OKLAHOMA GEOLOGICAL SURVEY
Chas. N. Gould, Director

BULLETIN No. 31

CRITERIA FOR THE RECOGNITION OF HEAVY MINERALS OCCURRING IN THE MID-CONTINENT FIELD

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NORMAN
DECEMBER, 1925

CONTENTS

CRITERIA FOR THE RECOGNITION OF HEAVY MINERALS OCCURRING IN THE MID-CONTINENT FIELD[1]

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ABSTRACT

This paper is in three divisions. First, a very brief resume' of methods used in the preparation of loose sediments for petrographic study; second, the procedure followed in the identification of mineral grains, with a summary giving actual notations, on a grain, in the order of their determination; third, tables for the recognition of heavy minerals occurring in the Mid-Continent field, preceded by some general remarks about the heavy residue minerals present. This is followed by petrographic descriptions for each mineral, of the optical properties that can be determined from a microscopic examination of loose and mounted grains, and that can be used as diagnostic criteria for the identification of any given grain.

INTRODUCTION

The science of petography has been based until very recently on the study of thin sections, and the student of petography has been taught methods of identifying minerals as they appear in thin sections. But when he is confronted by his first slide of heavy minerals he is bewildered by a multitude of unfamiliar grains. Many of the criteria used in the identification of minerals in thin sections are not applicable to individual grains. For example, the interference color of a mineral grain is different from that of the same mineral in a thin section, and the rules of mineral association in igneous rocks do not apply to the component grains of a sedimentary rock.[1]

Most textbooks on petrography are also based on the study of thin sections, and no one contains all the criteria that can be applied to the identification of heavy mineral grains. Three or four books must frequently be consulted. This is cumbersome and tedious, and in order to facilitate research, the following

[1]In this connection, I quote the following paragraph of a letter from A. N. Winchell to the writer:

"Slides of heavy residues are unlike thin sections of igneous rocks in a very important way, with which you are doubtless quite familiar. I refer to the fact that a study of an igneous rock section can proceed much more rapidly because after identifying a single crystal all other crystals of the same kind can be recognized almost at a glance. Furthermore, the total number of minerals sufficiently abundant to be of any importance in an igneous rock slide is usually very small. On the other hand, in these heavy residue slides on account of the greater variations in the thickness of grains, it is much more difficult to recognize other grains of the same mineral, and so it becomes necessary to study several grains, at least, of a single mineral, in detail. And also, the number of different kinds of minerals of significance and importance is likely to be considerably greater than in the igneous rock slides."

tables were compiled. These tables are not intended as complete mineralogical descriptions, but rather as a ready compilation of the characteristics that can be told by a microscopic examination of loose and mounted grains and that can be used as diagnostic criteria for their identification.

The study of mineral grains has been demonstrated to be of great value, both to stratigraphers and to petroleum geologists. There are still many difficulties to be overcome, as in any new field of endeavor, and these, perhaps have been unduly emphasized in recent papers, or have been experienced to a discouraging degree by many people. But he who devotes time and serious study to the subject will find himself repaid many fold. In order to encourage those who wish to take up the study of residal heavy mineral grains, and to give them such benefit as may be derived from this research, the present paper is presented.

ACKNOWLEDGMENTS

The writer wishes to acknowledge her indebtedness to Dr. Clarence S. Ross, of the U. S. Geological Survey, who has very kindly checked this manuscript.

I.

BRIEF DESCRIPTION OF THE METHODS USED IN THE PREPARATION OF SEDIMENTS FOR PETROGRAPHIC STUDY

The methods used in heavy mineral investigations are described in detail elsewhere.[1] In order to enable the reader to follow the discussion more readily, however, a brief summary of the technique that has been used will be given here. The methods are equally applicable to outcrop samples or those obtained from drill holes.

If the rock is consolidated, it is crushed (not ground) in a deep iron mortar. Frequent screening (through a *clean* screen of medium grade) prevents undue crushing of the finer particles. If a quantitive measurement of soluble matter is desired, the sample is weighed, after which it is put in a pyrex beaker and boiled about half an hour in a 50 percent solution of HCl, which removes the carbonates and most of the iron oxide. The acid is washed out thoroughly, the water poured off (after a reasonable amount of time to allow for settling has elapsed) and the sample dried, still in the beaker. By subtracting its weight at this stage from the previous weight, "loss on boiling," or "loss," is determined. The sample should now be clean and white.

Separation of the heavy minerals from the light ones, is

[1]Cayeux, L., L'Etude Petrographique des Roches Sedimentaries Paris, 1916, I. Texte; II. Atlas.

Reed, R. D., Some Methods for Heavy Mineral Investigation, Economic Geology, Vol. XIX, No. 4, June-July, 1924.

made in a lilted evaporating dish, about six inches in diameter by the use of bromoform (sp. gr. 2.9) which allows quartz, feldspar, muscovite, calcite, etc. to float, and the "heavy minerals" to sink. The light grains are poured off onto filter paper, after which the heavy concentrate is washed with benzol onto a second filter paper. The grains are dried and are now ready for study and mounting.

A temporary mount for preliminary study of either the light or heavy minerals, can be made by placing the grains in a drop of clove oil (or methylene iodide, or bromoform, or monochlornapthalene) on a glass slide. If the "crop" of heavy minerals is small, so that it is desirable to save grains used in this way, they can be washed with a little xylol from the glass slide into a filter paper and dried by evaporation, when they become available for permanent mounting. In a research problem it has been found desirable to make permanent mounts of all grains studied, as it frequently is necessary to have them for comparison.

Permanent mounts are made in Canada balsam. Good ones are made only after considerable practice. The glass slides to be used for mounting must be very clean, so that a drop of distilled water will form a thin film. The grains are placed in this water, which is then slowly dried, leaving the minerals to be studied evenly and firmly attached to the slide. Balsam is squeezed from the tube onto the grains, and the slide heated very slowly. Bubbles which come to the center of the balsam can be skimmed off with the point of a mounted needle. When the balsam has been cooked until it is brittle, the slide is removed from the hot-plate, placed on a cold iron plate or block, and the cover glass attached on one side. The slide is next put back on the hot-plate, and as the balsam warms, the cover glass settles gradually, forcing the air out ahead of it. When balsam begins to come out around all the edges of the cover glass, the slide is removed, the cover glass pressed down firmly, and the whole allowed to cool. Excess balsam is removed with a knife, after which the slide is cleaned with xylol. The slide is now complete and ready to study or file away.

II.

PROCEDURE FOLLOWED IN THE IDENTIFICATION OF MINERAL GRAINS

A definite order of procedure is more or less necessary in determining what mineral constitutes a given detrital grain. If a grain comes into view which is not recognized at once, the color, pleochroism, relief, extinction angle and birefringence are noted practically at a glance. Next an attempt is made to obtain an interference figure. These can be obtained from mineral grains much more frequently than ones experience with thin sections would indicate. The figures may not be perfect, but usually the uniaxial or biaxial, positive or negative, character can be told. With the information now at hand, the worker next turns to the reference books.

The most suggestive reference at this point is Johannsen's Tables.[1] There may be only one mineral in these tables that has the characteristics of the one under investigation, thus giving reasonably certain identification. Often none, or several minerals will be suggested by the tables, in which case it becomes necessary first, to find out more about the unknown mineral; second, to supplement the tables or to investigate the more detailed characteristics of each mineral suggested by consulting other texts.

