The Serpentine-Group Minerals

GEOLOGICAL SURVEY PROFESSIONAL PAPER 384-A

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The Serpentine-Group Minerals

By GEORGE T. FAUST *and* JOSEPH J. FAHEY

STUDIES OF THE NATURAL PHASES IN THE SYSTEM $MgO–SiO_2–H_2O$ AND THE SYSTEMS CONTAINING THE CONGENERS OF MAGNESIUM

GEOLOGICAL SURVEY PROFESSIONAL PAPER 384-A

Correlation of the physical and chemical properties in terms of crystal chemistry, and the application of geochemical data to the petrogenesis of serpentine and ultrabasic rocks



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STUDIES OF THE NATURAL PHASES IN THE SYSTEM MgO-SiO_2-H_2O AND OF THE SYSTEMS CONTAINING THE CONGENERS OF MAGNESIUM

THE SERPENTINE-GROUP MINERALS

By GEORGE T. FAUST and JOSEPH J. FAHEY

ABSTRACT

Twenty-eight chemically analyzed specimens—for 19 of which the analyses have not been published previously—and many unanalyzed specimens of serpentine-groups minerals were studied by various techniques, including chemical, optical, static dehydration, and differential-thermal-analysis (DTA), and X-ray powder diffraction methods. The various data were correlated and used to interpret the mineralogy of the serpentine group. This study demonstrates once again the necessity of using many experimental techniques in the identification of these fine-grained minerals. The admixture of small amounts of foreign phases in serpentine must always be suspected, and each of the various techniques has its special field of application in disclosing their presence. Admixtures of the polymorphous members of the serpentine group amongst themselves, when they are present to the extent of 25 percent or more, can usually be identified by X-ray powder diffraction methods, commonly by differential-thermal-analyses, and almost always by a combination of these methods and the use of the solution technique of Nagy and Bates (1952). The problem of identification of these admixtures becomes more difficult when the amount of a second polymorph is 10 percent or less of the sample. In such specimens the solution technique and electron microscopy may prove very valuable and may yield an unequivocal answer.

The calculation of the chemical analyses of selected and carefully purified members of the serpentine group to the structural formula $X_6Y_4O_{10}(OH)_8$ reveals the closeness of the agreement between the analyses and the structural formula. X ranges from 6.04 to 5.81, and Y ranges from 4.00 to 4.09.

A compilation of 219 analyses from the literature is given.

The chemical uniqueness of antigorite in the serpentine group is affirmed. An examination of the data shows that with one exception, sample F–53, all the specimens that show a deficiency of 0.19 to 0.16 ion in octahedral coordination are antigorites. This compositional difference sets apart the antigorites from the chrysotiles and lizardite.

Considering the possibility of analytical error, the close agreement of the structural formulas calculated from analyses of the chrysotiles and lizardite with the theoretical formula is remarkable and is evidence of the constancy in composition. The numerical expressions in the structural formula are admirably suited as cartesian coordinates, and a plot of the sum of the ions in tetrahedral sites versus the sum of the ions in octahedral sites is very informative. Plotting the formula of stevensite in terms of the serpentine formula and connecting it with a tieline to the theoretical formula of serpentine brings to light the true nature of the analyses of those deweylites which lie astride or near the tieline. These are admixtures of serpentine and stevensite, a disclosure confirmed by DTA (see below) and X-ray studies.

From the information revealed by the study of the analyses of these specially selected and purified samples, it is possible to interpret the analyses of the serpentine group minerals taken from the literature. That the material called deweylite is an admixture of serpentine and stevensite is again confirmed.

A critique of the differential-thermal-analysis (DTA) method as applied to a group of minerals shows the limitations that must be placed on the interpretation of the significance of the temperature of endothermic and exothermic reactions, of the differences in temperature between such reactions, and of the angular relations of the endotherms. The DTA method is very valuable for differentiating between antigorite and the pair chrysotile-lizardite. It is very helpful in detecting and estimating the amounts of many common admixtures of other minerals with serpentines.

According to the paragenetic and the spectrographic data given in this paper and the geochemical and petrological data from the literature, the geochemistry of the serpentine group minerals is related to their mode of origin and to the genesis of ultrabasic rocks. Geochemical studies show that there is a relation between the minor-element content of serpentines and their geologic origin. Serpentines derived from ultrabasic rocks through deuteric or subsequent hydrothermal replacements are rich in the suite of minor elements consisting of nickel, chromium, cobalt, and scandium, whereas serpentines derived from various types of metamorphic limestones and dolomites, from contact metamorphic deposits and from hydrothermal replacements and hydrothermal veins in these rocks, are notably poor in this suite of minor elements. From these observations and data from various petrologic and geochemical studies in the literature it is concluded that minor-element studies lend no support to the proponents of the theory that ultrabasic rocks are produced by metamorphism from magnesian limestones, dolomites, or other magnesian sedimentary rocks.

