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AN X-RAY AND OPTICAL INVESTIGATION OF THE SERPENTINE MINERALS

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ABSTRACT

More than 100 specimens belonging to the serpentine group have been investigated optically and by means of x -rays. Essentially all of the species now classed within the serpentine group can be referred to two main divisions, each of which shows slight modifications in the intensities of certain lines. The first division, which is referred to as the mineral serpentine, consists of varieties whose patterns are similar in atomic spacing to that of serpentine, best represented by patterns of chrysotile. The name chrysotile is reserved for serpentine occurring in veins and consisting of flexible fibers. The second division, which is referred to as the mineral antigorite, consists of varieties whose patterns are similar in atomic spacing to that of antigorite, from Antigorio valley, Piedmont.

Fragments from the specimens of each division have been examined by the immersion method and their optical properties noted. Nearly all of the specimens have been studied in thin section. The fundamental structures of both divisions appear to be fibrous. From the x -ray and optical studies it appears that the matrix of chrysotile is serpentine and not antigorite as thought by some authors.

General comparisons have been made between chemical analyses compiled from the literature. Based on the results of the x -ray and optical studies and the chemical discussion it is proposed to drop the names schweizerite, metaxite, pyroidesine, marmolite, retinalite, thermophyllite, bastite and vorhauseite as distinct mineral species in favor of the one term serpentine. Likewise it is proposed to drop the names picrossmine, picrolite, williamsite, bowenite, porcellophite, and baltimorite for the term antigorite. The term serpentinite is suggested for rocks composed of serpentine or antigorite or a mixture of both.

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INTRODUCTION

Numerous varieties of serpentine have been described and given distinct mineral names. These names have been given because of slight variations in physical properties or chemical composition from those ordinarily recognized for common serpentine. Recent studies indicate that the mineralogy of the serpentine group is a proper subject for revision, particularly in view of the existence of optical and x -ray technique not available at the time the original descriptions of the so called serpentine minerals were made. Such a study has shown that many of the varieties of serpentine, which have been given specific mineral names, have similar interplanar spacings and optical properties. It is believed that, on the basis of this study, most of the names can be eliminated as distinct mineral species and essentially all the varieties now classed within the serpentine group can be referred to two main divisions. X -ray patterns of each division exhibit slight modifications in the intensities of certain lines, but the essential patterns are consistent throughout the groups.

ACKNOWLEDGMENTS

The problem was undertaken at the suggestion of Dr. Paul F. Kerr of the Department of Geology and Mineralogy of Columbia University, to whom sincere appreciation is extended for his valuable suggestions and friendly criticism during the progress and completion of the investigation. The writer wishes to express his indebtedness to the late Professor R. J. Colony and Dr. Philip Krieger for their advice throughout the preparation of the manuscript. Mr. J. J. Fahey, of the U. S. Geological Survey, has made the chemical analyses of a number of serpentine samples used in this study. Although the results of his work have been available for this report, it has been thought best, for purposes of publication, to treat the chemical phases of the study in a separate paper.

The study has been aided by a grant from the Kemp Fellowship Fund and the liberal use of specimens from the Egleston Mineralogical Collection of Columbia University. Dr. W. F. Foshag of the United States National Museum has also cooperated in furnishing specimens for study. Dr. Clarence S. Ross of the U. S. Geological Survey has supplied specimens of saponite for comparison as well as certain types of serpentine.

THE NOMENCLATURE OF THE SERPENTINE GROUP

Precious and common serpentine were known to the ancients but none of the specific varieties were described until the beginning of the 19th century. Some 27 minerals have been listed, either definitely or

tentatively, as belonging to the serpentine group. The list could be expanded, in a few instances, by including miscellaneous but only partly substantiated names. The varieties listed below are given in the order of their original appearance in various publications.

Serpentine. Discordides; *Materia Medica*. About 50 A.D.

Bastite. Talkart v. Trebra, *Erfahr. Inn. Gebirge*, p. 97, 1785. Originally described with other minerals showing schillerization under the name of schiller-spar.

Haidinger, Wm., *Handb. der Mineralogie*, p. 523, 1845.

Picrolite. Hausmann, J., *Moll's Efemeriden der Berg und Huttenkunde*, vol. 4, p. 401, 1808.

Marmolite. Nuttall, I., Observations on the serpentine rocks of Hoboken, in New Jersey and on the minerals which they contain: *Am. Jour. Sci.*, vol. 4, p. 19, 1822.

Nephrite. (Bowenite of Dana). Bowen, G. T., Analysis of a variety of nephrite from Smithfield: *Am. Jour. Sci.*, vol. 5, p. 346, 1822.

Picrosmine. Haidinger, Wm., *Treatise on Mineralogy*, by F. Mohs. Translation by Wm. Haidinger. Vol. 3, p. 137, 1825.

Metaxite. Breithaupt, A., *Vollständige Charakteristik des Mineral-Systems*, p. 113 and p. 326, 1832.

Retinalite. Thomson, T., *Outlines of Mineralogy, Geology and Mineral Analysis*, 1, p. 201, 1836.

Antigorite. Schweizer, E., Ueber den Antigorit ein neues Mineral von Edward Schweizer in Zurich: *Pogg's Annalen der Physik und Chemie*, vol. 49, p. 595, 1840.

Porcellophite. *K. Vet.-Akademiens Handlingar, Stockholm*. 1840.

Chrysotile. (Asbestos). Kobell, Fr. von, Ueber den schillernden Asbest von Reichenstein in Schlesien: *Jour. für praktische Chemie*, vol. 2, p. 297, 1834.

Baltimorite. Thomson, T., Notice on some new minerals: *Taylor's Philosophical Magazine*, 3rd series, vol. 22, p. 191, 1843.

Schweizerite. Schweizer, E., *Jour. für praktische Chemie*, vol. 32, p. 378, 1844.

Williamsite. Shepard, C. U., On new minerals from Texas, Lancaster Co., Penn.: *Am. Jour. Sci.*, vol. 6, p. 249, 1848.

Zermattite. Nordenskiöld, N., *Ueber das atomische-chemische Mineral-System und das Examinations System der Mineralien*, p. 132, 1848.

Bowenite. Dana, J. D., *Mineralogy*, p. 265, 1850.

Jenkinsite. Shepard, C. U., Two new minerals from Monroe, Orange Co.: *Am. Jour. Sci.*, series 2, vol. 13, p. 392, 1852.

Thermophyllite. Nordenskiöld, A. E., *Beskrifning ofver de i Finland funna Mineralier*, p. 160, 1855.

Vorhauserite. Kennigott, A., *Mineralogischer Forschungen*, p. 71, 1856.

Pyroidesine. Shepard, C. U., *Cat. Meteorites*, 1872.

Radiotite. Brauns, R., Der oberdevonische Pikrit und die aus ihm hervorgegangenen Neubildungen: *Neues Jahrb. für Mineralogie, Beilage-Band* 18, p. 314, 1904.

Fe-Antigorite. Eckermann, Harry von., *Geol. För. Förh. Stockholm*, vol. 47, pp. 299-309, 1925.

Related Varieties

Deweylite. Emmons, E., *Manual of Mineralogy and Geology*, p. 133, 1826.

Hydrophite. Svanberg, *Pogg's, Annalen der Physik und Chemie*, vol. 51, p. 525, 1839.

Gymnite. Thomson, T., *Taylor's Philosophical Magazine*, 3rd series, vol. 22, p. 191, 1843.

Genthite. Genth, *Kell & Tiedm. Monatsb.*, vol. 3, p. 487, 1851.

Ekmannite. Igelström, L. J., *Öfv. Vet. Ak. Stockholm*, vol. 22, p. 607, 1865.

Due to the fact that virtually all of the members of the serpentine group were described before the development of present day optical and x -ray technique, the observed physical properties and chemical compositions played the major role in the original descriptions. The megascopic nature of the specimens originally described combined with their chemical analyses have probably determined the nomenclature of serpentine as we find it today. The types of serpentine may be divided in a general way into three classes when considered from the standpoint of structure in the hand specimen.

- (1) MASSIVE. Serpentine, bowenite, retinalite, schweizerite, vorhausserite, porcellophite, williamsite and pyroidesine.
- (2) LAMELLAR. Antigorite, marmolite and thermophyllite.
- (3) FIBROUS. Chrysotile, picrolite, baltimorite, metaxite, jenkinsite, and picrosmine.

Optical and x -ray studies demonstrate, however, that this classification of types is independent of the mineralogical nature of the material.

METHODS OF STUDY

Different specimens of the ordinary varieties described in the literature were selected for their apparent purity in the hand specimen. Portions of each were chosen for the x -ray and optical studies. A classification of the varieties was first made by comparison of x -ray diffraction patterns. These were secured by the standard powder method, using the $K\alpha$ series of molybdenum radiation and computing the measured distances from the zero beam according to the formula $n\lambda = 2d \sin \theta$. The standard patterns used for comparison purposes and for the recorded measurements were carefully checked against sodium chloride.

The optical investigation was divided into two parts: (1) the optical properties of sized fragments of each specimen were noted by means of the oil immersion method; (2) nearly all of the specimens were examined in thin section for purity and compared for structural similarity and difference. The optical descriptions are based on the results obtained from the combined studies.

X-RAY STUDIES

More than 100 specimens of the serpentine group and chemically related types were examined by means of x -rays. The patterns obtained from the specimens foreign to the serpentine group were used, partly, to check against lines in the serpentine patterns due to impurities and, partly, to check the likelihood of similarity to the serpentine group in interplanar spacing. Of these deweylite is included in the discussion of the serpentine group. Patterns of ekmannite, asbeferrite, sepiolite, saponite, meerschaum, celadonite and common chlorite are found to be

quite different from those of the serpentine group. Weak patterns of cerolite from Frankenstein, Silesia and of garnierite from New Caledonia show a close relationship to deweylite. The patterns of celadonite from Verona indicate that the material is not a member of the serpentine group, but is perhaps related to glauconite.

The patterns of micaceous specimens labelled ekmannite from Grythyttan, Sweden, do not resemble any patterns of the serpentine or chlorite groups. This mineral is thought to be a manganiferous ferroantigorite by some authors. The x -ray pattern and the birefringence of the mineral indicate that it is not an antigorite although Winchell finds that it fits into his chlorite diagram very well except for its high birefringence (0.048).

