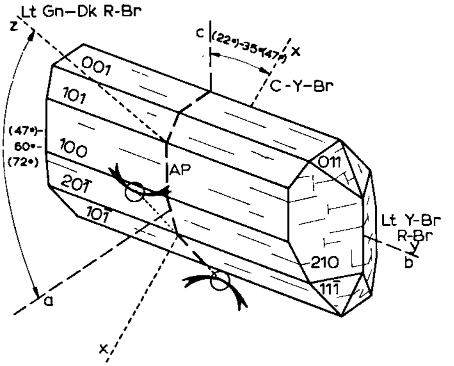


Fig.92. Allanite.

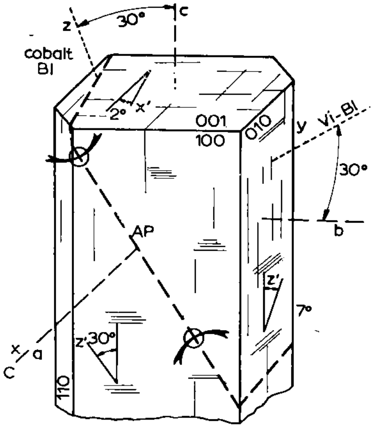


Fig.93. Kyanite.

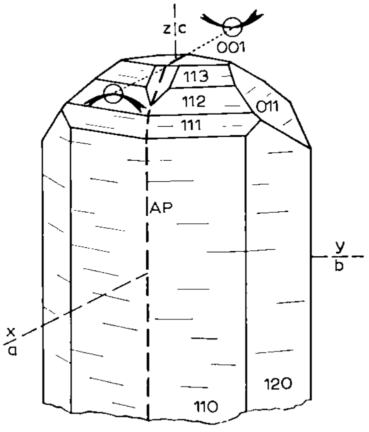


Fig.94. Topaz.

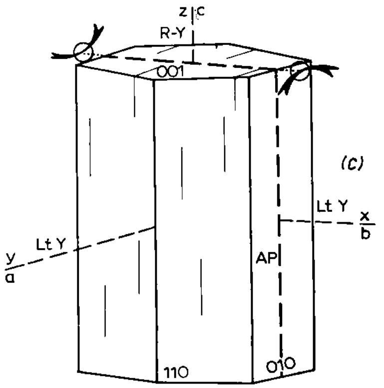


Fig.95. Staurolite.

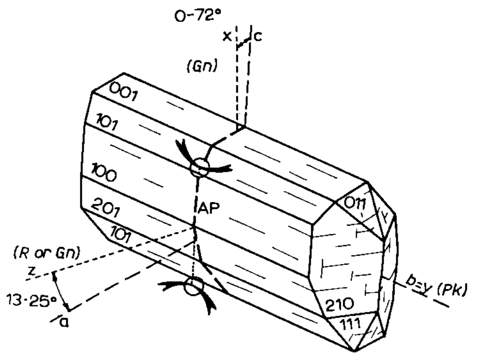


Fig.96. Clinozoisite.

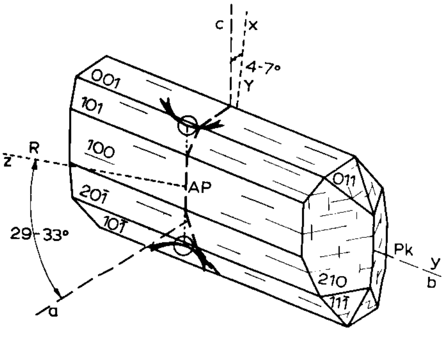


Fig.97. Piedmontite.

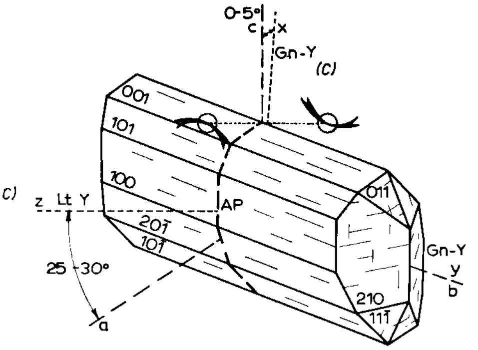


Fig.98. Epidote.

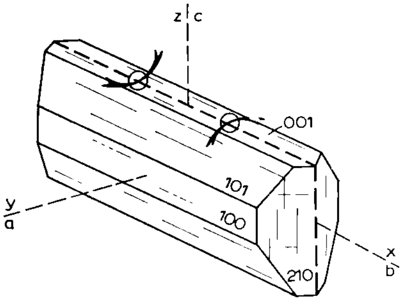


Fig.99. Zoisite.

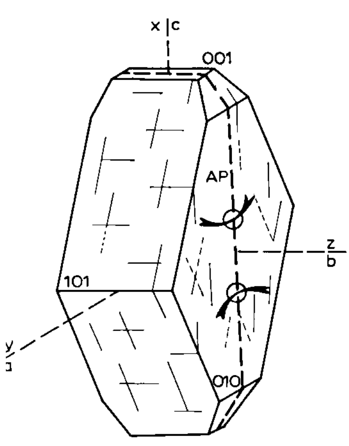


Fig.100. Lawsonite.

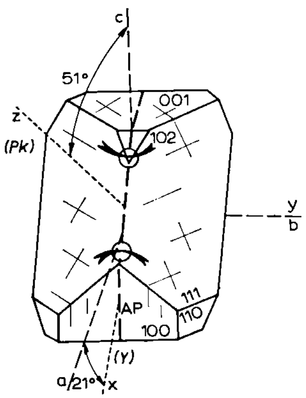


Fig.101. Sphene.

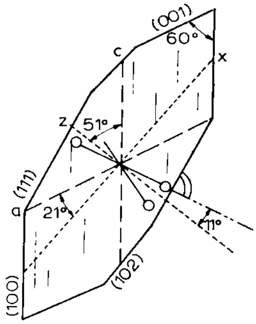


Fig.102. Sphene (cleaved).