Several aids help one to find out more about the unknown mineral. One such aid is a marked set of mounted fragments of the minerals occurring most frequently as resistant detrital grains. A set of this sort should be available in the laboratory, as it is most useful for comparing the unknown with known fragments of the suggested mineral or minerals.[2]

Orientation-cleavage diagrams are invaluable aids in the identification of mineral grains, as suggested by Reed.[3] The preparation of a set of such diagrams is a great help in fixing the properties of the various minerals in the mind of the student. Later the diagrams will prove a valuable reference in the laboratory.

If there is still considerable doubt as to the identity of the grain being studied, its index or indices of refraction can be determined by the use of a set of immersion fluids. Although most of the heavy minerals have indices greater than balsam, the laboratory set of liquids should run from 1.40 to 1.80.

The student has now listed most of the optical properties of the mineral he is studying. If Johannsen's tables suggest several minerals with properties similar to the one under investigation, the detailed characteristics of each of the suggested minerals will

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[1]Johannsen, Albert, Essentials for the Microscopic Determination of Rock Forming Minerals and Rocks. Chicago, 1922.

[2]This list should include the following heavy minerals: anatase, andalusite, anhydrite, apatite, aragonite, augite, barite, biotite, brookite, chlorite, corundum, cyanite, eudialyte, eucolite, epidote, fluorite, garnet, glaucophane, hornblende, hypersthene, monazite, muscovite, olivine, rutile, sillimonite, spinel, staurolite, topaz, tourmaline, titanito, xenotime, wollostonite, zircon. It should further include, of the light minerals: albite, alunite, anorthite, brucite, calcite, cordierite, dolomite, glauconite, gypsum, labradorite, orthoclase, quartz.

[3]Reed, R. D. Some Methods for Heavy Mineral Investigations. Economic Geology, Vol. XIX, No. 4, June-July, 1924. p. 334.

be found by consulting other texts. By comparing these descriptions with the properties of his unknown mineral, the student is able (by elimination) to identify any given detrital grain.[1]

For correlative purposes, in which time is an element, it is not always necessary to give a name to a mineral immediately. Enough optical properties can be determined to enable the worker to recognize a given grain as the same mineral in each slide, and it can be given a number or a letter for reference, which will serve temporarily as well as a specific name.

SUMMARY

To summarize, actual notations on an unknown grain will be given in the order of their determination:

Colorless, prismatic grains with beveled edges.

Extinction parallel.

Relief high, and changes on rotation of stage.

Birefringence high. Colors almost as high as calcite.

Cleavage good in three directions, at right angles.

Elongation negative.

Specific gravity such that it occurs in both light and heavy bromoform concentrates.

Grains do not give good interference figures. They look like obtuse bisectrix figures.

Two grains gave figures at right angles to an optic axis.

These figures were biaxial positive, optic angle less than 45°. The interference figures had colored rings close together. (cf. calcite).

Both indices of refraction less than 1.68; less than 1.62.

Both indices of refraction greater than 1.57.

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[1]References:

Johannsen, A., op. cit. and Manual of Petrographic Methods," 2nd ed. N. Y., 1918.

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Larsen, E. S., The Miscroscopic Determination of Non-Opaque Minerals, U. S. Geol. Surv. Bull. 679, 1921.

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Alpha is parallel to long dimension of grain; greater than 1.57, less than 1.58.

Gamma is parallel to short dimension of grain; greater than 1.61, less than 1.62.

Gamma minus alpha is 0.03 ±.

The mineral is anhydrite.

III.

TABLES FOR THE RECOGNITION OF HEAVY MINERALS OCCURRING IN THE MID-CONTINENT FIELD

THE MID-CONTINENT MINERALS

It will no doubt surprise many readers to see how many minerals are listed in the following tables as occurring in Mid-Continent sands. Zircon is the most abundant mineral, tourmaline next, followed by barite, topaz, rutile, garnet, anatase, epidote, titanite, staurolite, cyanite, in the order named. The other minerals occur only rarely. One slide seldom has as many as ten different minerals, and the relative abundance of the component minerals varies at different horizons. Practically all of the Mid-Continent grains are very much worn, and the easily destroyed minerals such as the amphiboles and pyroxenes, are conspicuous by their almost total absence. This is a marked contrast to the grains in the California Tertiary sediments, where pyroxenes and amphiboles generally predominate, and where the grains are much more nearly euhedral.

The tables herewith presented were prepared during a study of the Simpson and Wilcox sands. A few minerals occurring in the Pennsylvanian sands have been added, as well as xenotime, which has not been seen in the Mid-Continent sands, but is described by Gilligan.[1]

Reed lists "colorless pyroxene" and "basaltic hornblende" in his most recent paper,[2] but without having seen them, the writer has not attempted to describe them. It is hoped that other students of sedimentary petrography will add to this list.

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[1]Gilligan, Albert, The Yorkshire Millstone Grit., Quarterly Journal of the Geological Society, LXXV, 1919-1920.

[2]Reed, R. D., Role of Heavy Minerals in the California Territory Formations, Econ. Geol. Vol. XIX, No. 8, December, 1924.

MINERALS ARRANGED IN CRYSTAL SYSTEMS

ISOMETRIC

HEXAGONAL RHOMBOHEDRAL

MONOCLINIC

TETRAGONAL

ORTHORHOMBIC

TRICLINIC

KEY TO HEAVY MINERAL TABLES

THE MINERAL IS OPAQUE

PYRITE Isometric. Cleavage very rarely, if ever, observed, indistinct parallel to *(100)* and *(111)*. Distinguished primarily by its brass-yellow color in reflected light, and euhedral crystals which often have striations on their faces. Non-magnetic. Because of its euhedral form in the midst of harder, but worn, grains, believed to have developed *in situ* in these sediments.

MAGNETITE Isometric. Iron-black color in reflected light. Occurs as octahedrons, cubes, or irregular grains. Derived from basic or ultra basic rocks.

ILMENITE Rhombohedral. Cleavage parallel to *(0001)*. Iron-black color in reflected light. Crystals usually thick tabular or hexagonal plates or grains, and when partially altered to leucoxene, may be distinguished from magnetite. Derived from basic and ultra basic igneous rocks. Not common in these sediments but believed to have been originally present, from the frequent occurrence of secondary anatase.

THE MINERAL IS ISOTROPIC

GARNET Isometric. No cleavage, but irregular fracture. The commonest garnet in these sediments is colorless, rough, and pitted, and the next frequent, pink; in one sample was green garnet (uvarovite). Relief so high the grains have a decided black rim around them. Index (1.7) higher than balsam. Grains are worn and seldom, if ever, show crystal faces. Derived from igneous and metamorphic rocks, particularly crystalline schists and gneisses.

FLUORITE Isometric. Habit cubic. Perfect octahedral cleavage, giving triangular fragments. Colorless. Low relief. Index (1.434) less than balsam. Derived from salic igneous rocks, metamorphic rocks, and limestones.

SPINEL Isometric. Has poor *(111)* cleavage and fracture irregular. Coffee brown color. Relief very high. Index (1.71) greater than balsam. Occurs usually in quadratic sections. Variety picotite. Derived from metamorphosed limestone, crystalline schist, and dolomitic limestone.