INTRODUCTION

The minerals of the serpentine group are layer structures, phyllosilicates, having the general formula $X_6Y_4O_{10}(OH)_8$, where X stands for the atoms in octahedral coordination—chiefly magnesium but also nickel, cobalt, manganese, ferrous iron, zinc, and generally lesser amounts of aluminum, ferric iron, chromium and titanium—and Y stands chiefly for silicon and in part for aluminum and ferric iron. Because the number of atoms in octahedral coordination for the ideal composition of the serpentine group is equal to 3 for half the unit cell, these minerals are considered

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structually as trioctahedral. The crystal structure of the chrysotiles is based on a cylindrical lattice (Whittaker, 1954; 1955a, b, c; and Waser, 1955), and their tubular character has been established by electron microscopy (Turkevich and Hillier, 1949; and Bates, 1951). Noll, Kircher and Sybertz (1958) have introduced the name "solensilicates" to be applied to these structures and have suggested its addition to the subgroup of the phyllosilicates in the Strunz (1938, 1957) classification of silicate structures. The prefix "solen", from the Greek, means "pipe." The most abundant serpentine minerals are hydrous magnesium silicates.

The classification followed in this paper is that of Whittaker and Zussman (1956) given herewith:

- Serpentine
  - Chrysotile
    - Orthochrysotile
    - Clinochrysotile
    - Parachrysotile
  - Lizardite
  - Antigorite

In addition, we use the term clinochrysotile (Globe type) to describe a group of specimens made up chiefly of clinochrysotile and probably admixed with orthochrysotile and best illustrated by the X-ray powder diffraction pattern of the silky chrysotile from the "Globe" district of Arizona.

The minerals of the serpentine group have been defined chemically as having a formula of the general type $X_6Y_4O_{10}(OH)_8$. This of course permits substitutions not only in the X and Y positions, but also in the positions allocated to (OH) where F and Cl may enter. Phase-rule theory also requires that any phase considered to be a polymorph of the serpentine-group minerals must adhere to the general formula.

Although we follow the established usage of considering antigorite as a member of the serpentine group, we do so with reservations, as will be explained later in the text. (See p. 37 and 40.)

Crystal chemical and structural relationships require that the ions entering into the octahedral and tetrahedral positions should have ionic radii similar in size to those of magnesium and silicon, respectively. In octahedral coordination occur Mg with an ionic radius, according to Ahrens (1952), of 0.67 A, Fe^{2+} with 0.74 A, Co with 0.73 A, Ni with 0.69 A, Mn^{2+} with 0.80 A, and Zn with 0.74 A. In addition Cr^{3+} with 0.63 A, Ti^{4+} with 0.68 A, Cu^{2+} with 0.72 A; Mn^{3+} with 0.66 A, and some or all of Fe^{3+} with 0.64 A, and Al with 0.51 A are assigned to octahedral positions. The assignment of Na with 0.94 A, Ca with 0.99 A and K with 1.33 A is provisional because we do not know (1) whether they actually belong in the serpentine structure, (2) whether they have been accidentally introduced during the analysis, and (3) whether they arise from impurities in the sample. The size of these ions is not compatible with that of ions known to be in octahedral coordination. It should be noted that lithium may be misidentified as sodium and reported as such in an analysis. Lithium with an ionic radius of 0.68 A can replace magnesium in octahedral coordination.

The chief ion entering into tetrahedral coordination is silicon with a radius of 0.42 A. Silicon is replaced in part by aluminum with 0.51 A and ferric iron with 0.64 A.

Within the serpentine group of minerals there is a wide range of substitutional solid solutions involving the aforementioned atoms. Most of these substitutional solid solutions involve the atoms in octahedral coordination. To specify such solid solutions use may be made of the hypothetical end-member formulas given below:

$Mg_6Si_4O_{10}(OH)_8$
$Fe_6Si_4O_{10}(OH)_8$
$Ni_6Si_4O_{10}(OH)_8$
$Co_6Si_4O_{10}(OH)_8$
$Mn_6Si_4O_{10}(OH)_8$
$Zn_6Si_4O_{10}(OH)_8$

Some of these end-member compositions have been demonstrated to exist as synthetic compounds. Bowen and Tuttle (1949) synthesized chrysotile with the formula $Mg_6Si_4O_{10}(OH)_8$; Noll, Kircher and Sybertz (1958) synthesized cobalt chrysotile; Noll and Kircher (1952) synthesized nickel chrysotile, as did several others including Roy and Roy (1954). In addition Roy and Roy succeeded in making serpentines of the composition $Mg_6Ge_4O_{10}(OH)_8$ and $Ni_6Ge_4O_{10}(OH)_8$.

Natural serpentines are rarely, if ever, composed of a single pure end-member but rather belong to multicomponent systems. Thus a serpentine represented by the formula $[Mg_{5.0}Ni_{0.5}Fe^{2+}_{0.5}]S_4O_{10}(OH)_8$ is actually a phase in the quinary system MgO-NiO-FeO-SiO_2-H_2O.

Much smaller quantities of calcium, sodium, potassium, and copper have been recorded in analyses, but just where these atoms fit into the structure is not known. Extremely small amounts no doubt are entrapped in sites in the structure. Significant amounts of calcium, sodium, and potassium usually indicate the presence of impurities, such as associated carbonates and silicates.