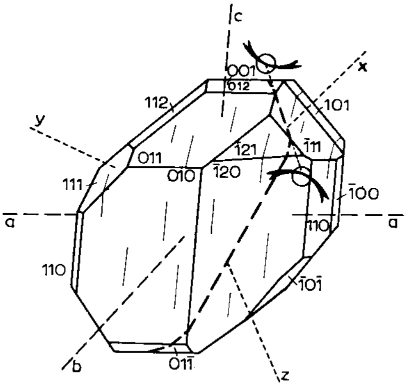


Fig.103. Axinite.

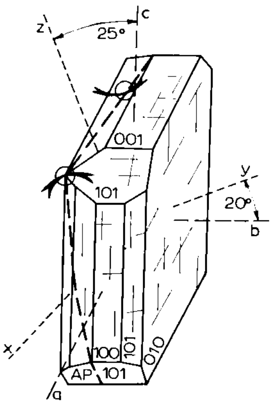


Fig.104. Rhodonite.

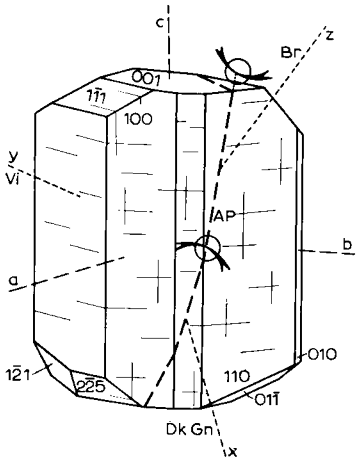


Fig.105. Babingtonite.

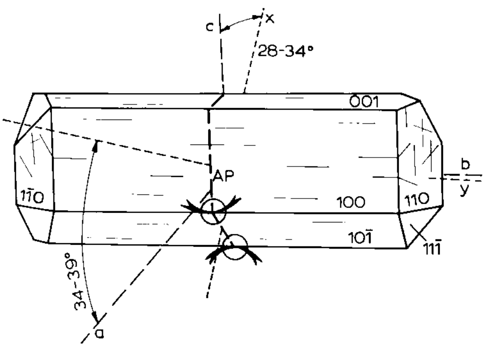


Fig.106. Wollastonite.

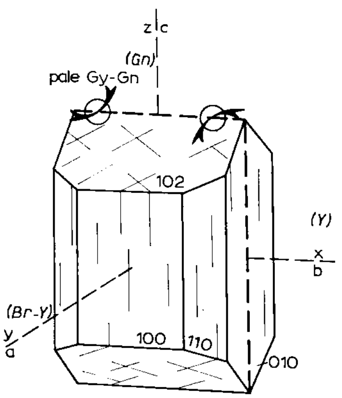


Fig.107. Enstatite.

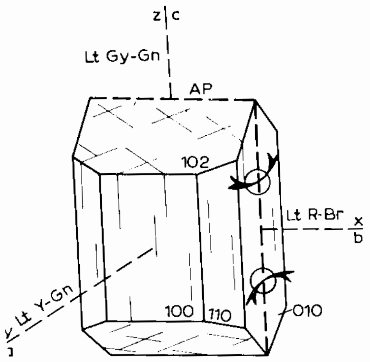


Fig.108. Hypersthene.

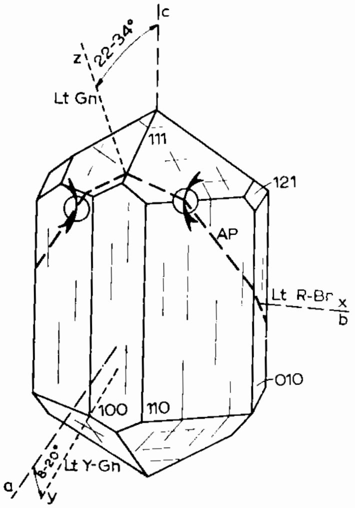


Fig.109. Clinopyroxene.

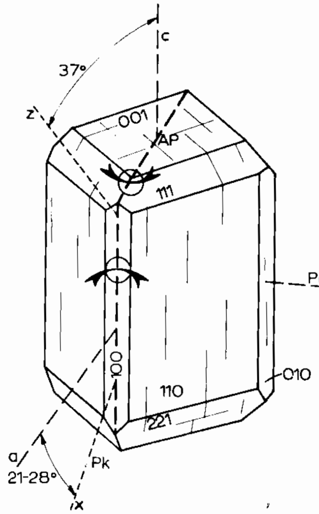


Fig.110. Pigeonite, Ca rich.

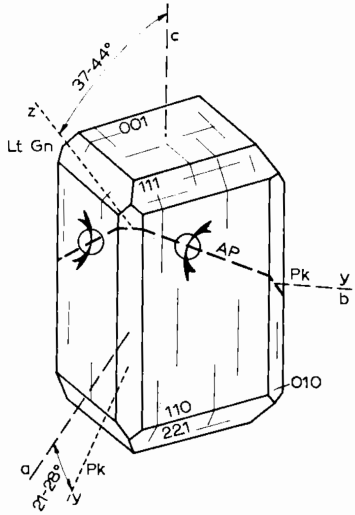


Fig.111. Pigeonite, Ca poor.

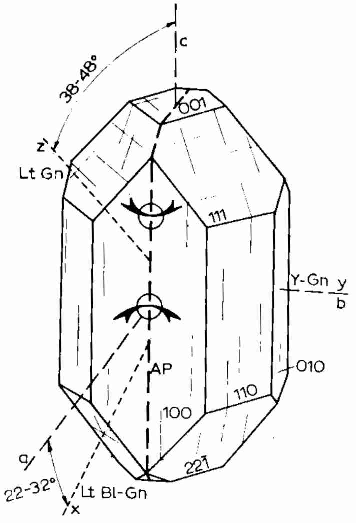


Fig.112. Diopside–Hedenbergite.

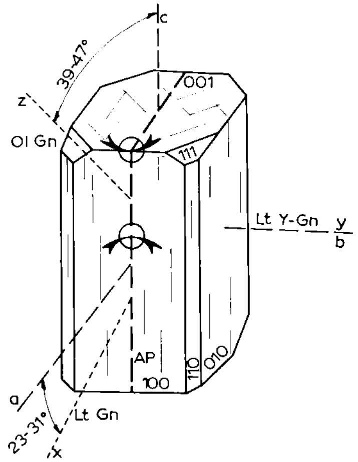


Fig.113. Augite.