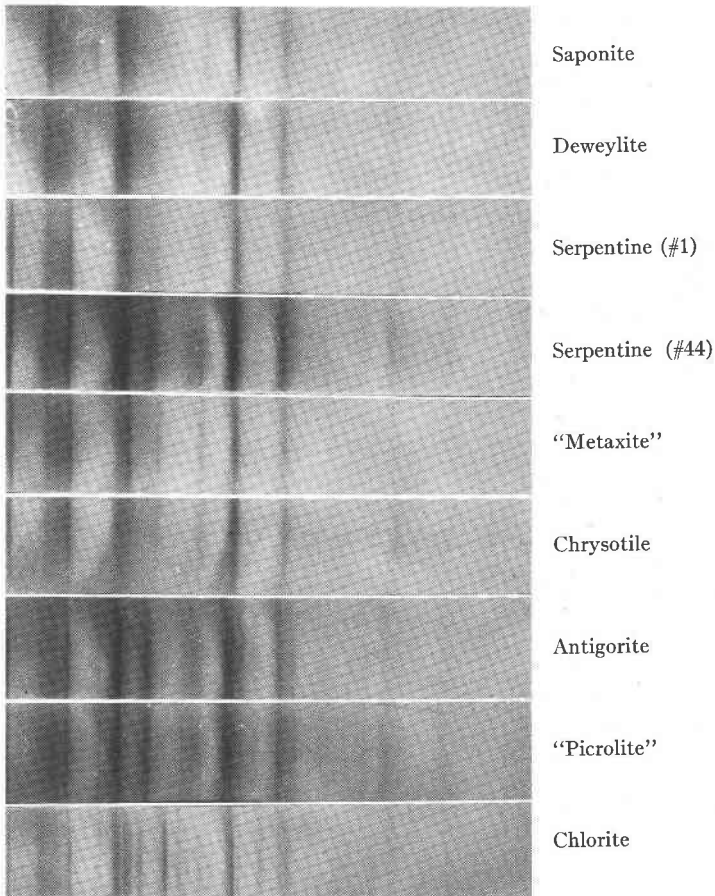


PLATE I. Showing the x -ray diffraction patterns of saponite, deweylite, serpentine (#1), serpentine (#44), "metaxite," chrysotile, antigorite, "picrolite" and chlorite.

A pattern of saponite has been included in the plate of x -ray patterns to show its similarity to weak patterns of deweylite.

Examination of the x -ray patterns of the minerals of serpentine indicates that the patterns can be divided into two groups, each with slight modifications in the sharpness and intensities of certain lines. The first, here considered to belong to the mineral serpentine, consists of varieties whose interplanar spacing is similar to that of chrysotile. (See Tables I, II and III). The name chrysotile, however, is reserved for serpentine

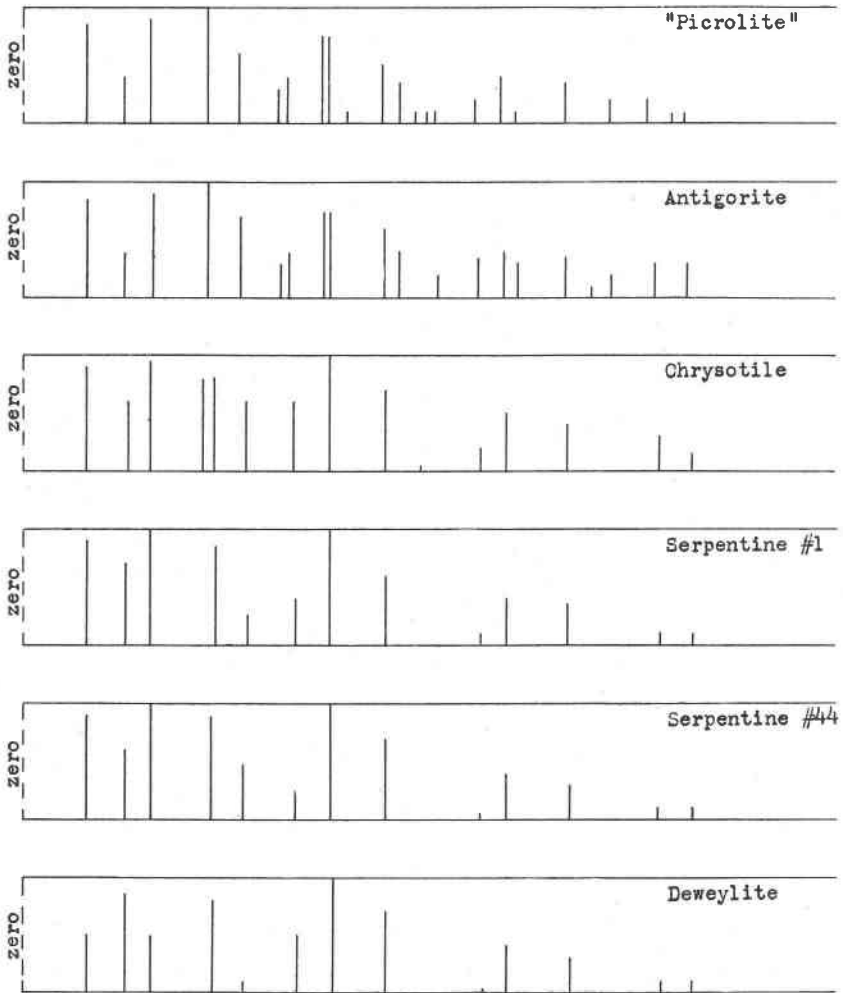


FIG. 1. Showing the relative positions and intensities of the lines for "picrolite," antigorite, chrysotile, serpentine and deweylite as measured in millimeters from the zero line

sharp doublet at 2.571 and 2.424 A.U., and fairly sharp lines throughout. (See Plate I; Fig. 1 and Table VI). The varieties included under serpentine in Table III show line 4.431 more intense, and line 2.571 A.U. less intense than the corresponding lines in the chrysotile pattern. Otherwise the patterns of Table III are identical. The nature of the variation is best shown in the patterns of metaxite (#53) and schweizerite (#38).

In the patterns of the varieties listed under Tables I and II the first line of the doublet is represented by a shaded area of variable width and intensity. It extends to the second line of the doublet which is in normal position. Certain of the remaining lines are less intense and less distinct than the corresponding lines in the chrysotile patterns. The patterns of the varieties listed under Table I vary from those listed under Table II in that the intensities of lines 2.098 and 1.724 A.U. are reversed. (See Fig. 1). This difference, although very slight, is distinctly noticeable in certain patterns. These two lines also vary slightly in the chrysotile patterns.

The above variations are not considered sufficiently significant to justify new mineral species, particularly in the absence of optical and chemical confirmation. The variations have been noted not for the purpose of dividing the group but for purposes of record. A slight intensity gradation can be traced in the patterns which seemingly parallels the corresponding change from the massive forms, listed under Tables I and II, through the brittle, splintery types of Table III to the flexible fiber, chrysotile. The modifications, presumably, are chiefly due to varying degrees in the development of crystallinity.

Antigorite is best represented by the patterns of antigorite from Antigorite valley and Traföss, Styria, and picrolite from North Carolina. The distinctive differences between the patterns of serpentine and antigorite are (1) the increase in the distance between lines 4.431 and 3.658 A.U.; (2) the disappearance of the chrysotile doublet; (3) the appearance of the antigorite doublet and (4) a slight increase in the number of lines. (See Plate I; Fig. 1 and Table VI). The varieties listed near the bottom in Table IV show lines 2.186, 1.845 and 1.794 A.U. less intense and the doublet less distinct than the corresponding lines in the type patterns. These variations are best shown in the pattern of porcellophite from Staten Island.

The patterns of several specimens of deweylite show that it has much the same interplanar spacing as the amber material from Turkey Mountain. The variation of the intensities of the first three lines of deweylite distinguishes it from serpentine. (See Plate I; Fig. 1 and Table VI).

Chemically it is closely related to serpentine, being slightly more hydrous.

A specimen of baltimorite from Lancaster Co., Pennsylvania, which was altering to a lavender colored chlorite, gave a pattern identical to one obtained from a chlorite labelled kammererite from Texas, Pennsylvania.

Identical patterns were obtained from several chlorites which included clinochlore from Chester County, Penn.; clinochlore from Pfitschthal; ripidolite from Tilly Foster; penninite from Zermatt, Valais; corundophilite from Chester, Massachusetts, and prochlorite from Cumberland, England. The patterns of thuringite from Zorm Sea, Corinthea, and kammererite from Texas, Pennsylvania, differed from each other and from the above group of chlorites. In his *x*-ray study of clinochlore and penninite Pauling¹ determined the unit cell as monoclinic, $a=5.2-3 \text{ \AA}$, $b=9.2-3 \text{ \AA}$, $c=14.3-4 \text{ \AA}$ and the space group as C_{2h}^3 .

From the study of the *x*-ray diffraction patterns of serpentine, antigorite and the chlorites, it does not appear that there is any definite structural reason for including antigorite as an end member of the chlorite series. The pattern appears to be as close to serpentine as to chlorite. The patterns show a greater difference than one would infer from the line drawings by Winchell.²

The *x*-ray study has shown that, fundamentally, chrysotile and serpentine are structurally the same. From the *x*-ray studies by Warren and Bragg³ the unit cell of chrysotile was determined to be monoclinic and composed of 4 molecules of the formula $2(H_4Mg_3Si_2O_9)$; $a=14.66 \text{ \AA}$, $b=18.5 \text{ \AA}$, $c=5.33 \text{ \AA}$ and $\beta=93^\circ 16'$. The space group is probably C_{2h}^3 . Later Jansen⁴ determined the identity period along the fiber axis of a chrysotile from Oberitalien to be 5.2 A.U. The mineral is monoclinic with $a=6.85 \text{ \AA}$, $b=5.16 \text{ \AA}$ and $c=13.38 \text{ \AA}$. Recently Syromyatnikov⁵ has described a new structural modification of chrysotile which he has called "Ishkyldite." Preliminary examination shows it to have an identity period along the fiber axis of 9.678 \AA . This is nearly twice that usually assigned to chrysotile.

PREVIOUS CLASSIFICATIONS BASED ON OPTICAL STUDIES

A review of the literature on the microscopical characteristics of the serpentine group furnishes one with many confusing ideas as to just what specific mineral is meant when the words serpentine, chrysotile and antigorite are used. Apparently these terms are used interchangeably to include one or more of the minerals designated by the three names. The need of more precise knowledge concerning the minerals of ser-

pentine may be shown from a review of the following extracts from publications by various authors.

*Winchell*⁶ has eliminated the serpentine group by including its members, with the exception of chrysotile, in the chlorite group. Chrysotile is described as usually occurring in a fibrous form with positive elongation. In the variety called asbestos the fibers are separable and flexible. It is optically positive with a small optic angle. Antigorite, which is described as an end member of the chlorite group, includes the lamellar rather than the fibrous varieties of serpentine which show good cleavage, positive elongation and a large negative optic angle. The birefringence is slightly less than that of chrysotile. Bastite is a coarse variety of antigorite, pseudomorphous after pyroxene. The optic plane is parallel to (010) for antigorite.

Rogers and *Kerr*⁷ use the name chrysotile to describe the fibrous form, asbestos. The optic sign and elongation are positive. The axial angle is small. It usually occurs in veinlets in serpentine which consists largely of the mineral antigorite. The latter is described as occurring in anhedral crystals or aggregates of fibrolamellar structure. The optic sign is negative with variable axial angle. The elongation is positive and the extinction is parallel. Chrysotile is distinguished from its dimorph, antigorite, by its fine fibrous structure. Antigorite is the main constituent of serpentine, a metamorphic rock. The optic plane of antigorite is parallel to (100).