The hydrous nickel-magnesium silicates are, in part, members of the serpentine-group, and some of these materials resembling or called deweylite exhibit identical relationships. Because this group of minerals is an entity all in itself, it will be described in detail in a later paper. Brief comments on this work are given on page 48.

The relation of the serpentine-group minerals to that of the chlorites was first proposed by Tschermak (1890,

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1891) who defined the chlorites in terms of the end-members "serpentine," ($H_4Mg_3Si_2O_9$) and amesite ($H_4Mg_2Al_2SiO_9$). Petrologists, such as Thorolf Vogt (1927), found these theoretical molecules of Tschermak to be useful in the interpretation of the reactions involving chlorite in metamorphic rock facies. Winchell and Winchell (1951) also follow Tschermak's concept and claim that serpentine is chlorite with no trivalent element. We shall not discuss this relationship of the serpentines to the chlorites in this study but will consider it separately in a later paper on the chlorites. The differentiation of chlorites from serpentine may be made by X-ray methods (Brindley, 1951; Shirozu, 1958a, b) by optical studies (Winchell and Winchell, 1951); by solution studies (Clarke and Schneider, 1890); by differential-thermal-analysis (MacKenzie 1957); and by a combination of these techniques. The optical properties of lizardite, which may be confused with antigorite, and chlorite are given by Midgely (1951).

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We are indebted to many colleagues for specimens of serpentine for study, and we particularly wish to acknowledge the following: the late Norman L. Bowen and O. F. Tuttle and H. S. Yoder, Jr., all of the Geophysical Laboratory, Carnegie Institution of Washington, for various synthetic products from the quaternary system MgO–Al_2O_3–SiO_2–H_2O; Paul F. Kerr and George C. Selfridge, Columbia University; Clarence S. Ross and Waldemar T. Schaller, U.S. Geological Survey; A. E. J. Engel, California Institute of Technology; and the late William F. Foshag, formerly curator of minerals in the U.S. National Museum.

Norman L. Bowen kindly furnished us with determinations of water content on the synthetic clinochrysotiles. Thermal-analyses (static method) of several serpentines were furnished by the late Perley G. Nutting. Harry H. Hess, A. E. J. Engel, Clarence S. Ross, Edward Bailey, and Donald L. Everhart kindly allowed us to use some of their unpublished chemical analyses.

We also wish to acknowledge the assistance of our colleagues in the U.S. Geological Survey. John P. Marble, Richard C. Erd, Donald H. Richter, Geraldine Windham Werdig, and Joseph R. Houston prepared most of the X-ray powder diffraction patterns. Daniel E. Appleman, using the known constants for the unit cell of lizardite, prepared on the digital computer the calculated *d*-spacings for this mineral. Michael Fleischer furnished us with pertinent references to the literature and we have benefited by discussion of the problems with him. Some of the chemical analyses were by John G. Fairchild, Margaret D. Foster, Marie L. Lindberg, Charles Milton, and Rollin E. Stevens. Some of the spectrographic analyses were made by Harry Bastron and Harry J. Rose. To these scientists and to all others mentioned in this report we are deeply indebted.

To our colleague K. Jack Murata we are under deep obligation. His transfer to the Hawaiian Volcano Observatory of the U.S. Geological Survey has not permitted him to cooperate in this work as was originally planned. He has kindly turned over to us four unpublished chemical analyses and spectrographic data.

THE TERM "SERPENTINE"

The minerals of the serpentine group and the rocks composed of serpentine minerals are common substances and have been known to man for a long time. Hintze (1897) and others believe our name serpentine applies in part to the substances called λιθος ὀφιτης by Dioscorides (A.D. 50) and ophites by Pliny (A.D. 77). The Greek term "ὀφις" means serpent. Many fanciful interpretations have arisen as to the selection of this term for the name of the mineral or rock. It has been suggested that ὀφις refers to the speckled color pattern of serpents; others believed it was so called because of its use against snake poison and Dioscorides recommended it for the prevention of snake bite.

Agricola in 1546 latinized the name to serpentaria and this form was widely accepted. Our English word "serpentine," derived from the Latin form, is common to many languages. In those languages which employ the Latin alphabet, the word "serpentine" or one of its variants is part of the vocabulary. In the languages of the Teutonic countries, Austria, Denmark, Germany, Norway, Sweden, and Switzerland, it is "serpentin"; of the Low Countries it is "serpentine" in Belgium and "serpentijn" in Holland; of the slavic countries it is "serpentin" in Czechoslovakia, "serpentinu" in Hungary and Yugoslavia (Croatian), "serpentină" in Rumania, and "serpentyn" in Poland. In the languages of the Romance countries it is "serpentine" in France, and "serpentino" in Italy, Portugal, and Spain.

Today the word "serpentine" has diverse meanings depending upon the interests of the user. In literary works it conveys the idea of winding, of turning first one way and then another. To the mathematician (Larsen, 1954) it signifies a curve which was defined by Sir Isaac Newton by the equation $(a^2+x^2)y=abx$ where $x=a \cot \phi$ and $y=b \sin \phi \cos \phi$, as illustrated in figure 1. To the sculptor it designates a green rock usually coming from Italy or Germany, commonly with a mottled appearance and suitable for small statuary, vases, and mantlepieces. Pliny observes that the use of serpentine by sculptors extends to ancient times.