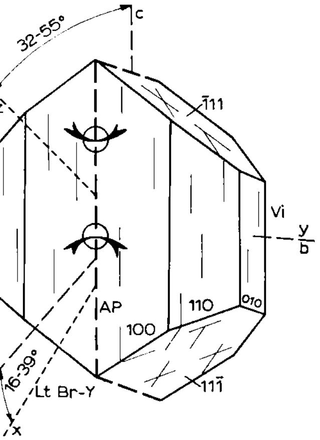


Fig.114. Titanaugite.

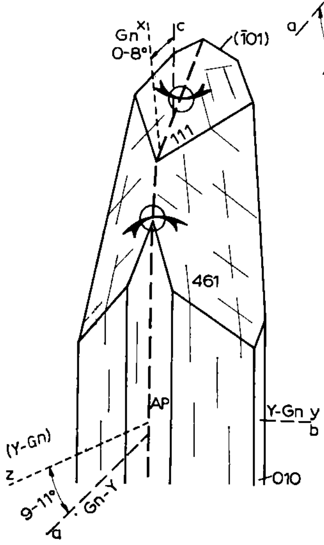


Fig.115. Aegirine.

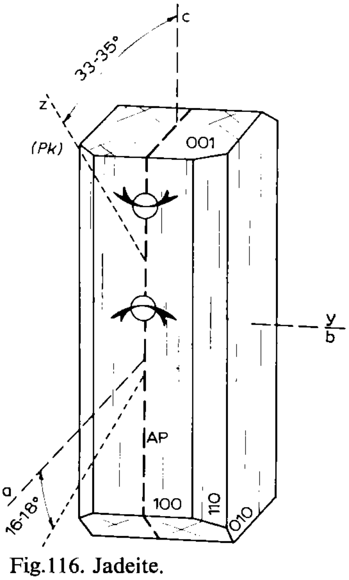


Fig.116. Jadeite.

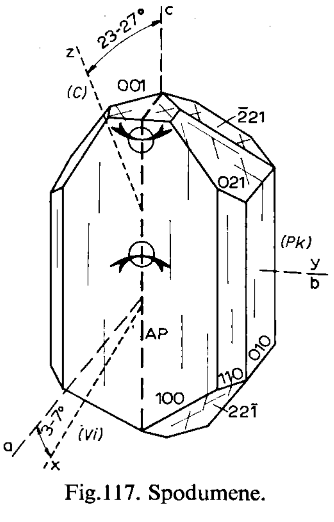


Fig.117. Spodumene.

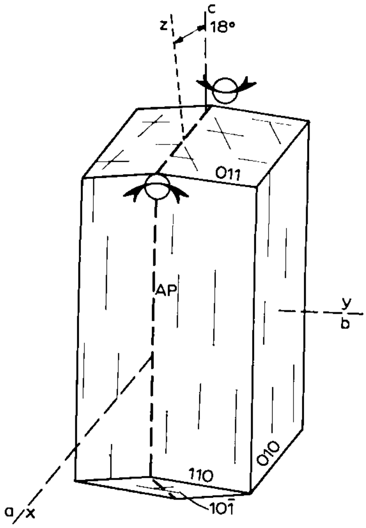


Fig.118. Cummingtonite.

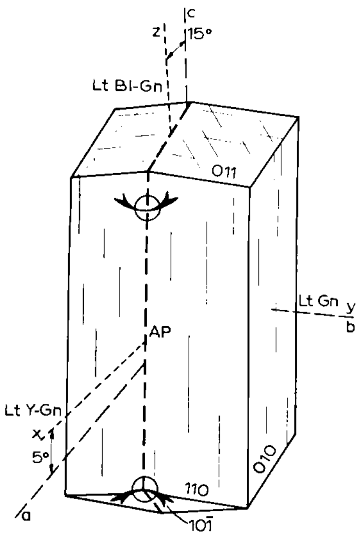


Fig.119. Actinolite.

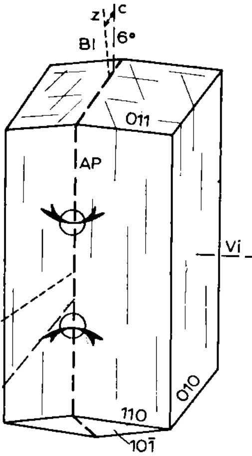


Fig.120. Glaucophane.

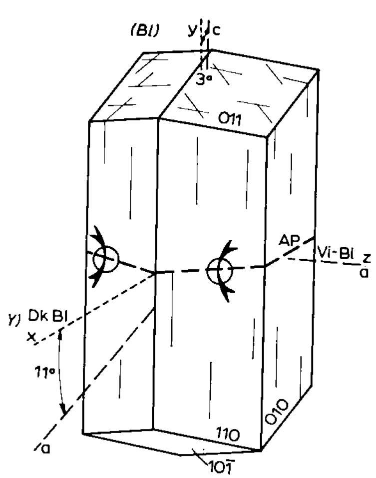


Fig.121. Crossite.

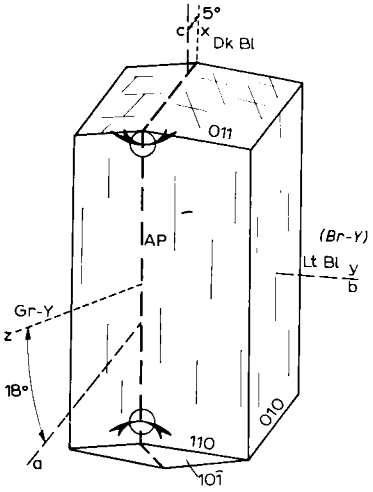


Fig.122. Riebeckite.

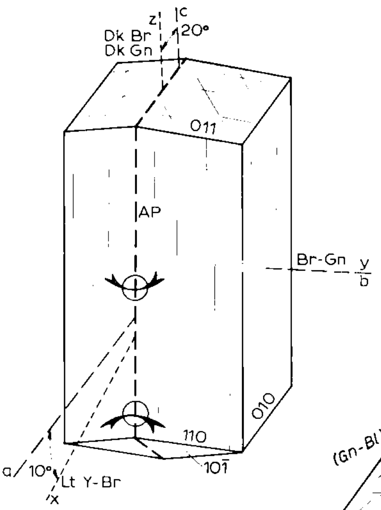


Fig. 123. Barkevikite–Hastingsite.