THE MINERAL IS ANISTROPIC, COLORLESS, UNIAXIAL, NEGATIVE

EUCOLITE, see Eudialyte. Hexagonal. Cleavage distinct parallel to *(0001)*. Extinction parallel. Colorless. Relief and birefringence about like apatite, and positive elongation. Eucolite and apatite are both uniaxial negative, but eucolite has positive elongation. Eucolite is a rare mineral associated with soda minerals in Greenland, Norway, and Arkansas.

APATITE Hexagonal. Crystals usually elongated and showing parting. Cleavage in traces parallel to *(0001)*. Fracture conchoidal. Extinction parallel. Colorless, sometimes blue. Relief moderate and index higher than balsam. Alpha=1.634, gamma=1.638. Birefringence weak, 0.004 (low first order colors). Elongation negative. Optically uniaxial negative. Derived from igneous rocks, especially granites and syenites.

CORUNDUM Hexagonal (scalenohedral class). Cleavage absent but rhombohedral parting greatly resembles cubic cleavage. Fracture conchoidal. Extinction parallel. Colorless. Relief very high and index greater than methylene iodide. Alpha=1.760, gamma=1.769. Birefringence weak (0.009) with first order colors. Elongation negative. Optically uniaxial negative. Grains usually worn so that original crystal form has been obliterated. Derived from igneous or metamorphic rocks, especially contact metamorphosed limestones.

THE MINERAL IS ANISTROPIC, COLORLESS, UNIAXIAL, POSITIVE

EUDIALYTE, see Eucolite. Hexagonal Crystals of varied habits. Cleavage distinct parallel to *(0001)*, indistinct parallel to *(11$\bar{2}$0)*. Extinction parallel. Colorless. Relief moderate, alpha=1.606, gamma=1.611. Birefringence weak, 0.005. Elongation negative. Ramsay considers that eudialyte and eucolite form an isomorphous series, with eudialyte, uniaxial positive, negative elongation at one end, and eucolite, uniaxial negative, positive elongation at the other end. Eudialyte is associated with sodalite, nepheline, acmite and other soda minerals, and is rare.

ZIRCON Tetragonal. Habit euhedral; prismatic; bipyramidal. Sometimes prisms elongated in the direction of the principal axis. Cleavage imperfect parallel to *(110)*, poor parallel to *(111)*. Fracture conchoidal. Extinction parallel. Generally colorless; sometimes brown, purple or pink. Relief higher than garnet, giving the grains a broader black border than that around garnets. Alpha=1.931, gamma=1.993. Birefringence high, giving irridescent, high order interference colors, sometimes causing the grains to appear silvery. Elongation positive. Optically uniaxial positive. Interference figures have many colored rings, close together. Zircon is the commonest heavy mineral in Mid-Continent sediments. The grains generally are very much worn and well rounded; only occasionally do euhedral zircons occur, and when they do, they are always much smaller than the rounded ones. Inclusions are common, and may be fluid, glassy, negative crystals, or consist of minerals such as apatite and possibly xenotime. Inclusions are sometimes arranged symmetrically; at other times they are irregularly distributed, and may be so crowded together as to give the grains a dusky appearance. Possible sources of derivation: Salic and intermediate igneous rocks; less commonly crystalline schists and limestones.

THE MINERAL IS ANISOTROPIC, COLORED, UNIAXIAL, NEGATIVE

EUCOLITE. Described under colorless, uniaxial, negative.

APATITE. Described under colorless, uniaxial, negative.

CORUNDUM. Described under colorless, uniaxial, negative. Colored corundum is sometimes pleochroic. Non-pleochroic pink corundum grains occasionally occur in these sediments.

TOURMALINE Hexagonal (rhombohedral). Crystals usually prismatic more or less elongated. Vertical faces often deeply striated vertically. Cleavage difficult parallel to *(11$\bar{2}$0)* and *(10$\bar{1}$0)*. Basal parting. Extinction parallel. Strongly pleochroic. Maximum absorption occurs when the longer dimension of the grain is perpendicular to the vibration plane of the lower nicol. Color ranges from white, through blue, pink, yellow, brown (most common), green, black. Inclusions very common. Relief great enough to give the grains a black outline when mounted in balsam. Alpha=1.642, gamma=1.687. Birefringence moderate. Elongation negative. Optically uniaxial negative. Prismatic grains do not give good interference figures. Tourmaline grains in these sediments are, for the most part, very well rounded, some being sufficiently spherical to give a centered interference figure. A few prismatic grains occur, but these are never entirely unworn. Possible sources of derivation: pneumatolytic rocks, salic igneous rocks, pegmatites, schists, gneisses, phyllites, limestones and marbles.

BIOTITE Monoclinic. Habit tabular with perfect basal cleavage and uneven fracture. Extinction parallel. Color dark green, brown to brownish black, also red-brown with the "bird's-eye maple" appearance characteristic of all micas. Pleochroism marked, maximum absorption parallel to the vibration plane of the lower nicol (in this respect, biotite is just the opposite of tourmaline). Inclusions of zircon, etc. with pleochroic halos around them common. Relief low, alpha=1.541, beta=1.574, gamma=1.574[1]. Birefringence high. Elongation positive. Biaxial negative, but optic angle small in certain varieties, giving pseudo-uniaxial figure. The plane of the optic axes is parallel to *(010)*. The negative acute bisectrix is very nearly normal to *(001)*, the cleavage. Cleavage flakes are almost dark between crossed nicols, and give a negative biaxial interference figure with a small axial angle (sometimes almost zero). Biotite is derived from igneous and metamorphic rocks.

ANATASE Tetragonal. Commonly octahedral in aspect; also tabular or prismatic. Cleavage distinct parallel to *(001)* and *(111)*. Extinction parallel. Basal sections isotropic. Color

[1]"Biotite ranges much higher in index than indicated in the books. Gamma may reach 1.73, and 1.67 is not rare." Clarence Ross, U. S. Geol. Survey, in a personal communication.

brown to black, indigo blue. Pleochroic in thick sections. Relief very high, alpha=2.489, gamma=2.562. Birefringence very strong. Elongation negative. Optically uniaxial negative. Anatase occurs in these sediments in only one form, that of square brown or blue tablets, transparent to opaque, which often contain many inclusions. The grains have high relief, with beveled black borders, are isotropic, or have lowest order interference colors. Milner says,[1] both primary and secondary grains are found, often in the same sample; the later are derived *in situ* from the decomposition of titaniferous minerals such as ilmenite, and usually show marked angularity. Since these anatase grains are always fresh and euhedral, in samples containing very much rounded tourmalines, zircons, garnets, etc., it is inferred that the anatase here is secondary.

THE MINERAL IS ANISOTROPIC, COLORED, UNIAXIAL, POSITIVE

EUDIALYTE. Described under colorless, uniaxial, positive.

ZIRCON. Described under colorless, uniaxial, positive. Larger grains may be slightly colored brownish or grayish, and be very faintly pleochroic. A deeply colored brown zircon, mounted in balsam, would probably be indistinguishable from rutile, if both grains were rounded, as they are characteristically in Mid-Continent sediments.