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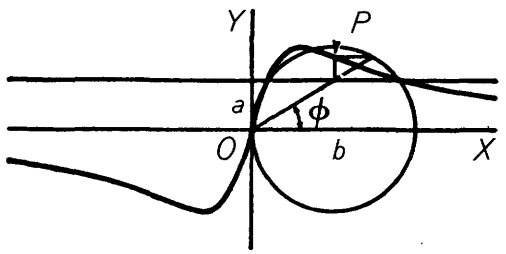


FIGURE 1.—The mathematical curve named serpentine and discovered by Sir Isaac Newton. Modified from Larsen (1954) and published by permission of Rinehard & Co., Inc.

To the architect the term "serpentine" denotes a rock, the classic example being the "verde antico" of the ancients; one serpentine was quarried on the island of Tinos in Greece (Kieslinger, 1951). Other serpentine rocks familiar to the architect are the verde di Polceverra, verde del Mare, verde de Genoa, and the verde di Pegli from the vicinity of Genoa, the verde di Prato from the quarries at Monteferrato near Prato, in Tuscany, Italy (Kieslinger, 1951), and the serpentine of Zöblitz (Zeblich) and Waldheim in Saxony (Agricola, 1546). Some of these rocks are actually serpentine marbles (ophicalcites) such as the verde di Prato. The so-called Irish green or Connemara marble from Galway County, Ireland, which has been popular with architects, is also an ophicalcite (Watson, 1916). According to Dana (1892, p. 671) "Any serpentine rock cut into slabs and polished is called serpentine marble."

To the soil scientist and to some farmers the word "serpentine" immediately suggests the infertile soils known as the "serpentine barrens" (Johannsen, 1928). The bastite locality, Todtmoos in the Wehra Tal, Schwarzwald, is described by Baedeker (1886) thus "The bold pine-crowned cliffs enclosing the valley are clothed with luxuriant vegetation broken here and there by imposing masses of barren rocks."

On August 29, 1960, Faust visited the bastite locality at Todtmoos in the Schwarzwald with W. W. Wimmenauer, geologist with the Geologisches Landesamt in Baden-Württemburg (Freiburg im Breisgau). At the time of the examination of this occurrence, huge blocks and the associated train of smaller fragments were exposed as part of a landslide. This landslide, apparently confined to the serpentine, took place during 1959. The description given by Baedeker (1886) possibly refers to the Wehra Tal. It is also possible that the creep of the soil mantle over the serpentines during the past 75 years has covered some of the barren exposures observed by the authors of Baedeker (1886). (See also Egller, 1955, p. 27–72.)

In the Alps, barren outcrops (bosses) of serpentine are known as "monts morts" to the farmers and dairymen. In a written communication dated April 20, 1959, Dr. J. V. Howell, Petroleum Geologist of Tulsa, Okla., wrote regarding this term:

> Actually this is a geographic or ecologic term and probably can be found much more readily in the literature of those disciplines. Dr. Schaetti states that the term is applied by the farmers and dairymen who pasture their cattle in the upper valleys of the Alps where the pasturage is excellent. On the serpentine bosses only a sparse growth of vegetation is found, whose contrast is so marked as compared with the lush growth of the valleys that they are termed "monts morts" or "dead mountains." So far as he is aware, the term has no geological connotation and possibly the term might be applied to similar "dead" areas underlain by rocks other than serpentine.

In a written communication dated January 5, 1961, Dr. Armin von Moos, of the Eidgenössischen Technischen Hochschule, Zürich, wrote:

> . . . I can tell you that on the so-called "todtalp" exist areas which carry no vegetation whatsoever. Underlying outcropping rock is serpentine either in place or as dry cone and debris of the above mentioned rock. The todtalp is about 2,500 m above sea level and is situated near the famous resort place Davos in the Grisons, Switzerland. This serpentine is also referred to as *todtalp-serpentine*. (Geologischer Führer der Schweiz, Fasc. XIV, 996. 1934. J. Cadisch: Weissfluhgruppe. Beiträge Geol. Karte der Schweiz, N. F. 49, I, 1921.)

In areas of weathered serpentines the forester and lumberman know serpentine to be characterized by stunted oaks, scrub pine, and mountain laurel. The botanist thinks of serpentine areas as the natural habitat of moss phlox (*Phlox subulata* L.), and of certain ferns (Wherry, 1932; Eberle, 1957; Rune, 1953).

Mineralogists and petrologists have used the word "serpentine" in two senses, generally with reference to the serpentine minerals and to a lesser extent for rocks. Haüy (1822) was one who considered serpentine to refer to a rock. Its more common use has been to the serpentine minerals and such is its usage today; rocks composed chiefly of serpentine minerals are commonly called serpentinites. This usage of serpentinite introduced by Lodočnikow (1936, p. 29 and 728) is gaining much favor. Lodočnikow defined it thus:[1] "I designate as serpentinite those rocks which are composed chiefly of serpentine group minerals." The older usage of the term by von Leonhard (1823–24, p. 131) as a synonym for gabbro has long since been forgotten.