*Johannsen*⁸ describes serpentine as being made up principally of fine fibers, thin prisms or thin laminated plates. Parallel fibers generally show positive elongation and parallel extinction. He quotes *Tschermak* as stating that fibrous serpentine has the axis of greater ease of vibration parallel to the fibers. The mineral may appear isotropic in felty aggregates.

*Krolov*⁹ writes that the serpentines are mostly of a type intermediate between chrysotile and antigorite, which are regarded as one and the same mineral. Chrysotile is optically negative (or rarely positive) with $2V$ ranging in different specimens from 0° to 52° . The sign of elongation may be either positive or negative, even in adjacent fibers. The refringence and birefringence of the fibers diminish towards the center of the mesh structure. Antigorite is of three types; needles, laths and scales, but these grade into each other. It is usually optically negative with $2V = 14\frac{1}{2}^\circ$ to 42° . The optic axial plane is perpendicular to the perfect cleavage. The elongation is always positive and pleochroism is absent.

*Graham*¹⁰ states that in none of the varieties does serpentine exhibit well-defined optical characters when examined in thin section under the microscope, owing mainly to its imperfect crystalline character. It is always biaxial, with refractive indices and birefringence rather higher than for quartz; the fibers are optically positive, but certain platy varieties appear to be negative. . . . Most frequently the serpentine that forms along the cracks is in the form of parallel fibers, lying transverse to the crack, while that around the margins (of olivine) also appears as fibers, more or less parallel, or rather radially arranged. Where the alteration has proceeded further, the interior of the olivine crystal is replaced, still by fibers, but these usually have no particular orientation and appear rather as an irregular network. . . . Structurally, then, the difference between chrysotile and massive serpentine is one of degree and not of kind. The former name is used to denote those occurrences in which the fibers are so long as to be visible to the eye. . . . When, on the other hand, the fibers are microscopic, with no regular orientation, their aggregation has built up the substance "massive" serpentine.

*Fisher*¹¹ describes antigorite as being commonly developed from olivine, the alteration beginning along fractures and preserving the characteristic mesh structure superimposed by the network of fractures. The stated pleochroism of antigorite is accidental rather than essential and has seldom been noted by the writer. Chrysotile is the fibrous form of serpentine, with fibration normal to the enclosing walls of the thin veinlets in which it usually

occurs. It also resembles antigorite but is characterized by delicate fibers that show positive elongation.

Dolmage,¹² describing serpentine from the Marble Bay mine, states that it has either a dark green or honey yellow color in hand specimen. It is homogeneous in appearance, has a flinty fracture, a greasy luster and is noticeably translucent. Under the microscope two varieties are observed, the fibrous variety, asbestos and the platy variety, antigorite. This parallel arrangement is, however, not common, the greater portion has a platy structure and therefore, belongs to the antigorite variety.

Several classifications of serpentine and antigorite, based on petrographic studies, have been made. These classifications have been based primarily on the fibrous nature of serpentine in contrast to the flaky structure of antigorite as originally described by Schweizer and later by Hussak.¹³

*Drasche*¹⁴ in his study of serpentines divided them into two classes; true serpentine and serpentine-like rocks. Both were very similar in chemical composition. The former showed the typical mesh structure of serpentine derived from olivine. The latter was both different in hand specimen and under the microscope. He described a specimen from Windisch Matrey in northern Tyrol as best representing the latter class. The groundmass consisted of a network of elongated sections of a rhombic mineral. These sections were rectilinear and sometimes so thin that they could be called needles. They showed parallel extinction and a perfect cleavage parallel to the long axis. Other sections, showing irregular boundaries were alternately birefringent and dark under crossed nicols. The mineral was biaxial. He inferred that the irregular sections were cut parallel to a cleavage, while the elongated sections were cut at right angles to a cleavage. He entertained the idea of chrysotile in a flaky form, but as it was insoluble in HCl, he decided to consider the mineral as bastite because of its association with pyroxene.

In 1905 *Bonney* and *Raisin*¹⁵ drew the following conclusions concerning the minerals forming serpentine:

(1) That a tint and pleochroism are accidental rather than essential characteristics of the variety of the mineral serpentine named antigorite.

(2) That, if low polarization tints be regarded as an essential characteristic of antigorite, a closely associated mineral must exist, which is distinguished only by higher birefringence. If the minerals can be isolated and subjected to analysis they may prove to be distinct: but the way in which, as described in the preceding pages, they seem to graduate one into the other, leads us to believe that they are varieties of a single mineral—antigorite. Both forms usually afford straight extinction but it is occasionally oblique, though the angle is small. Thus, either the mineral is dimorphous, or its optical characters have been affected by pressure, or it is really monoclinic.

(3) That it is doubtful whether any hard-and-fast line can be drawn between the rather fibrous forms of the mineral in the ordinary serpentine-rocks and the mica like (antigorite) of certain others.

(4) That the most typical antigorite occurs when the rock has been considerably affected by pressure, but that it becomes rather less typical when the pressure has been very great (that is in the most slaty serpentines).

*Tertsch*¹⁶ is able to distinguish two minerals in all of the serpentine occurrences of the Dunkelsteiner Granulitmassives. Both are finely fibrous with $n=1.54$ and the birefringence varying from .006 to .010. They are usually colorless in thin section, exceptions being colored light chrome green without recognizable pleochroism. The two minerals are distinguished by the optical character of the fiber axis. The first, which he calls gamma serpentine, is optically comparable to chrysotile. It usually shows weaker refringence and birefringence than the second, which he calls alpha serpentine. This type has negative elongation.

These two minerals occur together in two different combinations, namely; mesh and window structures. (See Figs. 2 and 3 of Tertsch, p. 188). In the mesh structure type the meshes are marked by lines of metallics. Bands of gamma serpentine, with the fiber axes normal to their length, run parallel to the lines of metallics. The enclosed field is composed of triangular sectors of alpha serpentine with the fibers oriented at right angles to the walls of the veins. Higher magnifications show a transverse parting in the alpha serpentine. Often a brownish turbidity runs parallel to the field boundaries. The birefringence of both of the minerals varies as the stage is rotated. The center of the field is almost isotropic and shows a small negative optic angle.

Serpentine with window structure shows the reverse relationship of the two minerals. Fairly regular parallelogram meshes are built by bands of alpha serpentine. The fields are composed of gamma serpentine. The fibers in both the bands and the fields are perpendicular to the length of the bands. The center of the field shows a probable uniaxial figure. Although no original mineral was found Tertsch concludes that it was olivine.

Angel and *Martiny*¹⁷ describe a mesh structure serpentine from Kraubath as chrysotile. The meshes surround fresh olivine. The centers of the veins are sometimes isotropic, weakly anisotropic or filled with antigorite. Figure 2 shows the optical orientation of the fibers described by them.

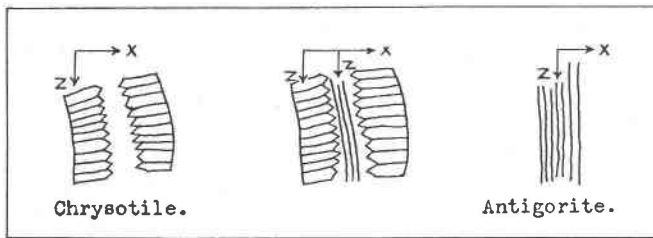


FIG. 2. Illustrating the optical orientation of the fibers of mesh structure serpentine from Kraubath. By Angel and Martiny.

*Angel*¹⁸ in his study of the Stubachit serpentine made the following classification to distinguish the forms in which antigorite and fibrous serpentine occur:

EINZELFORMEN UND ZWILLINGE (after Angel)

I. Blätterserpentin (Antigorit)

$\alpha \perp$ zur Blattfläche und Spaltung.

(A) Grobblättriger.

1. Kluffantigorit,
2. Freier Fächerantigorit,
3. Füllungs-Fächerantigorit.

(B) Feinblättriger.

1. Feinantigorit.

II. Faserserpentin.

(A) Goldfaserserpentin (Chrysotil).

c = Faserachse.

1. Kluffchrysotil,
2. Rahmenchrysotil,
3. Bastitfaser,
4. Villarsitfaser.

(B) Gemeiner Faserserpentin

α = Faserachse.

1. Gemeine Klufffaser,
2. Gemeine Rahmenfaser.

Explanation of Angel's Terms.

The "Kluftantigorit" consists of coarse leaves of some length visible to the unaided eye in hand specimen.

The "Freier Fächerantigorit," which is common to the Ganoz serpentine, is composed of fan-shaped twins interlaced through one another to form an aggregate. In a single fan the orientation varies from leaf to leaf giving wavy extinction. The widths of the leaves also vary from one to another in a single fan-shaped twin. In many of the serpentines the simple fan stands out stronger than the aggregate.

"Füllungs-Fächerantigorit" at the first glance presents an hour glass figure. Closer study shows it to be a lattice structure with fairly developed sectors, whose contacts are not rectilinear but bowed or crumpled. It is composed of twinned antigorite with the leaves cut at right angles to the base. The fields are made up of roll-like, superimposed antigorite leaves. At times the fan shapes can be seen. This type of antigorite has only been observed with such clearness in the Ganoz serpentines. The difference between the preceding class and this, is that the antigorite is seen as sheafs with almost ravelled out ends in the former, while the ends of the "Füllungs-Fächerantigorit" are cut off evenly.

"Feinantigorit" accompanies the coarser, building felted masses.

The "Kluftchrysotil" is found in veins.

The "Rahmenfaser" which belongs, in part, to chrysotile and, in part, to the common type fills the spaces in lattice structures.

The "Bastitfaser" type consists of single fibers which have the form of "sphärischen Zweiecks," of moderate length and with Z parallel to the long axis. This can be regarded as similar to a crystal of chlorite that has developed along the *c*-axis resulting in a columnar to fibrous form instead of the normal platy form after (001). This conception is supported by the fact that a cleavage runs at right angles to the length of the fibers that can be coaxial with that of the antigorite cleavage. This type occurs with pyroxene.

The "Villarsitfaser" likewise deals with oriented fibers as in bastite but occurs in olivine.

FRAGMENT STUDIES

Sized fragments of each of the specimens of the two groups were examined by the immersion method. All of the available optical properties were noted together with any detail that might lead to a clue that would help to differentiate the two groups optically. The color, purity, shape of fragment, elongation, optic sign, birefringence and the indices were recorded wherever possible. The indices were indeterminate in certain specimens because of a clouded condition of the fragments which destroyed the usefulness of the Becke line. The physical structure of the different varieties was much more evident in the shapes of the fragments than in the thin sections. Many of the types in both groups, whose fragments were splintery, gave no indication of their splintery nature in the thin sections.

The most important properties have been tabulated in Tables I to IV inclusive. These also include some data compiled from the study of the thin sections. In the column marked "Extinction of fragment" only the extinction of the elongated fragments is recorded. Usually, the extinction is complete in these. Larger fragments are occasionally slightly

mottled with mass extinction essentially parallel to the elongated direction of the fragment. The massive type of fragment gives aggregate to complete extinction on rotation of the stage.