RUTILE Tetragonal. Habit prismatic, acicular. Sometimes twinned. Cleavage good parallel to *(110)* and *(100)*, occasionally parallel to *(111)*. Fracture subconchoidal. Extinction parallel. color deep reddish brown. Deeply colored varieties usually show weak pleochroism, with maximum absorption parallel to principal axis. Relief very high (higher than zircon). Alpha=2.616, gamma=2.903. Birefringence extremely strong. Elongation positive. Optically uniaxial positive, but grains rarely give good interference figures. Rutile grains in these sediments are generally worn and rounded as much as the zircon. Rutile can best be distinguished from zircon by color and relief. Grains of rutile may be confused with those of staurolite, but rutile is more deeply colored, has higher relief and higher birefringence than staurolite. Staurolite is biaxial. Rutile in sediments may have been derived from salic igneous rocks, or crystalline metamorphic rocks. It is frequently derived *in situ* from the decomposition of ilmenite. The rounded and worn aspect of rutile grains in the Mid-Continent sediments suggests that, in this case, they are detrital.

XENOTIME. See Milner, op. cit., p. 82.

[1]Loc. cit. p. 30.

THE MINERAL IS ANISOTROPIC, COLORLESS, BIAXIAL OPTIC AXIAL ANGLE (2V) LESS THAN 45°, NEGATIVE

WOLLASTONITE Monoclinic. Crystals are commonly tabular parallel to *(100)* or *(001)*, usually more or less elongated parallel to "b." Cleavage perfect parallel to *(100)*, less perfect parallel to *(001)*, sometimes distinct parallel to $(\bar{1}01)$, and also $(\bar{1}02)$. Angle between *(100)* and *(001)* cleavage traces is 84.5°. Extinction parallel. Color white, gray, rarely yellow or reddish. Relief high, alpha=1.619, beta=1.632, gamma=1.634. Birefringence low. Elongation positive or negative. Optically biaxial negative. 2V=40°. Inclined dispersion distinct. Axial plane parallel to *(010)*, and hence perpendicular to the elongation. The negative acute bisectrix is nearly perpendicular to $(\bar{1}01)$, and, in sections parallel to *(010)*, makes an angle of 32° with traces of *(100)* cleavage and an angle of 38° with the basal plane *(001)*. Since monoclinic minerals have parallel extinction in *(100)*, *(001)* and *(h0l)* sections, and wollastonite has cleavage in these three directions, the cleavage fragments will have parallel extinction. A fragment parallel to *(100)* will not give an interference figure. A fragment paralleel to *(001)* will give a figure nearly perpendicular to an optic axis. A fragment parallel to $(\bar{1}01)$ will give a figure which shows the emergence of the acute bisectrix a little to one side. Wollastonite has no cleavage parallel to *(010)*, so grains will not show maximum extinction angles unless they are worn and happen to lie in the slide with an *(010)* face uppermost. Grains of wollastonite may be confused with cyanite (both being colorless, biaxial, negative), but a grain of cyanite parallel to the cleavage is perpendicular to the acute bisectrix, gives an excellent interference figure, and has a 30° extinction angle. Cyanite has higher relief and a wider optic angle than wollastonite. Both minerals have about the same birefringence, but dispersion in cyanite is very weak. Wollastonite is always metamorphic in origin and results from the contact metamorphism of limestones.

ARAGONITE Orthorhombic. Crystals often acicular. Cleavage distinct parallel to *(010)*, in traces parallel to *(011)* and *(110)*. Extinction parallel. Colorless or white. Relief high, alpha=1.53, beta=1.682, gamma=1.686. Birefringence very strong, producing high order, irridescent interference colors. Elongation negative. Optically biaxial negative. 2V=18°. Interference figure has many bright colored rings close together. The plane of the optic axes is parallel to *(100)*. The negative acute bisectrix is normal to *(001)*. Fragments prismatic, and do not give good interference figures. Distinguished from calcite, dolomite, etc., by acicular form leading to usual absence of cleavage, parallel extinction, and biaxial character. Aragonite occurs in many igneous and metamorphic rocks as an alteration product, probably usually due to the action of hot solutions. Occurs also in gypsum deposits, occasionally in vesicles in basalt, and as the material of certain fossil shells and corals. Since aragonite is soluble in hydrochloric acid, it should not be present in heavy mineral concentrates.[1]

THE MINERAL IS ANISOTROPIC, COLORLESS, BIAXIAL, 2V LESS THAN 45°, POSITIVE

BARITE Orthorhombic. Crystals often tabular parallel to *(001)*, or prismatic, with basal plane strongly developed. Cleavage perfect parallel to *(001)* and *(110)*, imperfect parallel to *(010)*. Prismatic grains give straight extinction; diamond shaped cleavage grains have symmetrical extinction. Colorless to white, gray, red, brown. Relief high. Alpha (parallel to *"c"*) =1.636, beta=1.637, gamma (parallel to *"a"*) =1.647. Birefringence low. Interference colors or rhombic fragments bright, on basal fragments first order. Elongation positive. Optically biaxial positive. 2V=35° to 37°. The plane of the optic axes is parallel to *(010)*; the positive acute bisectrix is perpendicular to *(100)*. Fragments of this mineral are varied in character. Frequently diamond shaped forms occur (with symmetrical extinction) which should give an obtuse bisectrix interference figure. Irregular prismatic flakes and sharply angular cleavage fragments are common; the former give an acute bisectrix figure leaning to one side, but the latter do not yield good interference figures. Grains of barite may be confused with celestite, wollastonite, topaz, sillimanite and cyanite. Barite may be derived from sandstones, in which it acts as a cementing medium, and, associated with calcite, from veins in limestones. Barite rarely occurs as detrital grains; its presence in residues is usually due to the disintegration of the cementing medium of a sand on treatment of the latter for heavy mineral analyses.

SILLIMANITE Orthorhombic. Habit prismatic, with irregular terminations, or fibrous, then often compactly interlaced. Cleavage perfect parallel to *(100)*. Straight extinction parallel to prism edge. Colorless. Relief high, alpha=1.6603, beta=1.6612, gamma=1.6818. Birefringence high (0.0215). Elongation positive. Optically biaxial positive. 2E=42°. The plane of the optic axes is parallel to *(100)*, that is, the plane of the cleavage, so the positive acute bisectrix is parallel to *"c"* and perpendicular to *(001)*. Milner says[2]: "Usually found as long slender prisms or fibres, sometimes flattened. Flattened grains parallel to *(001)* exhibit good biaxial figures with low birefringence. Grains with regular striations are comparatively rare; curved

[1]Loc. cit. p. 75.

[2]"Calcite is often biaxial, probably twinning and 2V may be very close to 18°. Very easily mistaken for aragonite." Clarence Ross, U. S. Geol. Survey, personal communication.

forms are occasionally met with. Sillimanite is essentially a local species." It has higher birefringence and smaller axial angle than topaz and andalusite. Topaz has negative elongation; andalusite, wollastonite, and cyanite are optically negative; cyanite and topaz both have wider axial angles than sillimanite.