MINERAL NAMES USED IN THIS STUDY

The serpentine group of minerals has associated with it an abundance of mineral names. In making this study of the minerals of the serpentine group it was necessary to investigate some of these materials and to consult the work of others for additional data. Table 1 summarizes these data and gives our observations and interpretations of them.

[1] Literal translation from the German abstract, by George T. Faust.

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TABLE 1.—*Mineral names used in this paper with interpretation of the pertinent data*

Varietal name	Proposed by—	Analysis No.—		Observations and interpretations
		From this study	From the literature	
Alumino-chrysotile	D. P. Serdyuchenko (1945)		3	Serdyuchenko's data suggest aluminian chrysotile. Data in figure 21 suggest an impure sample.
Antillite	C. U. Shepard (1872)		214	Based on the data of Nagy and Faust (1956) this is probably a mixture of lizardite and chrysotile.
Aquacreptite	C. U. Shepard (1868)		177, 179	Data in figure 21 suggest that although these samples are somewhat impure they are chiefly stevensite and chrysotile.
Baltimorite	T. Thomson (1843)	F–19	31	F–19 is antigorite and chrysotile. Data in figure 5 suggest a mixture of antigorite and chrysotile.
Barettite	L. Bombicci (1868)			The original sample analysed by Prof. Sestini contains gross impurities. Kouřimský and Šatava (1954) believe it to be antigorite. Their DTA curve is a complicated curve and shows that the material is impure. D'Ambrosio (1924) reanalyzed this mineral and stated that it consists of serpentine and brucite. Recomputation of his analyses gives $[Mg_{5.55}Fe^{2+}_{.16}Al_{.23}][Si_{3.87}Al_{.13}]O_{10}(OH)_8$ and $[Mg_{5.26}Fe^{2+}_{.26}Al_{.32}][Si_{3.99}Al_{.01}]O_{10}(OH)_8$ which fall within the limits of composition of serpentine-group minerals.
Bastite	W. Haidinger (1845)		255, 256, 257	Some of the analyses obtained from the literature may refer to this variety. Whittaker and Zussman (1956) studied three bastites and found that two specimens from the type locality are mainly lizardite as is also a specimen from Scotland.
Bowenite	J. D. Dana (1850)	F–8	83, 126, 150, 163, 208, 209, 211, 218.	F–8 is antigorite. The data in figure 21 suggest that the samples used for analyses 126 and 150, are representative; that Nos. 83, 208, 209, 211, and 218 are probably contaminated with a little carbonate; and that No. 163 is rather impure. DTA curves obtained by Caillère (1936) suggest that her samples are antigorite.
Dermatine	A. Breithaupt (1830)		13	The data obtained by Caillère (1936) suggest that this mineral is antigorite.
Deweylite	E. Emmons (1826)	F–3, F–26, F–40, F–42, F–43, F–48, F–49, F–50, F–52.	124, 131, 140, 154, 159, 165, 170, 171, 174, 176, 181, 193,	The results of this study show that most of the material called deweylite is a mixture of chrysotile or lizardite with stevensite. See figure 21.
Hydrophite	L. F. Svanberg (1839)		237	Analysis 237 suggests that hydrophite is an iron-rich serpentine. The DTA, and optical data of Kouřimský and Šatava (1954) suggest that similar material is chrysotile and magnetite. Dana (1892) notes that hydrophite is decomposed by HCl.
Jenkinsite	C. U. Shepard (1853); Winchell (1927, p. 378) considered jenkinsite a ferriferous antigorite.		235, 236	The data in figure 21 suggest that the sample used for analysis 236 may be an admixture of chrysotile and stevensite. Dana (1892) notes that jenkinsite is decomposed by HCl.
Karachaite	N. E. Efremov (1936)		175	The position of the analysis in figure 21 suggest that the sample is a mixture of chrysotile and stevensite.
Lithomarge [1]			151	The data in figure 21 suggest that the sample consists of chrysotile (or lizardite) and some stevensite.
Marmolite	T. Nuttall (1822)		125, 220	The physical appearance, the studies of Nagy and Faust (1956), and the chemical data in figure 21 suggest that this mineral is chiefly lizardite with some chrysotile. Whittaker and Zussman find that two specimens of marmolite from Hoboken, N.J., are different: one is chiefly chrysotile, the other chiefly lizardite. The data of Kouřimský and Šatava (1954) suggest similar conclusions. Brush and Penfield (1898) state it to be "readily decomposed by acids."

See footnotes at end of table, p. 7.