Several significant features are apparent in the tabulation. Massive, lamellar and fibrous varieties in hand specimens occur in both serpentine and antigorite. The average indices for serpentine are slightly lower than those for antigorite. The general range of the indices of serpentine is, from that of balsam 1.538, to 1.570. The indices of antigorite range from 1.558 to 1.577. From these figures one may select the average limits 1.538 to 1.570 for serpentine, and 1.555 to 1.580 for antigorite. There is so little difference in the average indices of refraction between the two groups that it would be impossible to differentiate the greater number of the specimens in thin section or fragments on the basis of indices alone.

With the exception of penninite, Winchell¹⁹ lists all of the optically negative chlorites with indices ranging from 1.580 to 1.640. These differences of indices would help to distinguish the remaining optically negative chlorites from serpentine and antigorite.

The average birefringence of serpentine in Tables I, II and III is from 0.007 to 0.008. This is from 0.002 to 0.003 greater than the average birefringence of antigorite. More optic signs, usually showing a small optic angle, were obtained in antigorite than in serpentine. A striking feature of the recorded optic signs throughout both groups is that, with three exceptions which occur in serpentine, they are all biaxial negative. Optically positive serpentines have been reported by Buerger,²⁰ Creveling²¹ and others. The index of the mineral reported by Creveling suggests that it is deweylite rather than serpentine. It is possible that a greater percentage of optically positive varieties exist, as optic signs were not obtained for all of the specimens studied. This was due either to the fineness of fiber, the diversity of orientation of the fibers or the cloudy condition of the fragments. Where one was able to determine the optical character in fragments, the determination could usually be repeated in the thin section.

The examination of the hand specimens of the three serpentines with positive optical character shows that No. 67 is definitely brittle and fibrous to columnar. Nos. 4 and 68 are massive. Nos. 67 and 68 come from the same locality but vary somewhat in hand specimen. The fragments of all three are splintery. Nos. 4 and 68 are probably on the border line, between massive serpentine and the coarse, brittle, splintery variety. These are the only two in Tables I and II that have splintery fragments. The thin sections were cut at right angles to their elongated structure, which was determined by breaking the specimens. None show their

TABLE I. SERPENTINE

No.*	Specimen and Locality	Description	Nature of fragment	Extinction of fragment	Elongation of fragment	α	γ	$\gamma-\alpha$	Optic sign
1	Serpentine, Turkey Mountain, New Jersey	amber, massive, translucent	massive			1.546	1.550	.004	2V(-)
4	Schweizerite, Dognacsa	greenish-yellow, massive, opaque	splintery	parallel	positive	1.556	1.564	.008	2V(+) small
6	Marmolite, Hoboken, New Jersey	light green, foliated, pearly luster	massive, semi-platy			1.545	1.551	.006	2V(-) small
21	Serpentine, Globe, Arizona	light tan, massive, opaque	massive			1.548	1.556	.008	
33	Gymnite, Fleims, Tyrol	white, massive, opaque	massive			1.543	1.547	.004	
40	Marmolite, Tilly Foster mine, N.Y.	grayish-green, massive, semi-platy	massive			1.538	1.545	.007	
41	Marmolite, Chester County, Penn.	gray, massive, opaque	massive			1.551	1.559	.008	
45	Serpentine, New Jersey	medium green, massive, opaque	massive			1.552	1.559	.007	2V(-)
46	Serpentine, Gawrilowsk mine, Urals	dark green, massive, opaque	massive			1.538	1.546	.008	2V(-)
47	Serpentine, Montville, New Jersey	grayish-white, massive, opaque	massive						
49	Serpentine, Easton, Penn.	yellowish-green, massive, translucent	massive			1.546	1.554	.008	2V(-)
59	Vorhauserite, Monzoni, Tyrol	brown, massive, opaque	massive						
60	Retinalite, Perth, Canada	dark grayish-green, massive, opaque	massive						

* Refers to collection number.

TABLE I. (Continued)

No.*	Specimen and Locality	Description	Nature of fragment	Extinction of fragment	Elongation of fragment	α	γ	$\gamma - \alpha$	Optic sign
62	Genthrite, Colerain Township, Can.	light green, massive, conchoidal fracture	massive						
66	Retinalite, Montville, New Jersey	yellowish-tan, massive, translucent	massive			1.544	1.551	.007	
68	Serpentine, Nil Desperandum, South Rhodesia, S. Africa	medium green, massive	splintery	parallel	positive	1.559	1.567	.008	2V(+) small
70	Marmolite, Tompkinsville, Staten Island, N.Y.	light tan, massive, opaque	massive			1.551	1.557	.006	
76	Marmolite, Chapin mine, Iron Mt., Mich.	white, brownish tinge, massive	massive			1.558	1.563	.005	
79	Serpentine, Newburyport, Mass.	dark green, massive, opaque	massive			1.554	1.561	.007	
93	Serpentine after dolomite, Tilly Foster mine, N.Y.	yellowish-white, massive, opaque	massive			1.543	1.551	.008	2V(-)
95	Serpentine after olivine, N.C.	medium green, massive, opaque	massive			1.529	1.537	.008	2V(-)
96	Serpentine after ripidolite, Tilly Foster mine, N.Y.	white, massive, opaque	massive			1.541	1.546	.005	
103	Retinalite, Greenville, Canada. U.S.N.M. R-4644	dark brown, massive, opaque	massive						
108	Mn-serpentine, Franklin, N.J.	brown, massive, translucent	massive						2V(-)

* Refers to collection number.

TABLE II. SERPENTINE

No.*	Specimen and Locality	Description	Nature of fragment	Extinction of fragment	Elongation of fragment	α	γ	$\gamma-\alpha$	Optic sign
3	Serpentine, Staten Island, N.Y.	light green, massive, opaque	massive			1.551	1.559	.008	2V(-)
10	Serpentine, Tilly Foster mine, New York	medium green, massive, pseudo-cubic	rectangular	parallel					2V(-)
12	Serpentine, Thetford, Quebec	yellowish-green, massive, translucent	massive			1.547	1.554	.007	2V(-)
17	Pyroïdesine, Regla, Cuba	grayish-green, massive, opaque	massive			1.564	1.570	.006	
19	Serpentine after chrysolite, Snarum, Norway	greenish-yellow, massive, opaque	massive			1.552	1.559	.007	
20	Serpentine, Somerville, N.J.	greenish-yellow, massive, opaque	massive			1.546	1.554	.008	2V(-)
43	Marmolite, Castle Rock, Hoboken, N.J.	grayish-green, massive, opaque	massive			1.558	1.564	.006	
44	Serpentine, Turkey Mt., N.J.	yellowish-green, massive, translucent	massive			1.552	1.560	.008	2V(-)
58	Serpentine, Snarum, Norway	greenish-yellow, massive, opaque	massive			1.552	1.560	.008	
77	Retinalite, Montville, N.J.	light yellow, massive, translucent	massive			1.553	1.560	.007	2V(-) small
97	Thermophyllite, Finland	gray, massive, with mica	massive						2V(-)
105	Bastite, Baste in Harz, Germany. U.S.N.M. R-2966	black, massive, with pyroxene	massive			1.556	1.564	.008	
109	Vorhauserite, Franklin, N.J.	brown, in veins, translucent	massive			$n =$ 1.563			2V(-)
110	Serpentine, Morrisville, Vermont	dark green, massive, opaque	massive						

* Refers to collection number.

TABLE III. CHRYSOTILE

No.*	Specimen and Locality	Description	Nature of fragment	Extinction of fragment	Elongation of fragment	α	γ	$\gamma - \alpha$	Optic sign
13	Chrysotile, Morris Co., N.J.	honey, amber, silky, $\frac{1}{2}$ in-fibers	fibrous	parallel	positive	1.544	1.551	.007	
14	Asbestos, Globe, Arizona	light tan, silky, 1 in-fibers	fibrous	parallel	positive	1.532	1.545	.013	
15	Asbestos, Staten Island, N.Y.	greenish-white, silky, $\frac{1}{2}$ in-fibers	fibrous	parallel	positive	1.537	1.553	.016	Variable
16	Chrysotile, Hance mine, Arizona	light tan, silky	fibrous	parallel	positive	1.542	1.550	.008	
30	Chrysotile, Thetford, Quebec	dark green, 1 $\frac{1}{2}$ in-fibers	fibrous	parallel	positive				
61	Asbestos, Gawrilowsk mine, Urals	dark green, $\frac{1}{2}$ in-fibers	fibrous						
75	Chrysotile, Montville, New Jersey	amber, silky, $\frac{1}{2}$ in-fibers	fibrous	parallel	positive				

SERPENTINE									
No.*	Specimen and Locality	Description	Nature of fragment	Extinction of fragment	Elongation of fragment	α	γ	$\gamma - \alpha$	Optic sign
38	Schweizerite, Zermatt, Tyrol	dark green, massive, semi-platy	splintery	parallel	positive	1.552	1.563	.011	2V(-)
53	Metaxite, Schwarzenberg, Saxony	grayish-white, radiating brittle fiber	splintery	parallel	positive	1.552	1.560	.008	2V(-)
54	Metaxite, Schwarzenberg, Saxony	light green, splintery, semi-platy	splintery	parallel	positive	1.545	1.560	.015	2V(-)
55	Metaxite, Silesia	gray, massive, conchoidal fracture	massive, platy			1.550	1.557	.007	
64	Schweizerite, Dognacsca	chalky-white, radiating, brittle fiber	splintery in part						
67	Serpentine, Shabani mine, S. Africa	medium green, brittle fiber	splintery	parallel	positive	1.551	1.559	.008	2V(+)

* Refers to collection number.

TABLE IV. ANTIGORITE

No.*	Specimen and Locality	Description	Nature of fragment	Extinction of fragment	Elongation of fragment	α	γ	$\gamma - \alpha$	Optic sign
2	Antigorite, Antigorio valley, Piedmont	grayish-green, thin lamellae	massive, platy			$\beta =$ 1.574			2V(-) small
5	Williamsite, State Line mine, Penn.	emerald green, massive, translucent	massive		positive	1.559	1.563	.004	2V(-)
7	Picrolite, North Carolina	dark green, brittle, splintery	splintery	parallel	positive	1.567	1.573	.006	2V(-)
23	"Serpentine," Manchuria. Antigorite. U.S.N.M. 94356	grayish-white, opaque, massive	massive			1.558	1.562	.004	
24	Picrolite, Buck Creek, Clay Co., N.C.	medium green, radiating brittle fiber	splintery	parallel	positive	1.562	1.567	.005	2V(-)
25	Picrolite, South Lorraine, Ont.	grayish-green, brittle fiber	splintery	parallel inclined	positive				
27	Bowenite, Smithfield, R.I.	grayish-white, greenish cast, massive	massive			1.557	1.562	.005	
28	Williamsite, Texas, Pennsylvania	grayish-white, massive, opaque	massive			1.555	1.560	.005	
29	Williamsite, State Line mine, Penn.	greenish-white, massive, translucent	massive			1.559	1.564	.005	2V(-)
36	Williamsite, Texas, Pennsylvania	dark green, massive, opaque	massive			1.563	1.568	.005	2V(-) small

* Refers to collection number.