ANHYDRITE Orthorhombic. Resembles barite in physical properties. The specific gravity of anhydrite is less than that of barite. Anhydrite is soluble in hydrochloric acid, whereas barite is insoluble in acids. Cleavage is good in three directions at right angles parallel to *(001)*, *(010)*, and *(100)*. Colorless. Relief high, alpha=1.571, beta=1.576, and gamma=1.614. Birefringence high (0.043). Optically biaxial positive. 2V=42°. The plane of the optic axes is parallel to *(010)*, so cleavage fragments in this plane will not give good interference figures. Positive acute bisectrix is normal to *(100)*, so fragments in this plane yield good interference figures. If the preparation of sediments for petrographic study, as outlined previously in this paper, has been thorough, anhydrite should all have been dissolved in the boiling acid. If present in large amounts, some of it may persist through the treatment. Anhydrite is usually associated with gypsum and rock salt. It changes by hydration to gypsum, sometimes in large masses.

THE MINERAL IS ANISOTROPIC, COLORLESS, BIAXIAL 2V GREATER THAN 45°, NEGATIVE

ANDALUSITE Orthorhombic. Crystals always more or less elongated parallel to the vertical axis. Cleavage good parallel to *(110)*, forming an angle of 90° 48′; in traces parallel to *(100)* and *(010)*. Color rose red, violet, whitish to colorless. Pleochroism variable in intensity even in a single crystal, from very pale yellow to rose red. Relief high, alpha=1.632, beta=1.638, gamma=1.643. Birefringence low. Elongation negative. Optically biaxial negative. 2V=86°. Optic plane parallel to *(010)*, with the negative acute bisectrix perpendicular to *(001)*. Cleavage fragments, which are irregular or prismatic with parallel extinction, will not give good interference figures. Andalusite in the metamorphic and sedimentary rocks often contains carbonaceous inclusions, usually arranged symmetrically, and is then known as chiastolite. Andalusite alters readily to colorless mica and rarely to a mixture of other minerals. The inclusions and alterations cause the mineral to appear turbid. These features serve to differentiate andalusite from topaz, with which it may sometimes be confused (topaz, however, being biaxial positive and having positive elongation), but the pleochroism of andalusite, when present, is an infallible guide.

CYANITE (Disthene) Triclinic. Usually in long bladed crystals, rarely terminated. Cleavages perfect parallel to *(100)*, distinct parallel to *(010)* making an angle of 74° are very characteristic, although they do not show in all sections. The parting parallel to *(001)* makes an angle of about 90° with the vertical axis in the cleavage face. Fracture ragged. Extinction oblique, about 30° from the vertical axis in section parallel to the cleavage. Colorless to blue, white. Thick sections often show pleochroism from dark blue, through violet to colorless. Relief marked, alpha=1.717, beta=1.722, gamma=1.729. Birefringence low. Elongation positive. Optically biaxial, negative. Optic axial angle (2V) about 82°, but slightly variable. Optic axial plane inclined at 30° to prism edge *(100), (010)*. The negative acute bisectrix is perpendicular to *(100)*, the best cleavage. Dispersion weak. Cleavage fragments parallel to *(100)* have a 30° extinction angle and give an acute bisectrix interference figure. Milner says[1]: "Varies greatly in physical characters, the commonest type being the subangular grain *(100)* elongated in the direction of the principal axis, irregularly terminated, and with or without traces of the *(001)* cleavage at right angles to the length of the grain. A more abraded form gives rise to the short stumpy grain, sometimes exhibiting re-entrants due to the fracture of the prism face. Compound cleavage fragments, due to differential abrasion of *(100)* and *(010)* are often observed, re-entrants in such cases being very marked; these fragments are usually sharply angular. Grains flattened parallel to *(010)* are rare; they give straight extinction and do not show the interference figure so typical of the *(100)* grains. Grains may be altered around the edges to micaceous material, containing abundant inclusions. Certain types of cyanite are characteristic of definite horizons. It frequently affords direct evidence of the source of origin of the material in which it occurs, and by the degree of abrasion suffered it may signify the nature and potency of the transporting medium. In a casual examination, cyanite may be easily confused with wollastonite (which also is colorless, biaxial negative, but has a smaller 2V and lower relief), topaz, barite and sillimanite. The latter, however, are orthorhombic, have parallel extinction and are biaxial positive. Sillimanite has a very narrow 2V, and topaz wide. Topaz has lower order interference colors than cyanite and sillimanite (whose colors are similar). Topaz has basal cleavage only.

HYPERSTHENE. Described under colored, biaxial negative.

EPIDOTE. Described under colored, biaxial negative.

MUSCOVITE Monoclinic (pseudohexagonal). Commonly lamellar masses. Perfect basal cleavage yielding thin elastic lamellae. Fracture ragged but rare. Extinction parallel to the strong cleavage. Colorless. Non-pleochroic, but relief varies with rotation of stage. Relief low, alpha=1.563, beta=1.598, gamma=1.601. Birefringence high, but that usually seen in cleavage flakes is very low. Elongation positive. Optically biaxial negative. 2V=89° 54'. The plane of the optic axes is normal to *(010)*. The negative acute bisectrix is practically normal to *(001)*, hence cleavage flakes always yield good interference figures. In sediments, muscovite occurs commonly as thin, colorless, platy grains, with characteristic low refractive index, and bluish-gray birefringence. Inclusions such as zircon, rutile, tourmaline and garnet are common. It is frequently found that two forms of muscovite occur in sediments, one in the light, and one in the heavy concentrate. Muscovite is derived from igneous and metamorphic rocks. This mineral is stable in deep seated rocks, but alters readily at the surface, chiefly by hydration. Wind acting on a sand would tend to remove mica flakes.

[1]Loc. cit. p. 58.

THE MINERAL IS ANISOTROPIC, COLORLESS, BIAXIAL 2V GREATER THAN 45°, POSITIVE

TOPAZ Orthorhombic. Crystals usually prismatic, often vertically striated. Perfect cleavage parallel to *(001)*, imperfect parallel to *(201)* and *(021)*. Fracture irregular, subconchoidal. Extinction parallel. Colorless, yellow, etc. Relief high, alpha=1.619, beta=1.620, gamma=1.627. Birefringence low; colors in grains are first and second order. Elongation positive. Optically biaxial positive. 2V=65°. Plane of the optic axes parallel to *(010)*. Positive acute bisectrix normal to *(001)*, the cleavage. Subangular or irregular grains are commonest in sediments. Basal grains are of frequent occurrence and these yield good interference figures, although the optic angle is so large it sometimes is difficult to determine the optical character. Grains of barite, cyanite, sillimanite, wollastonite and topaz all look much alike in a heavy mineral concentrate. All are biaxial; topaz, barite and sillimanite are positive, but sillimanite has a narrower optic angle than topaz. Cyanite and wollastonite are both negative; wollastonite has a very narrow optic angle, whereas that of cyanite is so wide the melatope is almost straight, and care must be taken lest the figure be thought to be uniaxial. Topaz may be derived from granite, greisenized and other contact metamorphosed rocks.

AUGITE. Described under anisotropic, colored, biaxial, wide 2V positive.

OLIVINE. Described under anisotropic, colored, biaxial, wide 2V, positive.