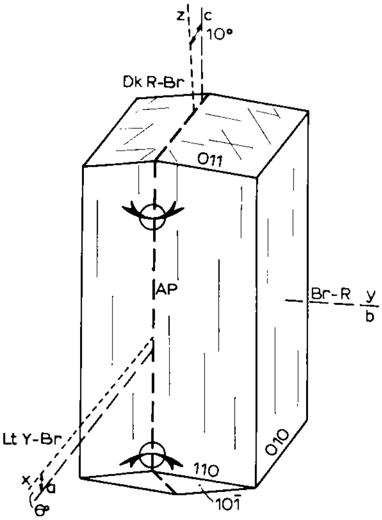


Fig. 124. Titanhornblende.

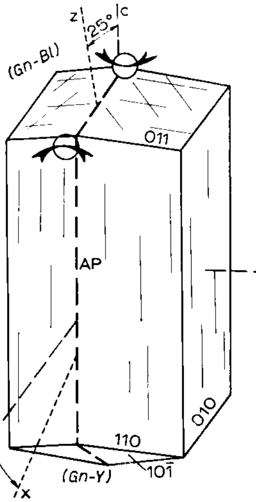


Fig. 125. Pargasite.

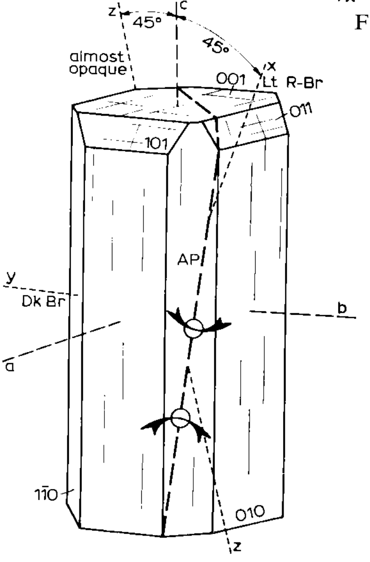


Fig. 126. Enigmatite.

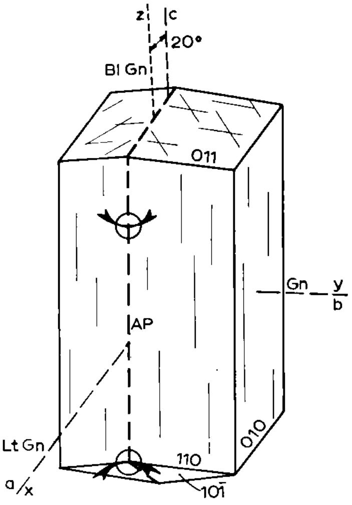


Fig. 127. Hornblende.

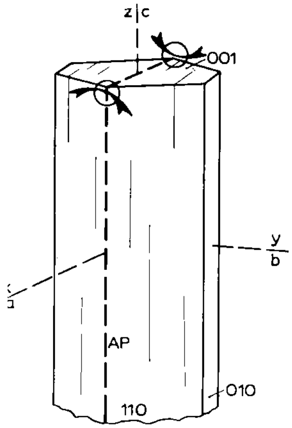


Fig.128. Sillimanite.

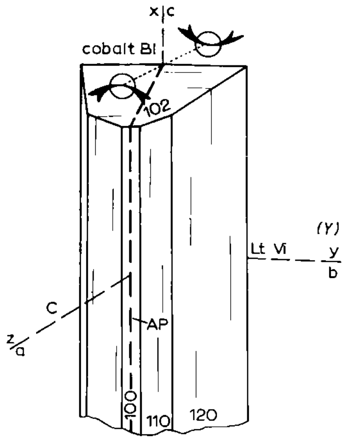


Fig.129. Dumortierite.

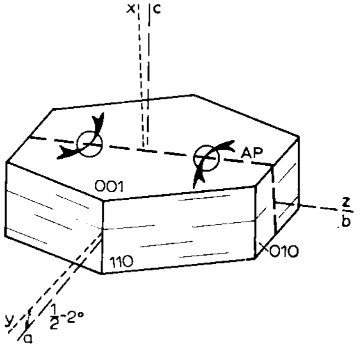
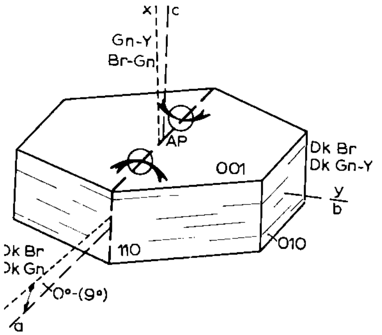


Fig.130. Muscovite.



ig.131. Biotite.

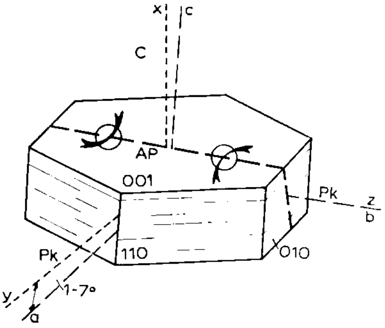


Fig.132. Lepidolite.

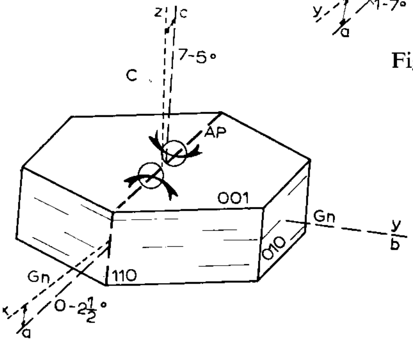


Fig.133. Clinochlore.

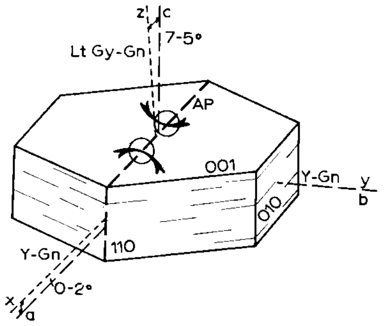


Fig.134. Prochlorite.