TABLE IV. (Continued)

No.*	Specimen and Locality	Description	Nature of fragment	Extinction of fragment	Elongation of fragment	α	γ	$\gamma - \alpha$	Optic sign
37	Antigorite, Trafoß, Styria	leek green, massive, platy	massive, platy			$\beta = 1.575$			2V(-)
42	Marmolite, New Zealand	dark green, semi-platy	splintery	parallel	positive	1.566	1.572	.006	small 2V(-)
57	Baltimorite, Bare Hills, Md.	grayish-green, brittle fiber	splintery	parallel	positive	1.559	1.565	.006	small 2V(-)
101	Bowenite, Lincoln, R.I. U.S.N.M. C-3772	grayish-white, massive, opaque	massive			1.557	1.562	.005	2V(-)
8	"Serpentine," Texas. Antigorite	green, brittle fiber to platy	splintery	parallel	positive	1.561	1.566	.005	2V(-)
52	"Serpentine," Chester Co., Penn. Antigorite	dark green, semi-platy	massive, platy			1.564	1.569	.005	2V(-)
63	Picrosime, Toblitz, Saxony	medium green, brittle fiber to columnar	splintery	parallel	positive	1.558	1.565	.007	small 2V(-)
69	"Serpentine," Staten Island, N.Y. Antigorite	dark green, brittle fiber to platy	splintery		positive	1.558	1.565	.007	small 2V(-)
78	"Serpentine," altered pyroxene, Md. Antigorite	green, massive to splintery	splintery	parallel	positive	1.563	1.568	.005	small 2V(-)
100	Porcellophite, Staten Island, N.Y.	grayish-green, massive, opaque	massive			1.558	1.563	.005	2V(-)

* Refers to collection number.

TABLE V. DEWEYLITE

No.*	Specimen and Locality	Description	Nature of fragment	Extinction of fragment	Elongation of fragment	α	γ	$\gamma-\alpha$	Optic sign
31	Deweylite, Texas, Pennsylvania. U.S.N.M. 9757	amber, incoherent masses	massive			near 1.500	near 1.509	.009	2V(+)
34	Deweylite, Delaware, Pennsylvania	white, granular, with quartz	massive			1.487	1.510	low	small
35	Deweylite, New Rochelle, N.Y.	white, massive, opaque	massive			var.	var.		
51	"Serpentine," after pectolite. Deweylite, Jersey City, N.J.	gray, massive, radiating	massive	parallel	positive	1.538	1.546	.008	
104	Deweylite, Lancaster County, Pennsylvania	light tan, gum-like masses	elongate massive			$n = 1.500$			2V(+)

* Refers to collection number.

splintery nature in thin section. Their optically positive character can possibly be explained on the basis of a closer optical relationship to chrysotile than to massive serpentine. It would have been of interest to find a serpentine with massive fragments and positive optical character.

The birefringence of chrysotile apparently has a much broader range than that of massive serpentine or antigorite. This is also true of some members of the brittle, splintery serpentine in Table III.

The optical properties of deweylite have been included in this study because of its close relationship to serpentine. These are listed in Table V. In general it appears that the indices of refraction of deweylite vary over a wide range. The material from Pennsylvania has $n=1.500$ as an average. The grains are composed of aggregates and concentric structures of radiating fibers similar in appearance to chalcedony. The extreme limits of the indices are those shown in #34. The actual birefringence is much lower than the indices indicate. It is probably in the neighborhood of .009 as is shown in #31. The indices listed here are those in which the index of refraction of the maximum number of grains appeared to equal that of the liquids.

No explanation could be found for the higher indices of No. 51. Duplicate x -ray patterns show that it is deweylite. Optically it approaches serpentine.

The indices of the manganiferous serpentine from Franklin Furnace have been determined by Larsen²² to be as follows: $\alpha=1.561$, $\gamma=1.568$, $\gamma-\alpha=0.007$. The mineral is biaxial negative. The indices fall close to those of bowlingite and antigorite in Larsen's Tables.

THIN SECTION STUDY

Various specimens from each group were selected for thin section study. Their selection was based on the results obtained from the x -ray and fragment studies. Minor amounts of impurities, chiefly carbonate or metallics, are present in some of the sections. Usually these are not found in sufficient quantities to give lines on the x -ray patterns. In several of the patterns of serpentine three extra lines appear which are attributed to some impurity. A chlorite like mineral is present in two of the thin sections made from specimens showing the extra lines in the x -ray patterns. In the pearly marmolite from Hoboken (#6) the impurity occurs in such a fine scaly form that it gives the whole thin section an iridescent appearance. The serpentine is seen by itself only on the edges of the thin section. This chlorite-like mineral is biaxial negative. The indices are similar to those of serpentine. Its birefringence is low. The lamellar structure of the serpentine is probably due to this mineral and not to an inherent characteristic.

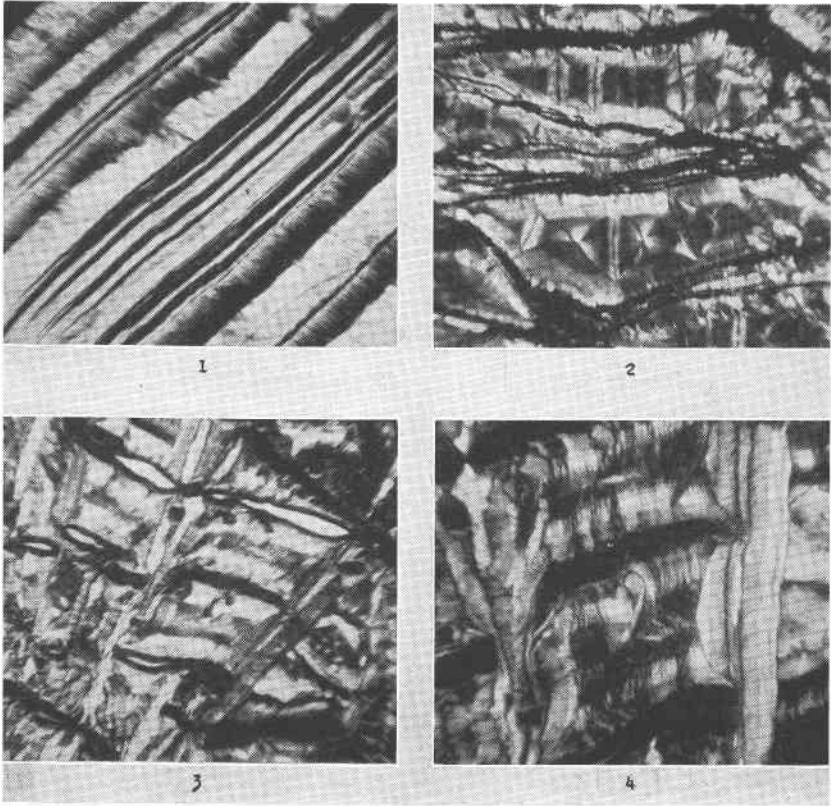


PLATE II

- FIG. 1. Serpentine (#1) from Turkey Mountain, N.J., showing fibers and bands. $\times 56$
 FIG. 2. Hour glass structure as developed in bastite from Baste, in Harz, Germany. $\times 56$
 FIG. 3. Serpentine (#20) from Somerville, N.J., showing mesh structure. $\times 30$
 FIG. 4. The same field as is shown in Fig. 3. $\times 56$

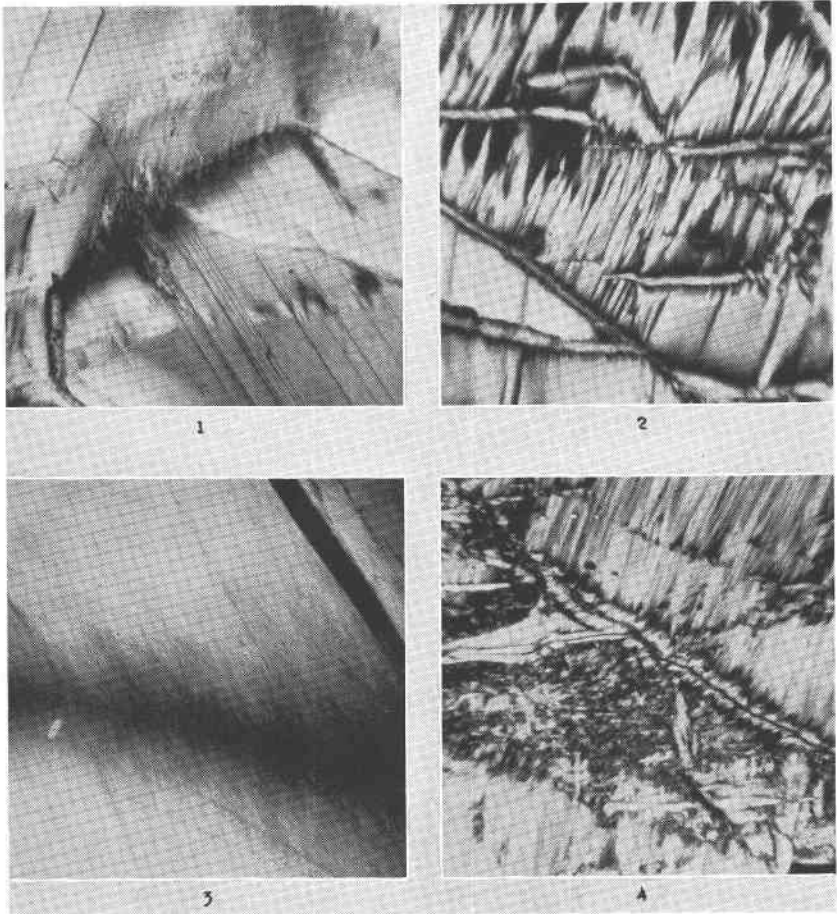


PLATE III

FIG. 1. Retinalite (#66) from Montville, N.J., showing pseudo-lamellae and severed fibers. $\times 56$

FIG. 2. Serrated structures in retinalite (#66) from Montville, N.J. $\times 23$

FIG. 3. Sweeping extinction in schweizerite (#38) from Zermatt, Tyrol. $\times 15$