THE MINERAL IS ANISOTROPIC, COLORED, BIAXIAL 2V LESS THAN 45°, NEGATIVE

GLAUCOPHANE Monoclinic. Habit prismatic; short stumpy crystals. Similar to hornblende in physical characters. Cleavage good parallel to *(110)*. Fracture uneven. Extinction practically parallel (3° to 11°) to the vertical crystallographic axis in the obtuse angle beta. Color blue to bluish-black. Pleochroism marked and characteristic; (alpha colorless, beta bluish-violet, gamma blue). Relief high, alpha=1.621, beta=1.638, gamma=1.639. Birefringence high. Elongation positive. Optically biaxial negative. 2V=45°, 2E=85°. Optic axial plane parallel to *(010)*. Negative acute bisectrix practically normal to *(100)*. In sediments, glaucophane commonly occurs as rounded or irregular prismatic grains of decided purplish-blue color with distinct pleochroism. Abraded cleavage plates *(110)* are also found. Grains often give interference figures. The mineral in Mid-Continent sediments most easily confused with glaucophane is blue tourmaline. The two minerals have almost exactly the same color, pleochroism and relief, but tourmaline is uniaxial, and might have inclusions. Glaucophane would probably have better cleavage than tourmaline. Glaucophane is derived from metamorphosed rocks, especially schistose types. It is common in some of the California Tertiary, but rare in the Mid-Continent sediments.

BIOTITE. Described under uniaxial, colored, negative.

THE MINERAL IS ANISOTROPIC, COLORED, BIAXIAL 2V LESS THAN 45°, POSITIVE

CHLORITE GROUP Monoclinic, pseudo-rhombohedral. Habit pseudo-hexagonal plates with beveled edges; tabular, with prominent basal plane. Structure foliated, massive, rarely crystalline. Cleavage perfect basal; cleavage flakes flexible. Extinction practically parallel to elongation. Color pale green. Pleochroism strong in deeply colored varieties, when the minimum absorption always occurs in the direction of the cleavage, *i. e.*, perpendicular to the base. Relief low, alpha=1.585, beta=1.588, gamma=1.596. Birefringence low. In ordinary light there is no extinction on account of the strong dispersion; instead the color is darker blue, changing to "ultra blue" in one direction and pale yellow in the other. Elongation positive or negative. Biaxial 2E has a wide range, but is usually nearly zero. The mineral often gives the interference figure of an uniaxial species on account of the combined effect of sub-microscopic twinning individuals. Plane of the optic axes usually parallel to *(010)*. The acute bisectrix, which is perpendicular to the base *(001)*, is usually negative, when rho is greater than V, but sometimes positive, when rho is less than V. Cleavage flakes of chlorite are common in sediments. In appearance, they somewhat resemble mica. Grains frequently exhibit interference figures, which with color, pleochroism, low relief, very low birefringence and strong dispersion aid materially in the identification of members of the chlorite group. If the specific gravity of the bromoform is somewhat less than 2.9, as it generally is, chlorite may appear in the heavy concentrate. The chlorites have a much narrower optic angle than muscovite. Chlorites are derived from phyllites, slates, and similar metamorphosed rocks.

MONAZITE Monoclinic. Crystals usually small tablets parallel to *(100)*. Cleavage good parallel to *(100)*, less commonly parallel to *(010)*; parting parallel to *(001)* sometimes perfect or distinct. Extinction 4° with the principal (vertical) axis. Color yellow, yellowish-brown, red. In thick sections, pleochroism distinct from light yellow to greenish-yellow. Relief high, alpha=1.795, beta=1.796, gamma=1.8411. Birefringence high. Elongation negative. Optically biaxial positive. 2V=24°. Plane of the optic axes normal to *(010)*, almost parallel to *(100)*. Positive acute bisectrix almost perpendicular to *(001)*, the parting. In sands, grains of monazite are usually rounded and lying on *(001)*. Such grains yield good interference figures. Monazite has a smaller optic angle than olivine, and smaller optic angle, weaker birefringence, weaker dispersion and different form than titanite. Monazite is derived from granites.

TITANITE Monoclinic. Crystals often wedge shaped and flattened parallel to *(001)*, but the forms are varied. Cleavage distinct parallel to *(110)*, difficult parallel to *(100)* and *($\bar{1}$12)*, rare parallel to *(111)*. Extinction inclined: gamma to "*c*"=51°; alpha to "*c*"=39°. Color yellow, brown, etc., often varying in a single crystal. Weakly pleochroic in brown and yellow tones. Relief very high, alpha=1.900, beta=1.907, gamma=2.034. Birefringence extremely strong. Elongation negative. Optic plane parallel to *(010)*. Positive acute bisectrix nearly normal to *(102)*. Optically biaxial positive. 2V=23° to 34°. Axial dispersion very strong, producing colored isogyres. In sediments, rounded diamond shaped grains are common, also irregular subangular cleavage fragments, both types often presenting dusky interiors due to decomposition. Pleochroism usually poor and brown coloration often much bleached. Some varieties of titanite traversed by a complex network of cracks due partly to fracture and partly to bad cleavage. Grains often give good interference figures, and this fact, together with the strong dispersion in titanite, aids in separating it from staurolite. Titanite is widely distributed in rocks of all kinds, particularly in crystalline schists and gneisses.

BROOKITE Orthorhombic. Crystals of variable habit. Cleavage in traces parallel to *(110)* and *(001)*. Extinction parallel. Color brown to black, sometimes weakly pleochroic. Relief very high, alpha=2.5832, beta=2.5856, gamma=2.7414. Birefringence very high. Elongation positive or negative. Optically biaxial positive. 2E=0° to 55°. Positive acute bisectrix always normal to *(100)*. In many crystals the plane of the optic axes is parallel to *(001)* for red and yellow light, and parallel to *(010)* for green and blue light. The interference figure for white light is a combination of these, that is the axial dispersion is so strong that the interference figure looks as a biaxial positive figure would look with the gypsum plate inserted. The mineral is uniaxial for a certain yellowish-green tint. In some crystals the plane of the optic axes is parallel to *(001)* for light of all colors. Cleavage fragments might give an axial bar figure for one color. The peculiar optical orientation and extremely strong dispersion aid in distinguishing brookite from rutile. In sediments, grains are usually subangular and irregular, sometimes occurring as tabular flakes of a distinctive yellowish-brown color. Sources of derivation are salic igneous and crystalline metamorphic rocks; it may also be derived *in situ* from the decomposition of a titanium bearing mineral. Brookite is a rare mineral in sands.

THE MINERAL IS ANISOTROPIC, COLORED, BIAXIAL 2V GREATER THAN 45°, NEGATIVE

CYANITE. Described under colorless, biaxial negative large 2V.

HYPERSTHENE Orthorhombic. Habit prismatic, usually elongated parallel to "*c*"; sometimes flattened parallel to *(100)* or *(010)*. Cleavage distinct parallel to *(110)*, fair parallel to *(100)* and *(010)*. Extinction parallel. Color yellowish-brown, dark brown, grayish-black. Pleochroism marked in more ferriferous varieties, in pink and green tints. Relief high, alpha=1.692, beta=1.702, gamma=1.705. Birefringence low. Elongation positive. Optically biaxial negative. 2V=90°. Plane of the optic axes parallel to *(010)*. Negative acute bisectrix normal to *(100)*. In basal sections (which show sharp cleavage lines at angles of approximately 90° with each other) orthorhombic pyroxenes show emergence of a bisectrix, whereas monoclinic ones show emergence of an optic axis. In a grain elongated parallel to "*c*" (and therefore showing cleavage lines parallel to the longer dimension) the elongation will be positive, as gamma is parallel to "*c*." Not a common mineral in sediments as a rule, though it may occur locally under suitable conditions, when it assumes a ragged, prismatic character, usually pleochroic, often full of minute inclusions. Very rare in Mid-Continent sediments, but common in some of the California Tertiary sediments. Hypersthene is derived from basic and ultra basic igneous rocks.