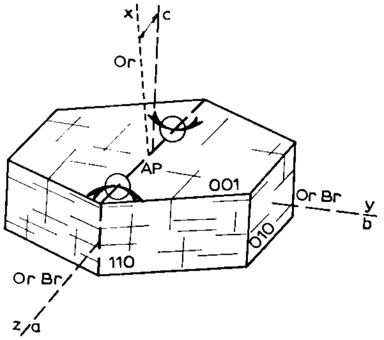


Fig.135. Iddingsite.

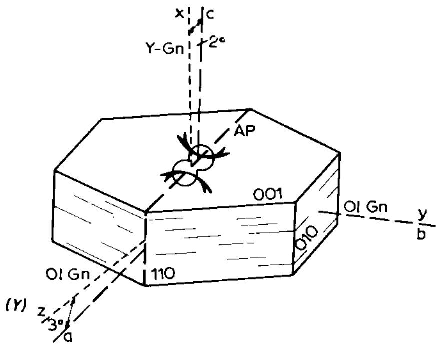


Fig.136. Glauconite.

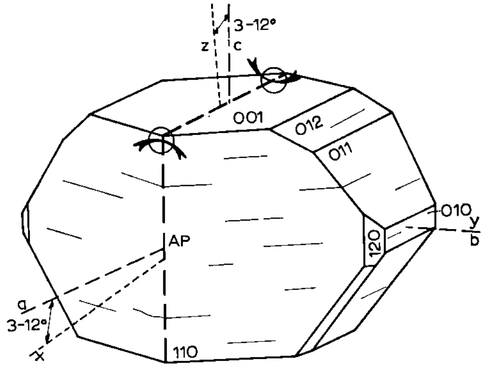


Fig.137. Gadolinite.

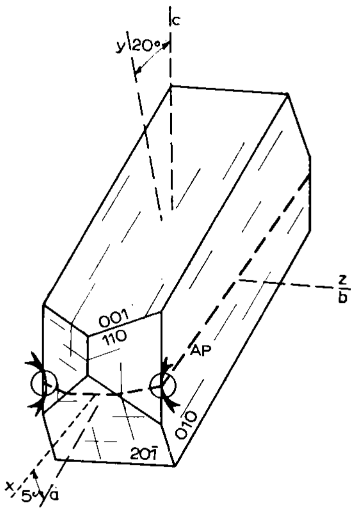


Fig.138. Orthoclase.

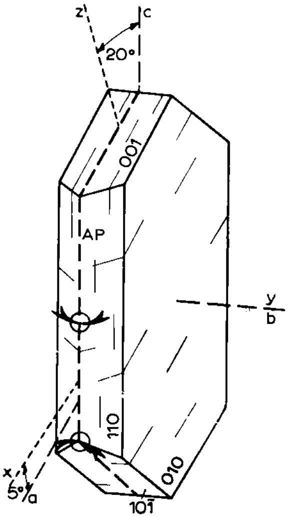


Fig.139. Sanidine.

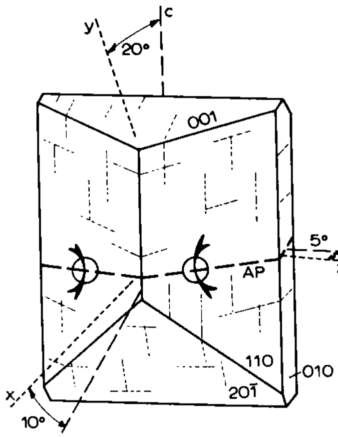


Fig. 140. Anorthoclase.

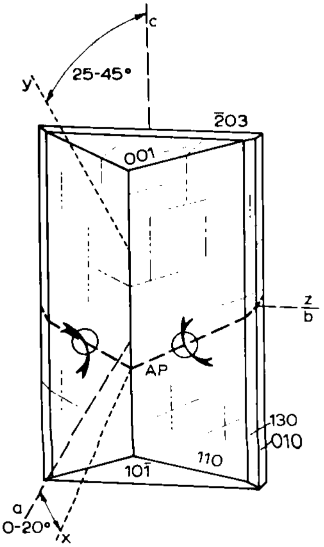


Fig. 141. Hyalophane.

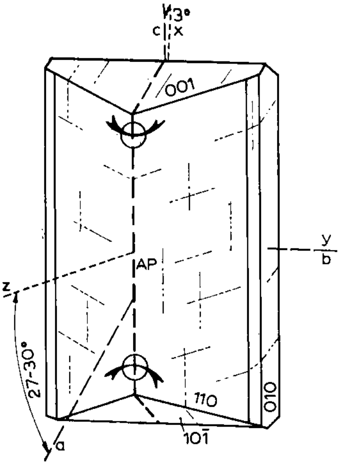


Fig. 142. Celsian.

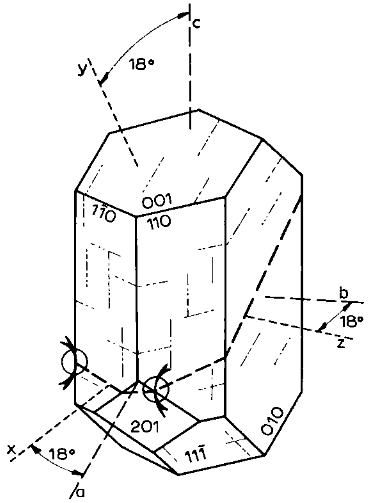


Fig. 143. Microcline.

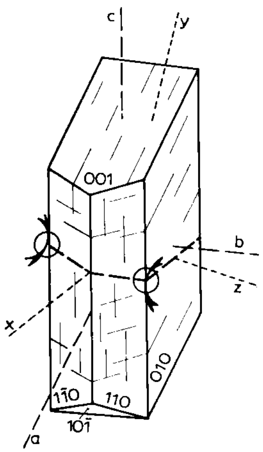


Fig. 144. Albite.

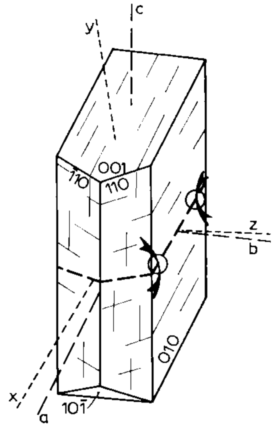


Fig.145. Oligoclase.