FIG. 4. Williamsite (#5) from the State Line mine, Pennsylvania. $\times 56$

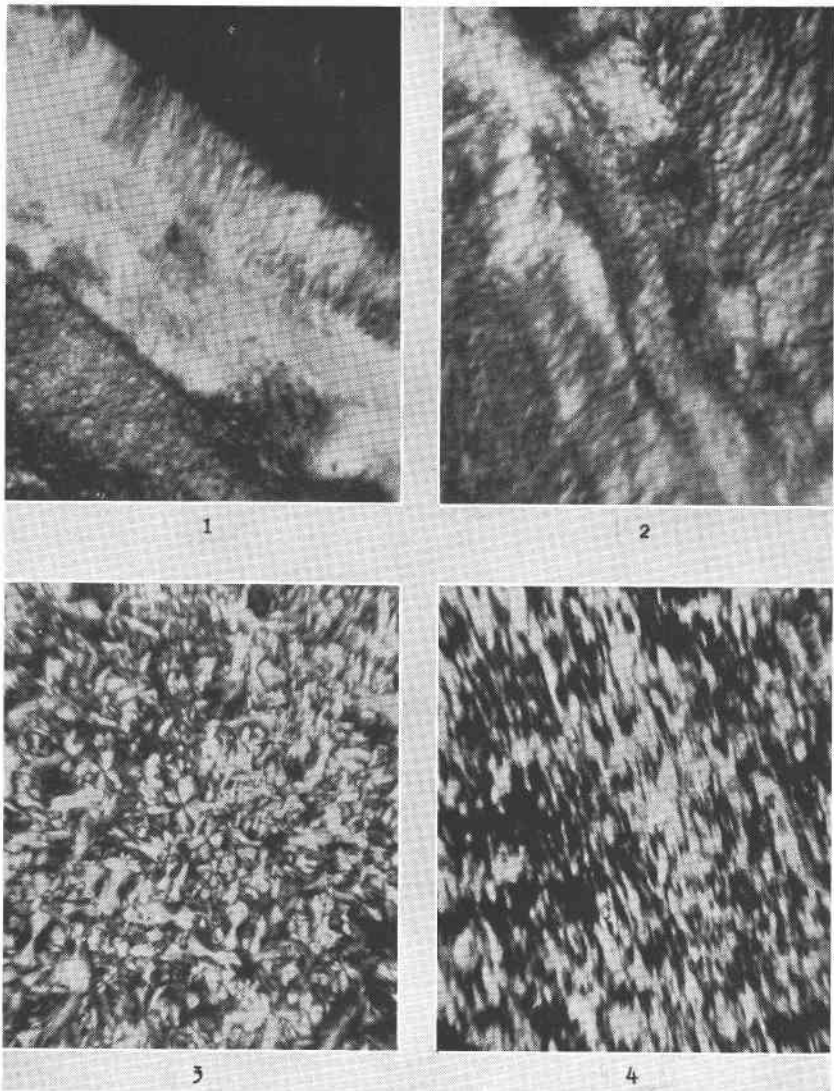


PLATE IV

FIG. 1. Vein-like mass of fibers in antigorite (#2) from Antigorio valley, Piedmont, Italy. $\times 56$

FIG. 2. Showing the vein-like mass of Fig. 1 on slight rotation of the stage. $\times 56$

FIG. 3. Bowenite (#27) from Smithfield, Rhode Island. $\times 56$

FIG. 4. Mottled extinction in picrosmine (#63) from Toblitz, Saxony. $\times 56$

The study of the thin sections of both groups shows that the fundamental structure of each can be considered as fibrous. This property is much more evident when strong artificial light is used. Very little detail can be seen in the sections in plain light because of their low relief and lack of color. They appear as flat, structureless surfaces with the iris diaphragm contracted. The slides of antigorite, Nos. 2 and 37, are the only ones showing a faint tinge of color. Pleochroism is not observable in any of the sections. The fibers form larger structural units of varying aspect depending on their orientation and size. A question might arise concerning the boundary between elongated cleavage units and fibers. When viewed under higher magnifications, needle-like to lath-like units are resolved into still finer units of clearly fibrous appearance. Some of the larger structural units have duplicates in both of the groups. In some cases it is difficult to distinguish optically the group to which a specimen belongs because of the similarity of these features. Aggregates, anhedral units, structureless fields, veins, mesh structures, hour glass structures, etc., occur both individually and in combinations of two or more. The typical mesh structure found in the alteration of olivine to serpentine is the only one limited to serpentine. It appears from the study of the thin sections of the two groups that both are composed of warped planes of fibers, which are bent and twisted. In antigorite these possibly form coarser, coherent units to give it the described cleavage which is so little evident in thin section. The description of various thin sections of serpentine and antigorite will present the difficulties that can be encountered when one attempts to draw a sharp line, optically, between the two groups.

Descriptions of Serpentine.

Specimen #17, labelled gymnite, is really serpentine as shown by the x -ray pattern, and not a variety of deweylite, although it has an appearance, in hand specimen, similar to that of deweylite #35. In thin section it is composed of short, lath-like units which form elliptical to polygonal boundaries around carbonate, and weakly anisotropic to isotropic centers of serpentine. These units appear to have followed the crystal boundaries of the carbonate. They are distinctly fibrous, possess positive elongation and show wavy, approximately parallel extinction. Cleavage is not observable. These brighter anisotropic units compose so much of the material that they would definitely show in the x -ray pattern if they were antigorite. These units are similar in appearance to some in the sections of bowenite and "serpentine" #23 in the antigorite group.

The fibrous nature of the amber serpentine (#1), from Turkey Moun-

tain New Jersey, is distinctly shown in Fig. 1, Plate II. The fibers occur, roughly oriented, in tabular to anhedral units of varying sizes. A possible parting can be seen along the severed ends of a few units. All of the fibers possess negative elongation. They are, therefore, optically similar to the alpha serpentine described by Tertsch. The extinction is distinctly wavy, indicating that the fibers are not oriented in a strictly parallel sense, but that they are interlaced with their fiber axes roughly oriented in one direction. Marked inclined extinction is not uncommon. Some of the units exhibit mottled extinction similar to that shown in Fig. 4, Plate IV, while others exhibit fine grained aggregate extinction.

The bands in the figure are not due to polysynthetic twinning as some of the finer ones appear to be under low magnification. They are tabular layers of fibers that have been cut diagonally. The layers vary in width and usually narrow down and pinch out on the ends as the three narrow bands do in the lower left hand corner of the photograph. This indicates warping of the fibrous planes in more than one direction. The bands usually occur in distinctly fibrous fields similar to those shown in Fig. 1, Plate III. This banding may become so fine that it appears as if the fibers run at right-angles to their true fiber direction. (See Fig. 3). This effect gives one an erroneous elongation. The banding is explained as due to microfolding of the fibers in an anhedral unit. The section is cut roughly parallel to the direction of the fibers. Each time there is a slight bending the fibers are cut off as shown in Fig. 4. The shorter the distance between the crests of the folds, the closer the bands lie together. This same banded effect is also produced by sharply folded, unsevered fibers that have been moved sidewise in the plane of the section. A serpentine (#3) from Staten Island shows this type of folding accompanied by microfaulting.

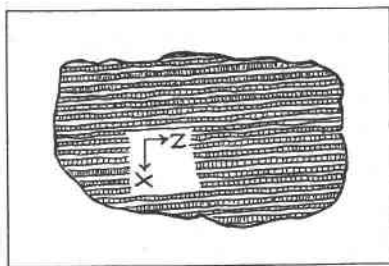


FIG. 3. A fibrous unit showing the optical orientation of the fibers in the false fiber effect produced by microscopic banding.

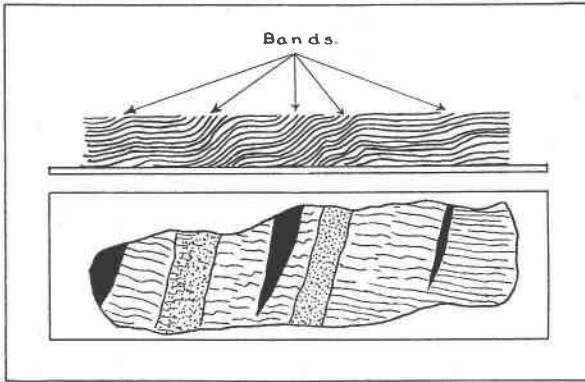


FIG. 4. A plan and section of a fibrous unit showing banding.

Fig. 1, Plate III, representing a section of retinalite (#66) from Montville, New Jersey, shows the pseudo-lamellar units that can be produced when a section is cut parallel to the direction of the fibers. The fibrous nature of the unit can be seen in the dark border and the area just above it. The units show wavy to mottled extinction, thereby indicating that the fibers are not perfectly parallel. The fibers have dominant negative elongation and variable angles of extinction. The dark lines, which are distinctly anisotropic, are not due to cleavage but to planes of differently oriented fibers. Under the microscope incipient serrated structures, similar to those shown in Fig. 2, Plate III, can be seen along the dark border. The borders produced by cutting off the fibers transversely or on the bias can be traced until they narrow down and disappear in a homogeneous, fibrous field. Several small cone-like bulges can be seen near the lower right hand corner of Fig. 1, Plate III. They owe their presence to a slight upwarp of the fibers in the unit. The bulges may become changed sufficiently in orientation to produce the borders or the serrated forms of Fig. 2, Plate III.

A fine structureless aggregate occurs where the anhedral units have been cut off at right angles to the length of the fibers. The thin sections consist of mixed areas of pseudo-lamellar fields, serrated fields and structureless aggregates due to the diversity of orientation and size of the fibrous, anhedral units composing the specimen.

Fig. 2, Plate III, is a photograph taken of the same thin section as Fig. 1, Plate III. Two tabular units, showing the severed ends of the fibers, join to form a V. Above these, the serrated figures are developed to a high degree. These serrated figures are formed in an adjoining unit which is differently oriented from the units composing the two surfaces

of the V. This serrated field can be traced upward with the number of peaks diminishing and finally ending in a fibrous, pseudo-lamellar field with undulous extinction and bordered with the ends of clipped fibers. Incipient serrated structures can be seen along the edges of the V. These are more clearly defined with a slight rotation of the stage. The serrated structures possess negative elongation when they have a small angle of extinction and closely parallel the fiber direction of the pseudo-lamellar unit.

Probably the most diagnostic structure of serpentine is the mesh structure which is formed in the alteration of olivine to serpentine. Excellent examples of this structure are found in serpentine (#20) from Somerville, New Jersey. (See Fig. 3, Plate II.) Rows of meshes are usually bounded by two veins of some length with short, transverse veins between them. The centers of the veins may be isotropic, weakly anisotropic or strongly anisotropic between crossed nicols. Sometimes they consist of a string of metallics. When the center of the vein is anisotropic, as distinctly shown in Fig. 3, Plate II, it is always found to have the axis of least ease of vibration normal to its length. (See Fig. 5). An undulous extinction indicates that it is probably fibrous. It is usually impossible to determine in what direction the fibers are oriented. However, a few of the centers show that the fibers are oriented normal to the length of the vein. This type of fiber is comparable to chrysotile and the gamma serpentine of Tertsch.¹⁶ The brighter birefringent centers may form lenses. At times these lenses pinch out until they are nothing more than a single line. This narrow line can be detected in many of the weakly anisotropic to isotropic centers. It always shows that the axis of least ease of vibration lies normal to its length.

The edges of the veins are composed of twisted fibers that appear interlaced under higher magnification. These form the borders of the meshes. They possess negative elongation and are, therefore, alpha serpentine. The centers of the fields, which are usually weakly anisotropic, sometimes react as if the fibers composing them had their axis of least ease of vibration parallel to their length. With closer study and higher magnification it is clearly seen, in all cases, that the centers of the fields are composed of the fibers bordering the edges of the mesh. The lower birefringence of the center of the mesh is probably due to the compensating effect of the matted fibers. This also explains the weakly anisotropic to isotropic fringes that separate the edges of the veins from the brightly anisotropic center.