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TABLE 1.—*Mineral names used in this paper with interpretation of the pertinent data*—Continued

Varietal name	Proposed by—	Analysis No.—		Observations and interpretations
		From this study	From the literature	
Meerschaum [2]			166	The data in figure 21 suggest that this material is a mixture of chrysotile (or lizardite) and stevensite.
Metaxite	A. Breithaupt (1832)		1, 6, 17, 61	From the data in figure 20 it appears that this substance is chiefly serpentine-group minerals. Analysis 1 is an impure mixture. Whittaker and Zussman (1956) find metaxite from type locality to be chiefly chrysotile.
Neolite	Scheerer (1847)		186	Analysis 186 yields a formula suggestive of stevensite. This material from Pennsylvania is described as colloidal. Dana (1892) questions the homogeneity of the original materials described as neolite.
Picrolite	J. F. L. Hausmann (1808)	F–46, F–47, F–66	14, 43, 136, 139, 153, 162, 190, 191	F–46 and F–47 are lizardite; F–66 is antigorite. The data in figure 21 suggest that analyses No. 14, 43, 136, and 153 are chiefly serpentine-group minerals; analyses 190 and 191 are probably contaminated with olivine (or brucite); analyses 139 and 162 may contain stevensite. The data for four specimens of picrolite given by Nagy and Faust (1956) show it to consist chiefly of antigorite with various amounts of chrysotile. Whittaker and Zussman (1956) find a picrolite from Taberg, Sweden, to be antigorite.
Picrosmine	W. Haidinger (1824)		11, 40, 44, 185	The description by Dana (1892) includes columnar habit, suggestive of the varieties picrolite and baltimorite. The data in figure 20 show that these samples are serpentine-group minerals. Analysis 185 indicates that this sample is chiefly stevensite. Whittaker and Zussman (1956) show that a specimen from the Tyrol is antigorite. Kouřimský and Šatava (1954) found one specimen to be a mixture of antigorite and chrysotile and another to be antigorite.
Porcellophite	J. D. Dana (1868)		123, 155	The data in figure 4 show that the analyses are typical of the serpentine-group minerals. The optical and solution data in Nagy and Faust (1956) suggest that their specimen is a mixture of chrysotile and lizardite.
Pyknotrope	A. Breithaupt (1832)		2	Analysis 2 of material from the type locality by Fikenscher is obviously erroneous (see fig. 21) Kouřimský and Šatava (1954) studied material from the type locality and found it to be a mixture of antigorite and chrysotile. Their DTA curves suggest a very impure substance.
Retinalite	T. Thomson (1836)	F–22, F–25	206	Specimen F–22 is clinochrysotile; F–25 is chrysotile and lizardite where C>L. Analysis 206 appears to have been made on slightly impure material.
Schweizerite	T. Scheerer (1847)	F–23	96, 133, 199, 207	Specimen F–23 is lizardite. Analyses 96, 133, 199, and 207 all fall within the general composition field of serpentine-group minerals. Whittaker and Zussman (1956) found schweizerite from Zermatt, Switzerland, to be pure clonochrysotile.
Steatoid	E. F. Glocker (1829)		47	The original usage for this term applied to the serpentine pseudomorphs from Snarum, Norway. Analysis 47 is typical of a serpentine-group mineral. Sample F–71 on probably similar material is lizardite and clinochrysotile where L>C. Whittaker and Zussman (1956) studies on the "serpentine mineral" from Snarum, Norway, showed it to be mainly lizardite with very little clinochrysotile.

See footnotes at end of table, p. 7.

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TABLE 1.—*Mineral names used in this paper with interpretation of the pertinent data*—Continued

Varietal name	Proposed by—	Analysis No.—		Observations and interpretations
		From this study	From the literature	
Stevensite	A. R. Leeds (1873)			Shown by Faust and Murata (1953) to be the magnesium end member of the montmorillonite group.
Thermophyllite	A. E. Nordenskiold (1855)		99, 113, 128	Analyses 99 and 113 suggest that this is a typical serpentine-group mineral.
Vorhauserite	A. Kenngott (1857)		137	Analysis 137 is that of a typical serpentine-group mineral. Kouřimský and Šatava (1954) identified as chrysotile a sample of this mineral from the Val di Fiemme.
6-layer orthoserpentine.	Zussman, Brindley, and Comer (1957).		33, 112	A serpentine-group mineral having a six-layer orthohexagonal cell.
Webskyite	R. Brauns (1887)		172, 182	Analyses 172 and 182 appear to be impure mixtures of a serpentine-group mineral and stevensite. Kouřimský and Šatava believe this mineral to be a mixture of chrysotile and antigorite. Their DTA curve suggests a mixture of a chrysotile (or lizardite) and stevensite.
Williamsite	C. U. Shepard (1848)	F–1	34, 85, 156, 173, 183, 201	F–1 is antigorite. Analyses 34, 85, and 201 probably represent antigorite. Analyses 156, 173, and 183 are probably admixtures of a serpentine-group mineral and stevensite. Kouřimský and Šatava (1954) found williamsite from the original locality to be chiefly antigorite with a little chrysotile.

[1] The usage of this name for a hydrous magnesium silicate is not in accord with the original definition.
[2] This usage is a misnomer.

Although we have made much use of Dana (1915), Doelter (1921–31), Hintze (1897), Hey (1955), and Strunz (1957), we have also checked almost all the literature references.

Many hydrous magnesium silicates having a composition approximating that of serpentine were described as new minerals, but many were soon discredited and by the time of the sixth edition of James D. Dana's "A System of Mineralogy" (1892) their number had been reduced. Weinschenk (1912, p. 313) stated the case very clearly with respect to serpentine.

> New names cannot be given to these dense aggregates simply because they have different habit as has been done in the antigorite varieties, *picrosmine*, *metaxite*, *picrolite*, etc., and likewise the microscopic forms of aggregation, e.g., the radial, which has lately given use to the name *radiotine*, cannot be recognized as sufficient ground for evolving a new name.