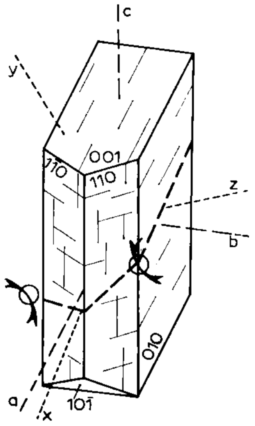


Fig.146. Andesine.

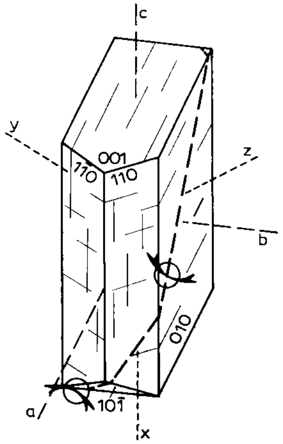


Fig.147. Labradorite.

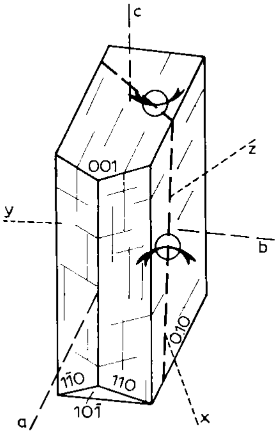


Fig.148. Bytownite.

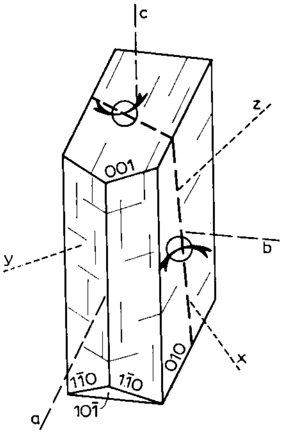


Fig.149. Anorthite.

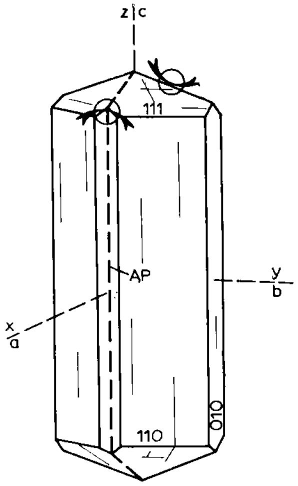


Fig.150. Natrolite.

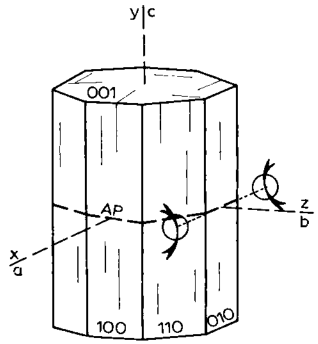


Fig.151. Thomsonite.

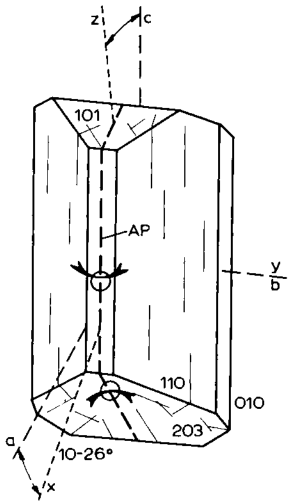


Fig.152. Laumontite.

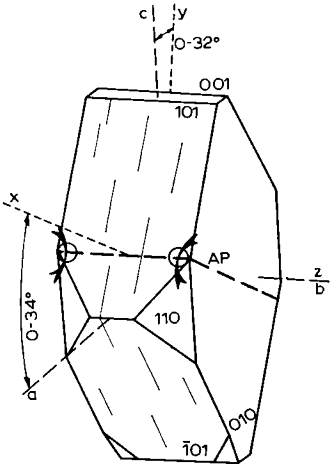


Fig.153. Heulandite.

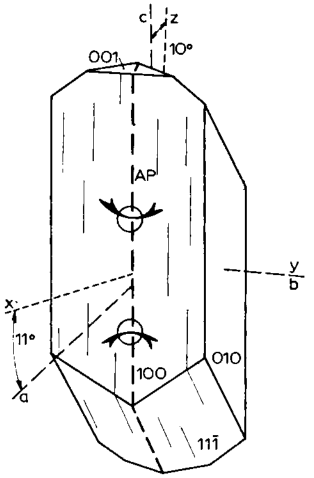


Fig.154. Epistilbite.

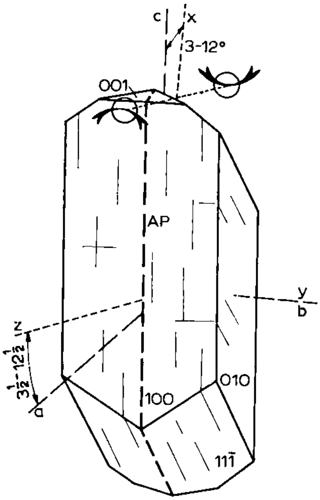


Fig.155. Stilbite.

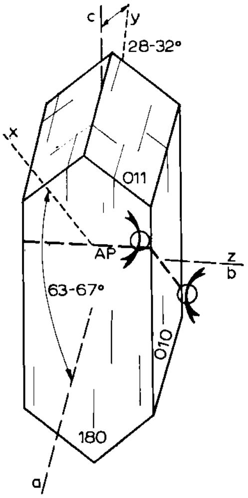


Fig.156. Harmotome.

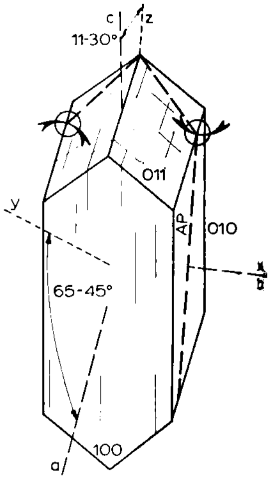


Fig.157. Phillipsite.