In tracing the centers of the veins they are found to vary from the

¹⁶ *Op. cit.*

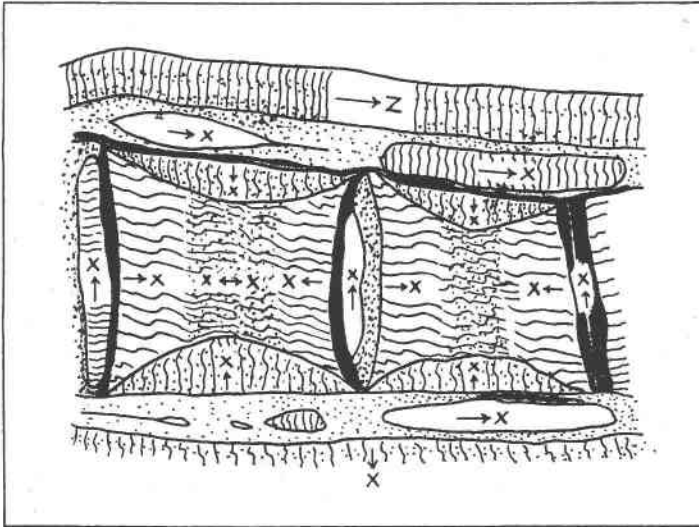


FIG. 5. A diagrammatic sketch showing the optical orientation of the fibers in mesh structure serpentine from Somerville, New Jersey.

distinctly anisotropic material through weakly anisotropic to isotropic material. At the same time the width of the centers narrows until it pinches out or continues only as a fine line with the result that the fibers bordering the vein meet in the center without a line of demarcation. This suggests that the material with positive elongation (gamma serpentine) possibly exists as lenses in a field of fibers with negative elongation (alpha serpentine).

A few scattered areas composed of brightly birefringent fibers with negative elongation are noted. They are bordered by weakly anisotropic material. This same type of fiber is sometimes noted to terminate the fibrous edges of veins that do not form mesh structures. They are usually coarser and lie more nearly parallel than the fibers that terminate in the centers of the meshes. Their birefringence is probably due to the fact that compensation, caused by matting of the fibers, is absent.

Some meshes possess higher birefringent fibers in their centers than on their borders, the reverse of what is shown in Fig. 3, Plate II. In all of the slides, the fibers immediately bordering the centers of vein-like structures possess negative elongation and, therefore, are alpha serpentine. No structures are to be seen comparable to the window structure described by Tertsch.

Fig. 2, Plate II, shows hour-glass structure as developed in bastite

(#105) from Baste, in Harz, Germany. The dark centers of the veins are usually composed of strings of metallics. Rarely a structureless, weakly anisotropic band is present instead of the metallics. The axis of least ease of vibration of this band, if present, is normal to its length. The bordering transverse fibers, which usually occur sufficiently coarse to be distinctly visible, possess negative elongation. The fibers of the fields forming the hour-glass structure vary from distinctly visible, twisted units down to such a size that their presence is only surmised by the wavy extinction produced by rotation of the stage. Their fiber direction is optically negative. The sectors of the fields in which it is impossible to determine the direction of the fibers show the axis of least ease of vibration normal to the length of the veins. Fundamentally this structure is comparable to the mesh structure described above.

The centers of the fields are usually weakly anisotropic to isotropic. The lines that mark the sectors are sometimes chiefly due to the effects of extinction rather than a visible demarcation between fibers of different orientation. The material as a whole is so finely fibrous that it is only with difficulty that the fibers bordering the centers of the veins can be traced into the centers of the fields as they were, with greater ease, in the mesh structure previously described.

A peculiar lense-like structure composed of hour-glass units is formed when two strings of metallics and their accompanying bands join to form one string. This is partially shown on the left hand side of the bottom row of hour glass structures in Fig. 2, Plate II.

Here, as in the mesh structure described above, the widths of the center of the veins are variable, whether they are composed of metallics or serpentine. They narrow down at times until there is no center left. The fibers then pass from one line of hour glass structures to another without interruption. Their fiber direction remains optically negative.

The bastite which has been described in this study is associated with a pyroxene which possesses a metalloidal luster in hand specimen. In thin section the veins of serpentine can be traced into the pyroxene. This type of bastite probably agrees more closely with the fibrous bastite described by Lewis²³ and referred to by Angel¹⁸ as "bastitfaser" than to the descriptions of platy varieties by Winchell,⁶ Du Rietz²⁴ and others.

A homogeneous field, composed of twisted, interlaced fibers, of schweizerite (#38) from Zermatt, Tyrol, is shown in Fig. 3, Plate III. The extinction sweeps across the field after a fashion which is similar to an isogyre of an optic figure. A coarser structure, which is barely evident

¹⁸ *Op. cit.*

⁶ *Op. cit.*, p. 377.

in the thin section, parallels the crack and the vertical cross hair. The section as a unit has positive elongation as was also noted in the fragment study.

The specimens described in the above thin sections are serpentine. These vary from material composed wholly of fibers with negative elongation, through material of mixed fibers of both positive and negative elongation, to fibrous material wholly composed of fibers with positive elongation. The fragments of the first four are massive while those of the last are splintery.

Descriptions of Antigorite.

Fig. 1, Plate IV, of antigorite (#2) from Antigorio valley, Piedmont, shows a distinctly fibrous vein-like mass running across a mottled field. Slight rotation of the stage causes it to blend into the surrounding matted field (Fig. 2, Plate IV). This vein-like mass has been formed by the severing of upturned fibers. Sometimes the fibrous masses are cut off in step-like forms showing positive elongation parallel to the length of the fiber and negative elongation along the direction in which the fiber has been cut. There is not the least indication of a lamellar structure as shown by the micas, chlorites, etc., even in specially cut oriented sections. There are a few higher birefringent, relatively long, wavy streaks that show the material has a fibrous or cleavable orientation. This is only observed where the material has been slightly pulled apart in making the thin section. Fine hair-like fibers usually join the separated units.

The material is somewhat impure as indicated by its cloudy appearance in thin section. The impurity is probably associated with it in fine, dispersed particles. In the original description by Schweizer the mineral was described as non-crystalline and thinly foliated. No mention was made of an existing cleavage. The term slaty would probably describe the hand specimen better than lamellar.

Fig. 4, Plate III, of williamsite (#5) from the State Line mine, Pennsylvania, shows the radial, interwoven, leaf-like forms with wavy extinction and positive elongation that appear somewhat similar to the serrated structures of serpentine (#66) shown in Fig. 2, Plate III. One difference noted is that the leaves appear as individuals rather than forming a unit as they do in specimen #66. The darker area is composed of the severed ends of the units. In some of the areas, where the units are finer grained, and come to points, they are identical to parts of specimen #66. Only a little parting or cleavage can be noted on small individual fragments that run transverse to the leaf structures. These usually occur on top of the clipped units. They possess positive elongation and parallel extinction, although the extinction usually appears wavy. Under higher

magnification the ends of the units have a ragged appearance and assume a brittle fiber aspect. The long diagonal veinlet traversing the center of the picture is due to the material being bent over in making the section. It has a typical fiber structure. The dark line down the center is due to a crack in the material. This specimen, which is grouped with antigorite, is probably the coarsest developed member of the group. It does not show either lamellar structure or pseudo-lamellar units. None of the individuals give a distinct total extinction. Regardless of size or orientation the extinction is always wavy.

Fig. 3, Plate IV, of bowenite (#27) from Smithfield, Rhode Island, shows a fine aggregate chiefly composed of structureless units possessing positive elongation. The extinction of all the aggregate is distinctly wavy or radial. In the center of the picture are two cross-like units composed of radiating members. When one observes the ragged ends of each small unit under high magnification, they appear to be definitely fibrous rather than lamellar. The extinction is undulatory even in the smallest unit. Cleavage does not appear in the aggregate. It is probable that Angel described material similar to this as being composed of interlaced antigorite twins. In contrast to this Niggli²⁵ states, "the nephrite-like, apple green to greenish-white bowenite is only recognizable as a fibrous aggregate under the microscope."

Fig. 4, Plate IV, of picrosmine (#63) from Toblitz, shows the mottled extinction produced under crossed nicols by a distinctly fibrous variety of antigorite. The sides and ends of the section are distinctly fibrous although there is not the least indication of a cleavage in the body of the section. The fibers are interlaced and differently oriented. With rotation of the stage neither a relatively light or dark field is obtained.

The fibrous nature of antigorite is further exemplified by baltimorite (#57). The material is associated with carbonate in the hand specimen. The mineral consists of brittle, columnar units of some length. These units can be divided into easily separable, fine, brittle fibers. In thin section the mineral forms a solid homogeneous field without cleavage indications. It possesses mass extinction. The true nature of the mineral is only seen on the ends of the slide and where it has been torn in making the thin section. Here the fine fibers are readily seen. Long lath-like units are formed where the material has been parted mechanically. They possess parallel extinction and positive elongation. Material such as this could be considered lamellar if occurring in a massive rock and surrounded by grains on all sides which would hold it together sufficiently to keep the fibers from being separated. Occasional parting parallel to the direction of the fibers could be considered as indications of cleavage.

Descriptions of Deweylite

The slide of deweylite (#104) shows the typical concentric forms attributed to the mineral. These are composed of a rim of radiating fibers enclosing an aggregate center. The structure developed by the fibers is similar to that of chalcedony. The fibers possess positive elongation and wavy, approximately parallel extinction. Their relief is definitely negative.

A thin section of deweylite (#51), pseudomorphous after pectolite, shows that the mineral was broken into numerous lath-like units in making the section. They parallel the length of the relict, radiating structure of the pectolite. The units possess positive elongation and parallel extinction. Concentric structures are not noted.

DISCUSSION AND CONCLUSIONS BASED ON OPTICAL STUDIES

The slides that have been described above are illustrative of the structural features observed. These slides were selected as examples and are considered typical. Many other slides have been studied which duplicate the features illustrated. Sometimes the entire slide serves as an illustration; at other times combinations of two or more of the described features may occur. The optical studies did not show that any of the specimens could be combinations of the two minerals, serpentine and antigorite. This is confirmed by the *x*-ray patterns.

Two platy varieties have been identified as the mineral serpentine. These are marmolite from Hoboken and thermophyllite from Finland. The marmolite was originally described as a thin foliated, brittle, lamellar mineral with a pearly luster. Although it was recognized from the chemical analysis that the mineral could be considered a serpentine, it was given a new name because of its crystalline character. Later Vanuxem²⁵ reanalyzed the mineral and concluded that marmolite corresponded with serpentine in all of its important physical and chemical characters with the exception of its crystalline structure and the luster. The study of the thin sections shows that a foreign mineral occurs in such fine laminated form that it gives an iridescence. It is due to the presence of this mineral impurity that marmolite owes its false foliation and luster. The optical properties of marmolite indicate that it is the mineral serpentine. This is confirmed by the *x*-ray pattern.