Of those that remained only two of the serpentine-group minerals have met the requirements for a good mineral species and these are chrysotile and antigorite.

The original description of chrysotile by von Kobell (1834) established this species. It was so named by combining the greek words for golden, χρῦσος, and fibrous, τίλος.

Antigorite likewise was well established at an early date by Schweizer (1840) and named for its occurrence in the Val Antigorio, Italy, by Bonney (1908).

Lizardite was first described by Midgley (1951) as the "magnesium analogue of kaolinite" and "probably a variety of antigorite with very little iron substitution." It was later redefined by Whittaker and Zussman (1956).

GEOLOGICAL OCCURRENCE OF THE SPECIMENS STUDIED

Data on the geological occurrence of the specimens studied were obtained through reference to the literature, personal communications from the collectors and donors of specimens, examination of the hand specimens, and examination in the field for many of the specimens. Faust, over a period of 25 years, has examined occurrences of serpentine in the eastern United States from Troup County, Ga., to Lamoille County, Vt. He has also examined the occurrence of deweylite in the mica-peridotite in Arkansas; the deweylite at Currant Creek, Nev.; and serpentine at several localities in California. Faust examined the famous serpentine quarries at Kemmelton bei Hospenthal, Canton Uri, Switzerland, as well as other Alpine serpentine localities in 1959, and in 1960 he examined the once much disputed occurrence at Snarum, Modum Canton, Parish of Buskerud, Norway, and the important locality for bastite in the Todtmoos, Schwarzwald,

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Germany. Fahey has examined occurrences of serpentine in Pennsylvania and Maryland.

The serpentine minerals reported on in this paper have been referred to two distinct types of paragenesis here designated classes A and B.

Serpentine minerals formed in ultrabasic rocks are referred to class A. We use the term ultrabasic rock in its widest sense, but it is recognized that this usage includes igneous rocks derived from several different lines of magmatic descent. Hess (1955) has emphasized this difference and he divides the ultrabasic igneous rocks into two suites: the ultramafic rock suite characteristic of the alpine-type mountain systems, which includes dunites, pyroxenites, peridotites, and related rocks, and the suite composed of alnöites, kimberlites, mica-peridotites, and related rocks which differ from the ultramafic suite not only in chemical and mineralogic composition, but also in their tectonic setting. Two of the specimens (F–40 and F–42) examined by us belong to the alnöite, kimberlite, mica-peridotite suite.

Serpentine-bearing rocks of various types of metamorphic origins are referred to class B. Class B includes metamorphosed limestones and dolomites, contact metamorphic deposits, and hydrothermal veins. Metamorphosed limestones contain ferromagnesian and magnesian minerals such as olivine, pyroxene, and amphibole, and these are commonly replaced by minerals of the serpentine group.

The process of serpentinization is usually defined as the formation of serpentine from preexisting ferromagnesian or magnesian minerals by hydrothermal solutions. Chlorite, talc, stevensite, saponite, and other hydrous magnesium silicates commonly occur with serpentine.

The description of the geological occurrence of the serpentine specimens studied by us is given for each specimen in the following section on the description of the minerals.

DESCRIPTION OF THE MINERALS

A given hand specimen of serpentine may be completely homogeneous—composed of a single serpentine mineral. Another hand specimen of serpentine may consist of several serpentine minerals in variable proportions in different parts of its mass. The amount of heterogeneity of a given specimen may be detected by a combination of the various methods described in this report.

Except for the silky luster and fibrous habit of chrysotile and the platy character and dark-green color of some antigorites, it is almost impossible to name serpentine minerals by sight identification alone.

Locality, likewise, is generally an unreliable means of identifying the serpentine minerals, although there are some exceptions. Varietal names such as deweylite and retinalite are also of little value, for they are not all referable to the same mineral of the serpentine group and quite commonly are mixtures. Even elaborate physical and chemical techniques are not always sufficiently sensitive in quantitative studies. The identifications given in the descriptions that follow represent the predominant mineral of the serpentine group found in the particular sample studied and apply only to this material. Thus a specimen characterized as antigorite consists entirely or almost entirely of antigorite (90 percent or more); one characterized as chiefly antigorite contains antigorite as the predominant phase (70 percent or more).

To facilitate the use of the data and the information on localities, two geographic finding lists are given at the end of this report. Table 27 gives the information for specimens used in this study and table 28 for the chemical analyses taken from the literature.

F–1

Name: Antigorite (labeled williamsite). Green, translucent, massive; associated with chromite (fig. 14). This is the type of serpentine commonly used as a gem material. It is cut as stones for rings and pendants, and as beads.
Locality: State Line Pits (Low's mine), Lancaster County, Pa. approximately 1.2 miles west-northwest of Rock Springs, Cecil County, Md.
Geological occurrence: Class A. Hydrothermal alteration of ultrabasic rocks.
Furnished by: Clarence S. Ross.
Reference: Gordon, 1921, W. T. Schaller, oral communication, 1954.