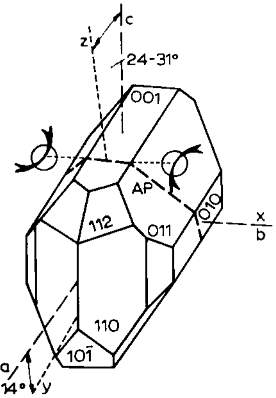
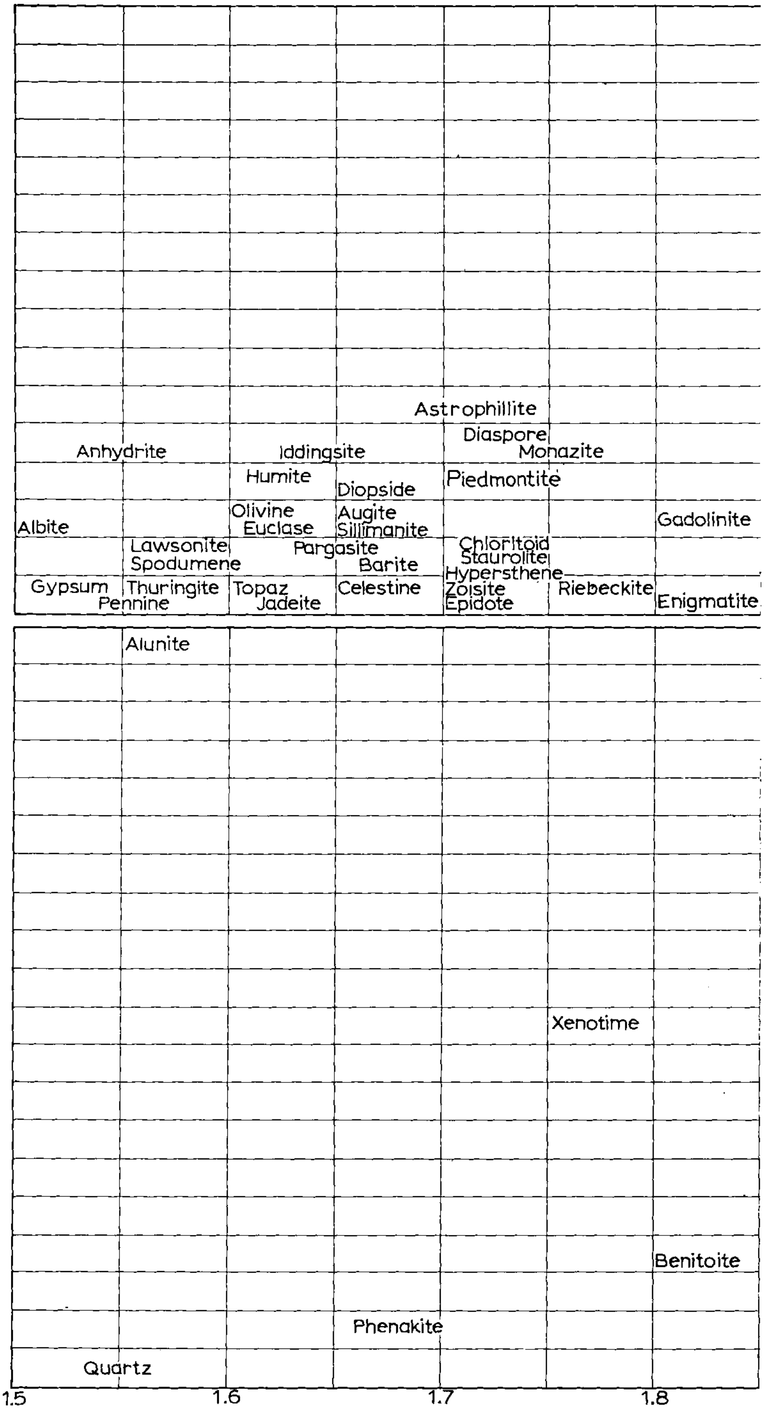


Fig.158. Whewellite.