In thin section thermophyllite shows abundant mica distributed through the serpentine. Here, as in the marmolite, the foliated structure is due to the impurity and not to the serpentine. Thus it appears that foliation is not an inherent characteristic of the mineral serpentine. Serpentine can then be described as occurring in hand specimen either in massive or brittle, splintery forms. Microscopically all of the specimens

are composed of fibers which form structureless aggregates or anhedral units of varying aspect. These fibers are of two classes: those that show negative elongation (alpha serpentine) and those that show positive elongation (gamma serpentine). The latter are comparable to chrysotile fibers. The optic sign may be either positive or negative with the negative sign predominating. When the fibers become of sufficient size and coarseness to be recognized in the hand specimen the mineral may be called chrysotile to denote its asbestos-like properties. The usage agrees with the original definition.

In the antigorite group doubt exists whether antigorite from Antigorio is truly lamellar as the micas, chlorites, etc., are considered, or whether the structure is a stress feature. This material breaks in large sheets with a slaty parting. In thin section it is distinctly fibrous. A certain twisting of the fibers is evident throughout the section. The fibers rarely appear to form thin, warped planes that are comparable to the units produced by the slaty parting. There is nothing in the sections that would indicate a lamellar mineral.

Breithaupt originally described picrosmine with a prismatic cleavage. Later Frenzel²⁷ described a picrosmine, with columnar structure, which was easily cleavable into parallel columns. Under the microscope this showed a finely fibrous structure. This is also true of the picrosmine (#63) described above. Such observations suggest that either fundamentally antigorite is composed of cleavage units so fine that the mineral has the appearance of being fibrous, or cleavage does not exist. Optically it would probably be difficult indeed to distinguish between the brittle, splintery type of serpentine and the corresponding type of antigorite. This is partially shown in Dana's System where metaxite, a serpentine mineral, is classed as a variety of picrolite, an antigorite mineral.

An interesting observation was noted in the thin section study. No veins of the type that form the mesh structures in serpentine were noted in any of the thin sections of antigorite. Further it was observed, both in thin section and in hand specimen, that chrysotile did not accompany any of the antigorite specimens of the study. Specimens Nos. 1, 12, 21, 44, 45, 46, 47, 66, 67, 68, 77 and 110 are associated with veins of chrysotile. These specimens are grouped in the serpentine tables. They represent material from Montville, N.J.; Globe, Arizona; Thetford, Quebec; the Ural mountains; Southern Rhodesia; and Morristown, Vermont. This suggests that the matrix of chrysotile is serpentine and not the mineral antigorite, as is thought by some authors. This appears more plausible when the interplanar spacings are considered. The transformation of serpentine to chrysotile would only require a recrystallization with probably negligible change in the interplanar distances. For chryso-

tile to originate in antigorite would not only require recrystallization but an appreciable change in the interplanar distances to account for the differences between the patterns of serpentine and antigorite. A detailed study of the matrix of chrysotile from many more localities will be needed to prove or disprove this suggestion, but it is significant, at least, that such a group of samples as listed above is in agreement.

THE CHEMISTRY OF THE SERPENTINE GROUP AND DEWEYLITE

Serpentine and antigorite are considered dimorphous forms of the same compound, $H_4Mg_3Si_2O_9$. Tables VII and VIII list analyses compiled from the literature. Some are the original analyses given with the description of the specimen while others are re-analyses of purer material. None are recent and, therefore, all are only relatively dependable.* They were selected, partly, to represent the type mineral species described and, partly, because the description of the analyzed specimens tallied closely with that of some of the studied specimens.

TABLE VII. SERPENTINE

No.	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MgO	CaO	H ₂ O	Na ₂ O	NiO	MnO	Total
1	43.50	0.40		2.08	40.00		13.80				98.78
2	41.58	0.42		1.69	42.61		13.70				100.00
3	42.42	0.63	0.62		41.01	tr	15.64		0.23		100.55
4	40.23	2.18	4.02		39.46		14.24				100.13
5	42.38	0.07	0.97	0.17	42.14		14.12				99.85
6	42.72	0.20	0.68		43.38	0.38	13.40				100.76
7	42.05		0.30	0.10	42.57	0.05	14.66				99.73
8	41.47	1.73		0.09	41.70		15.06				100.05
9	41.59		2.43		42.32		13.55				99.89
10	41.87	2.30			42.43		13.40				100.00
11	42.00	0.26		0.90	41.00		15.00				99.16
12	42.73			2.79	40.37	0.40	12.17	1.52			99.98
13	41.48	5.49		1.59	37.42		10.88	2.84			99.70
14	43.66	0.64		1.96	41.12		13.57				100.95
15	43.12	4.91		1.99	34.87		13.13	1.33			99.36
16	41.21			1.72	39.24		16.16			0.30	98.63

1. Chrysotile, Reichenstein. Kobell.²⁸
2. Chrysotile, Goujot. Delesse.²⁹
3. Chrysotile, Montville. Clarke and Schneider.³⁰
4. Serpentine (green), Montville. Merrill.³¹
5. Serpentine (yellow), Montville. Merrill.³¹

* Mr. J. J. Fahey has kindly supplied more recent analyses which largely confirm the selection included in this paper. A few may be modified slightly on re-analysis. Mr. Fahey will cover this subject in a later paper. In the present discussion the chemical nature of the serpentine minerals is considered only in general terms.

6. Serpentine, Montville. Hillebrand.³²
7. Serpentine (dull green), Montville. Clarke and Schneider.³⁰
8. Serpentine (dark green), Newburyport. Clarke and Schneider.³⁰
9. Serpentine, Snarum. Fogy.³³
10. Serpentine (pseudo-cubic), Tilly Foster. Allen.³⁴
11. Marmolite, Hoboken. Kobell.³⁵
12. Metaxite, Reichenstein. Bauer.³⁶
13. Thermophyllite, Finland. Northcote.³⁷
14. Schweizerite, Zermatt. Schweizer.³⁸
15. Thermophyllite, Finland. Hermann.³⁹
16. Vorhauserite, Monzoni. Kennigott.⁴⁰

TABLE VIII. ANTIGORITE

No.	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MgO	CaO	H ₂ O	NiO	Total
1	41.58	2.60		7.22	36.80		12.67		100.87
2	41.14	3.82	3.01		39.16	0.40	11.85		99.38
3	42.94		3.33	1.88	36.53		13.21	1.61	100.22
4	43.79			2.05	41.03		12.47		99.34
5	41.13	1.23		1.49	43.65	0.17	12.46		100.13
6	42.20	tr		1.56	42.50	tr	13.28		99.54
7	42.50	tr		0.95	43.15	tr	12.84		99.50
8	42.60			1.62	41.90		12.70	0.40	99.22
9	44.50	0.75		1.39	39.70		12.75	0.90	99.99
10	40.95	1.50		10.05	34.70		12.60		99.80
11	44.08	0.30		1.17	40.87		13.70		100.49

1. Antigorite, Antigorio, Brush.⁴¹
2. Antigorite, Sprechenstein. Hussak.⁴²
3. Picrolite, Buck Creek, Clay County, N.C. Clarke and Schneider.³⁰
4. Picrolite, Texas, Pennsylvania. Rammelsberg.⁴³
5. Bowenite, Shigar, Kashmir. McMahon.⁴⁴
6. Bowenite, Smithfield, R.I. Smith and Brush.⁴⁵
7. Bowenite, Smithfield, R.I. Smith and Brush.⁴⁵
8. Williamsite, Texas, Pennsylvania. Smith and Brush.⁴⁵
9. Williamsite, Texas, Pennsylvania. Herman.⁴⁶
10. Baltimorite, Bare Hills, Md. Thompson.⁴⁷
11. Porcellophite. Dana's System.⁴⁸

DEWEYLITE

No.	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MgO	CaO	H ₂ O	Total
1	43.15	tr			35.95		20.25	99.35
2	40.16	tr	1.16		36.00	0.80	21.60	99.72

1. Deweylite, Texas, Pennsylvania. Brush.⁴⁶
2. Deweylite, Bare Hills, Md. Thompson.⁴⁷

A review of the analyses of serpentine in Table VII shows that all agree reasonably well. The same is true of the analyses of antigorite in Table VIII. In comparing the average analyses of serpentine and antigorite a few minor differences can be noted. The magnesia and water content are slightly lower in antigorite than in serpentine. The difference in the water content is more marked than the difference in the magnesia content. This decrease in water in antigorite appears to accompany the slight increase in the average indices of antigorite over those of serpentine.

The analyses of deweylite are included because of the close structural and chemical relationship between deweylite and serpentine. The formula of deweylite is considered to be $4 \text{ MgO} \cdot 3 \text{ SiO}_2 \cdot 6 \text{ H}_2\text{O}$. The formula of serpentine, given in the same way, is $3 \text{ MgO} \cdot 2 \text{ SiO}_2 \cdot 2 \text{ H}_2\text{O}$. The close structural and chemical relationship between the two minerals, along with published analyses of varying water content, suggests that there may be a series of isomorphous minerals between the two groups. This could only be verified by a combination of detailed optical, chemical and *x*-ray investigation of the hydrous magnesium silicates that are listed close to deweylite and serpentine. The low indices of deweylite from Pennsylvania are accompanied by a marked increase in the water content of the mineral.

The deweylite pattern of specimen #51, which displayed optical characters similar to those near the low index end of serpentine, indicates the need for further study of the relationship between deweylite and serpentine. Likewise the low indices of refraction of serpentine #95 are difficult to explain in view of the data at hand.

CONCLUSIONS BASED ON COMBINED X-RAY AND OPTICAL STUDIES AND CHEMICAL DISCUSSION

The *x*-ray and optical studies show that the varieties listed under serpentine are similar in interplanar spacing and closely related optically. The chemical composition does not vary sufficiently to divide the group into different minerals. Although the varieties have a distinctive structural appearance in thin section, this should not be considered a sufficient basis for a separate name. The structures are not characteristic of the mineral serpentine, but are relict structures superimposed on the mineral by an environmental condition. It appears, therefore, that the names schweizerite, metaxite, pyroidesine, marmolite, retinalite, thermophyllite, bastite and vorhausserite should be dropped as distinct species names in the favor of the one term, serpentine.

For the same reasons given in the case of the mineral serpentine, it is

proposed in the case of the mineral antigorite to drop the names picrolite, williamsite, bowenite, porcellophite and baltimorite.

The mineral names serpentine and antigorite have been used in this study in a definite sense. Chrysotile is the flexible fiber form of serpentine. The mineral serpentine continues to designate the type of mineral to which the name was originally applied. The usage proposed in this paper continues the name antigorite, now in common use (although picrolite has priority) as a distinct mineral of the serpentine group. Antigorite and serpentine may not be dimorphous, although chemical analyses do not agree well enough to definitely prove or disprove this relationship.

The term serpentinite is suggested for rocks composed either of serpentine or antigorite, or both together. This rock term would lend itself more easily to the field or laboratory description until the mineral composition is correctly determined. Confusion would thus be avoided in designating the two minerals and the rock.

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