HORNBLENDE Monoclinic. Habit prismatic, usually elongated parallel to the vertical axis; sometimes in short well formed crystals. Cleavage perfect parallel to *(110)*; less distinct parallel to *(100)* and *(010)*. Cleavage traces in sections normal to prism zone intersect at angles of 56° and 124°. Fracture uneven, subconchoidal, frequently at right angles to prismatic cleavage. Extinction angle approximately 15°. Color green, greenish-blue, brown or black; sometimes colorless or gray. Pleochroism marked, maximum absorption in direction parallel to principal axis of crystal. Has many inclusions but none that are characteristic. Relief high, alpha=1.639, beta=1.643, gamma=1.656. Birefringence low. Relief and birefringence increase with the percentage of iron. Elongation positive. Optically biaxial negative. 2V=59° to 84°. Optic axial plane parallel to *(010)*. Negative acute bisectrix inclined at low angle to normal of *(100)*. Inclined dispersion distinct, with rho less than V. Cleavage fragments parallel to *(100)* should give an acute bisectrix figure slightly off center. Hornblende grains, in sediments, usually angular or subangular, often of a bleached yellowish-green color. Slender brown or green cleavage fragments are also common. Extinction angle varies from 5° to 20°. Marked pleochroism, extinction angle and amphibole cleavage serve to distinguish hornblende from augite. Hornblende is common in California Tertiary sediments. Its occurrence in Mid-Continent sediments is confined almost entirely to limestones and dolomites. Hornblende is derived from igneous and metamorphic rocks.

EPIDOTE Monoclinic. Crystals nearly always elongated parallel to the "*b*" axis; faces in this zone striated parallel to "*b*." Cleavage very good parallel to *(001)*, imperfect parallel to *(100)*. Extinction angle about 5°. Color pistachio green, sometimes yellow or nearly colorless. Sometimes weakly pleochroic in yellowish and brownish tones. Relief high, alpha=1.729, beta=1.768, gamma=1.754. Indices vary with the percentage of iron present. Birefringence strong, giving third and fourth order interference colors. Elongation positive or negative. Optically biaxial, negative. 2V=88°. Plane of the optic axes parallel to *(010)* and therefore perpendicular to the basal cleavage. Cleavage flakes give an interference figure consisting of an axial bar and concentric rings, due to the emergence of an optic axis. Fragments are irregular or prismatic, with parallel extinction. Transverse sections, give inclined extinction. Epidote may be recognized by its pistachio green color, irregular and rather angular grains, high relief, brilliant interference colors and axial bar interference figure. Epidote is confined, among Mid-Continent sediments, almost exclusively to limestones and dolomites. Epidote is furnished to sediments by crystalline metamorphic rocks, especially altered impure limestones, and by altered igneous rocks originally rich in ferromagnesian minerals.

THE MINERAL IS ANISOTROPIC, COLORED, BIAXIAL 2V GREATER THAN 45°, POSITIVE

STAUROLITE Orthorhombic. Crystals short prisms with base and brachypiacoid. Cruciform twins common. Cleavage good parallel to *(010)*, in traces parallel to *(110)*. Fracture subconchoidal, "hackly." Extinction parallel in prismatic sections. Color deep reddish-brown, brownish-yellow, brown. Pleochroism moderate, brown to straw-yellow. Inclusions, especially quartz, common, arranged symmetrically or in subparallel bands. Inclusions of garnet, tourmaline, rutile, biotite and carbonaceous matter have all been observed; such inclusions usually more common in the deeper colored varieties. Relief high, alpha=1.736, beta=1.741, gamma=1.746. Birefringence low. Elongation positive. Optically biaxial positive. 2V=89°. Optic axial plane parallel to *(100)*. Positive acute bisectrix normal to *(001)*. Axial dispersion weak. Sections at right angles to an optic axis give a figure consisting of a straight bar, due to the wide optic angle, but grains giving an interference figure are extremely rare. Well crystallized grains in sediments are comparatively rare. When present, they are irregular or somewhat platy, determined by cleavage, and have marked hackly fracture. Intensity of pleochroism varies greatly. Staurolite in limestone is sometimes filled with carbonaceous matter, rarely arranged regularly (as in chiastolite). Grains may decompose superficially to a form of chlorite or mica. Staurolite may be distinguished from titanite by the following criteria: grains of staurolite giving an interference figure are extremely rare; staurolite typically has more inclusions than titanite; staurolite has much less dispersion than titanite. Staurolite generally is lighter in color than rutile, and has lower birefringence. Rutile is uniaxial. Staurolite may be derived from crystalline schists and contact metamorphic rocks. It may be associated with garnet, cyanite and sillimanite, both in the metamorphic rocks, and in the sediments derived therefrom.

AUGITE Monoclinic. Crystals usually short, thick prisms; often coarsely lamellar parallel to *(001)* or *(100)*. Cleavage good parallel to *(110)* more rarely parallel to *(100)*, meeting roughly at 90° angles. Fracture uneven. Extinction position 38° to 54° from the "*c*" axis. Color green, greenish-black, brown; rarely colorless. Thin fragments are only slightly pleochroic, if at all. Relief very high, alpha=1.698, beta=1.704, gamma=1.723. Birefringence rather strong. Elongation positive or negative. Optically biaxial positive. 2V=59° to 62°. In sections showing parallel extinction, the plane of the optic axes is parallel to *(010)*. In olivine it is parallel to *(001)*. Acute bisectrix inclined 38° to 54° with the "*c*" axis. Grains usually either rounded prismatic forms, or irregular cleavage fragments. Fragments have bright interference colors, large extinction angles, and often show the emergence of an optic axis. The very weak, or lacking, pleochroism of augite usually distinguishes it from hornblende. Augite is very rare in Mid-Continent sediments. Intermediate and basic igneous rocks serve as possible sources of augite.

OLIVINE Orthorhombic. Crystals often flattened parallel to *(100)* or *(010)*. Cleavage good parallel to *(010)* and *(100)*. Fracture conchoidal. Grains elongated parallel to the principal axis give parallel extinction. Color olive-green; by alteration yellow, brown or red; also colorless. Non-pleochroic. Relief high, alpha=1.662, beta=1.680, gamma=1.699. Birefringence high. Elongation positive or negative. Optically biaxial. Plane of optic axes parallel to *(001)*. Acute bisectrix either normal to *(010)*, when crystal is negative, or normal to *(100)*, when crystal is positive. Fragments irregular and colorless with bright interference colors. Olivine usually occurs in sediments as irregular and much fractured grains, showing traces of decomposition, and giving good axial bar interference figures. Olivine is a comparatively rare detrital mineral and is usually found in such deposits as shore or dune sands occurring in the vicinity of ultra basic rock masses. It is derived from basic and ultra basic igneous rocks.

One set of indices only has been assigned to minerals that are included in important mineral groups, such as garnet, spinel, tourmaline, epidote, biotite, chlorite, hornblende, augite and olivine. The indices of none of these groups are fixed; beta alone ranges in the olivine series from about 1.652 to about 1.88. The student should consult the standard texts for indices, in these mineral groups, other than those given in this paper.