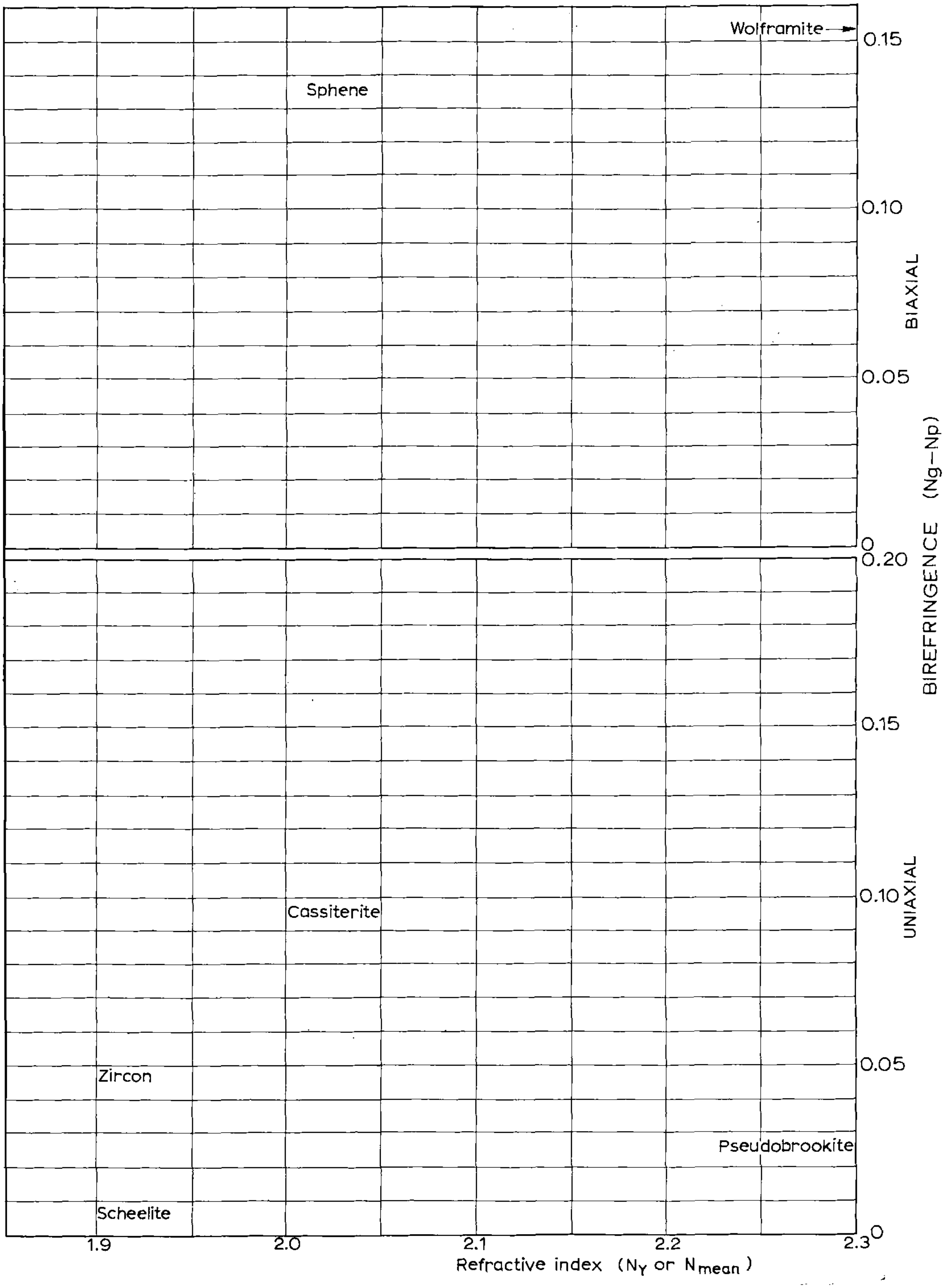
APPENDIX III

OPTICAL PROPERTIES OF SOME POSITIVE (+) ROCK MINERALS



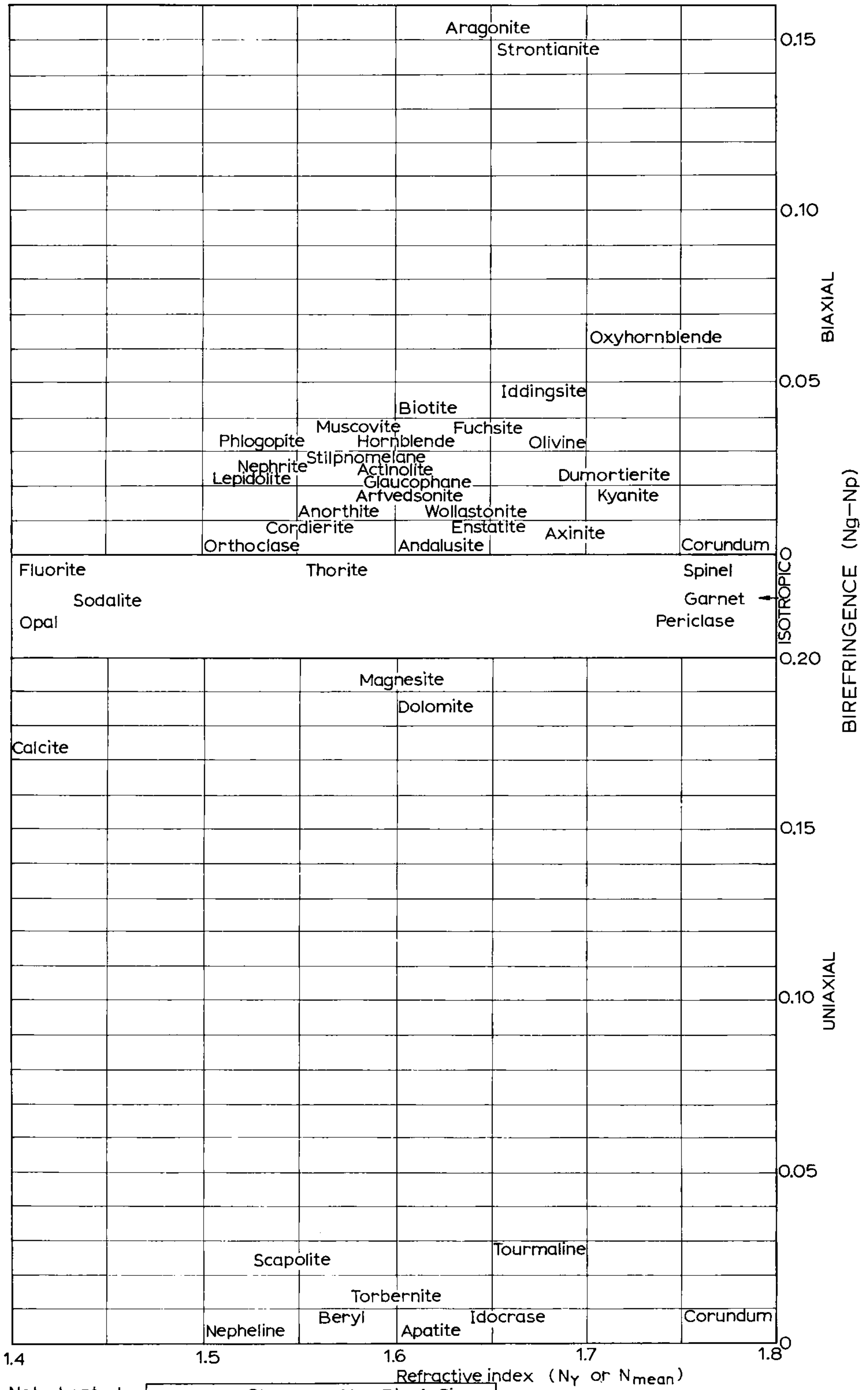
Not charted:

	Class	N	Biref.	Sign
Sulphur	Biaxial	2.3	0.29	(+)
Rutile	Uniaxial	2.7	0.28	(+)
Perovskite	Isometric	2.4		
Sphalerite	Isometric	2.4		
Brookite	Biaxial	2.6	0.12	(+)


Wolframite
Sphene
Cassiterite
Zircon
Pseudobrookite
Scheelite
0.15
0.10
0.05
0
0.20
0.15
0.10
0.05
0
BIAXIAL
UNIAXIAL
BIREFRINGENCE (Ng−Np)
1.9
2.0
2.1
2.2
2.3
Refractive index (N$_Y$ or N$_{mean}$)

APPENDIX IV

OPTICAL PROPERTIES OF SOME NEGATIVE (—) ROCK MINERALS



Not charted:

	Class	N	Biref.	Sign
Anatase	Uniaxial	2.5	0.07	(−)

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INDEX[1]

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[1] Numbers given in brackets indicate a orientation-cleavage crystal drawing of the mentioned mineral.