Identification of minerals by means of immersion fluids is the most rigorous method that has ever been devised, as it requires less guess work and less exercise of individual judgment. This method should, by all means, be used whenever sufficient material is available. Unfortunately, the material is, at best, not abundant, so that the use of the fluids requires much time and very skillful manipulation. The student should not begrudge the time thus spent, particularly when he is first learning his minerals, as the accurate determination of the indices is the only method yet devised to make certain his mineral identifications.

PLATE I.

HEAVY MINERALS IN SIMPSON SANDSTONE

473 feet from top of Simpson, SW. ¼ sec. 21, T. 2 S., R. 1 E.

T=Tourmaline, all colors	75%
Z=Zircon	25%
Q=Quartz	

PLATE II.

HEAVY MINERALS IN REAGAN SANDSTONE

West Timbered Hills, sec. 19, T. 1 S., R. 1 E.

Z=Zircon	85%
An=Anatase	10%
Tourmaline fragments	1%
Rutile	1%
Staurolite	1%
Topaz	1%
Epidote	1%
Glauconite	
Chlorite	

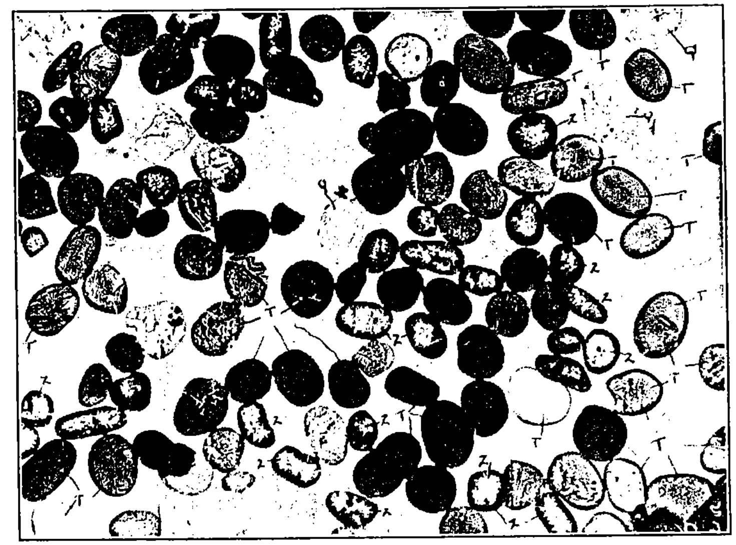

PLATE I.

PLATE II.

PLATE III.

HEAVY MINERALS IN SIMPSON LIMESTONE

1603 feet from top of Simpson, sec. 21, T. 2 S., R. 1 E.
Rock is composed of 78% lime, 12% sand.

Z=	Rounded zircon	32%
	Black opaque	27%
T=	Rounded tourmaline	12%
G=	Garnet	9%
	Staurolite	8%
	Euhedral zircon	5%
E. T.=	Euhedral tourmaline	3%
	Anatase	2%
"X"=	Unknown "X" (new mineral)	2%
	Apatite	Present

PLATE IV.

HEAVY MINERALS IN SIMPSON GREEN SHALE

4697 feet from top of Simpson, NE. ¼, sec. 20, T. 1 S., R. 1 E.

Z=Zircon, rounded and euhedral
G=Garnet, colorless and pink
Rutile
Staurolite
T=Tourmaline, rounded and euhedral
To=Topaz
Ep=Epidote
Titanite
Augite
Hornblende
Anatase
Brookite
Wollastonite
Glaucophane
Augite

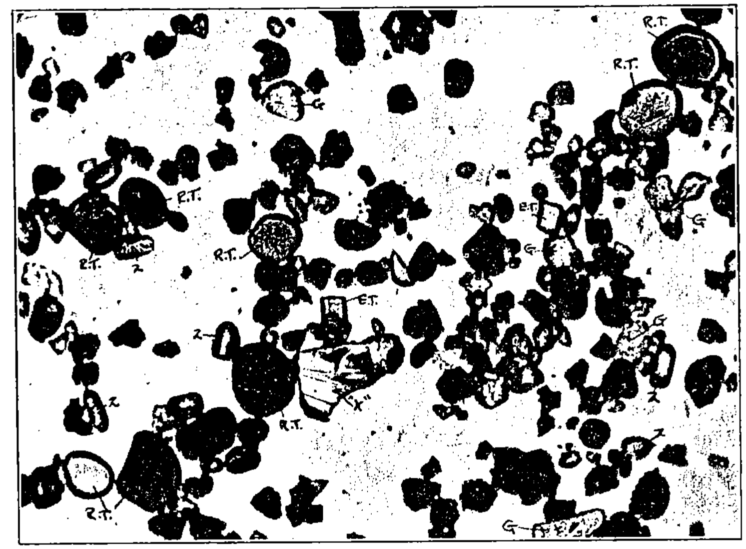

PLATE III.

PLATE IV.

INDEX TO SPECIES

TABLE OF HEAVY MINERALS

ISOTROPIC					OPAQUE			
MINERAL	Page	Opt. Char.	XYL. SYS.	Opt. Ang	MINERAL	Page	Opt. Char.	XYL. SYS.
Fluorite	13		Isom		Magnetite	13		Isom
Spinel	13		Isom		Ilmenite	13		Rhom
Garnet	13		Isom		Pyrite	13		Isom

ANISOTROPIC

	UNIAXIAL				BIAXIAL				
Colorless	Eucolite	13, 14	—	Rhom	Less Than 45°	Wollastonite	17	—	Mono
	Apatite	13, 15	—	Rhom		Aragonite	17	—	Orth
	Corundum	14, 15	—	Rhom		Barite	18	+	Orth
	Eudialtye	14, 16	+	Rhom		Sillimanite	18	+	Orth
	Zircon	14, 16	+	Tetr		Anhydrite	19	+	Orth
					Greater Than 45°	Andalusite	19	—	Orth
						Cyanite	19, 24	—	Tric
						Hypersthene	20, 24	—	Orth
						Epidote	20, 25	—	Mono
						Muscovite	20	—	Mono
						Topaz	21	+	Orth
						Augite	21, 26	+	Mono
						Olivene	21, 27	+	Orth
Colored	Eucolite	13, 14	—	Rhom	Less Than 45°	Glaucophane	22	—	Mono
	Apatite	13, 15	—	Rhom		Biotite	15, 22	—	Mono
	Corundum	14, 15	—	Rhom		Chlorite	22	+	Mono
	Tourmaline	15	—	Rhom		Monazite	23	+	Mono
	Biotite	15, 22	—	Mono		Titanite	23	+	Mono
	Anatase	15	—	Tetr		Brookite	23	+	Orth
	Eudialyte	14, 16	+	Rhom	Greater Than 45°	Cyanite	19, 24	—	Tric
	Zircon	14, 16	+	Tetr		Hypersthene	20, 24	—	Orth
	Rutile	16	+	Tetr		Hornblende	24	—	Mono
	Xenotime	16	+	Tetr		Epidote	20, 25	—	Mono
						Staurolite	26	+	Orth
						Augite	21, 26	+	Mono
						Olivene	21, 27	+	Orth