F–3

Name: Lizardite and clinochrysotile, labeled deweylite (fig. 5). Cream colored, earthy, massive; adheres to the tongue.
Locality: Near Forest Hill, Harford County, Md.
Geological occurrence: Class A. Hydrothermal alteration of ultrabasic rocks.
Furnished by: Oliver Bowles and Clarence S. Ross.
Reference: Johannsen, 1928.

F–8

Name: Antigorite (labeled bowenite). Pale greenish gray, translucent, massive.
Locality: Smithfield, Providence County, R.I.
Geological occurence: Class B. Hydrothermal alteration of ferromagnesian minerals in metamorphosed limestone beds.
Furnished by: Professor Paul F. Kerr, Kerr No. R–19.
Reference: Bowen, 1822, Emerson, 1917.

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F–13

Name: Chiefly antigorite (labeled "pseudomorphic" serpentine). Grayish green, cuboidal masses.
Locality: Tilly Foster iron mine, near Brewster Station, Putnam County, N.Y.
Geological occurrence: Class B. Hydrothermal alteration of ferromagnesian minerals in a contact metamorphic deposit.
Furnished by: U.S. National Museum, USNM 82509.
Reference: Koerberlin, 1909; Brendler, 1912; Dana, 1915; Manchester, 1931.

F–14

Name: Chiefly antigorite (labeled "Hsiu-yen stone" known as "Yu-Yen Shi stone" in the jewelry trade). Pale greenish gray, translucent, massive; resembles jade in appearance. (fig. 13.) This material is commonly cut as an ornamental stone, as vases and table weights. It sometimes is cut as chopsticks.
Locality: Pei-wa-kou (and Lao-yeh-ling), Hsiu-yen Hsien, Liaoning Province, Manchuria.
Geological occurrence: Class B. Hydrothermal replacement of ferromagnesian minerals in metamorphosed dolomite of Precambrian age.
Furnished by: U.S. National Museum. The specimen is designated as a standard "Yu Yen Stone" and bears the number USNM 94356.
Reference: Merrill, 1922, p. 96; E. P. Henderson, oral communication 1954; S. Yabe, 1930 and written communication 1954.

F–15

Name: Antigorite. Grayish green, massive, breaks to form gently folded plates. (fig. 15; an oriented specimen from the same locality is shown in fig. 16.)
Locality: North of Domodossola in Val Antigorio, Novara Province, Piedmont region, Italy. According to Bonney (1908, p. 158), "But its occurrence *in situ* in the Val Antigorio itself is very doubtful. Thus the original specimen may have been obtained, either from an erratic in the lower part of that valley, or from an actual outcrop in a tributary one (such as the Val Devero or the Val Bognanco), to which the name of the main valley has been rather inaccurately attached."
Geological occurrence: Class A. Hydrothermal alteration of an ultrabasic rock (augite-olivine rock).
Furnished by: Professor Paul F. Kerr, Kerr No. R–18.
Reference: Schweizer 1840; Bonney, 1908; Brendler, 1912.

F–19

Name: Antigorite and chrysotile (labelled baltimorite). Grayish green, tight bundles of fibers up to 6 inches in length (fig. 12). Baltimorite is a synonym for picrolite.
Locality: Bare Hills, Baltimore County, Md.
Geological occurrence: Class A. Hydrothermal alteration of ultrabasic rocks.
Furnished by: U.S. National Museum, USNM 80500.
Reference: Knopf and Jonas, 1929.

F–20

Name: Clinochrysotile (Globe-type). Light golden brown, fawn, silky fibers of 2¾ inches in length.
Locality: Asbestos deposits, Gila County, Ariz. The label on this specimen bears a reference to Globe, but this is a town from which asbestos is shipped. Many deposits are scattered through 25 townships in Gila County.
Geological occurrence: Class B. Hydrothermal vein deposits in limestone.
Furnished by: Clarence S. Ross.
Reference: Bateman, 1923, Stewart and Haury, 1947, Bromfield and Shride, 1956.

F-20A

Name: Clinochrysotile (Globe-type). The chrysotile is intimately associated with very fine grained calcite. Color flesh pink, massive, pyrognomic (fig. 2).
Locality: Asbestos deposits, Gila County, Ariz. The label on this specimen bears a reference to Globe, but this is a town from which asbestos is shipped. Many deposits are scattered through 25 townships in Gila County.
Geological occurrence: Class B. Hydrothermal vein deposits in limestone.
Furnished by: Clarence S. Ross.
Reference: Bateman, 1923, Stewart and Haury, 1947. Bromfield and Shride, 1956.

F–22

Name: Clinochrysotile (labeled "serpentine"; this appears to be the variety retinalite).
Locality: Turkey Mountain, near Montville, Morris County, N.J.
Geological occurrence: Class B. Hydrothermal alteration of diopside in metamorphosed limestones.
Furnished by: Dr. George C. Selfridge, Jr., Selfridge No. 1.
Reference: Merrill, 1888, Shannon, 1927.

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F–23

Name: Lizardite (labeled schweizerite). Greenish yellow, opaque, massive.
Locality: Dognacska, 10 kilometers west from Reschitza, Severin Province, Hungary, now Dognecea, Rumania.
Geological occurrence: Class B. Hydrothermal alteration of ferromagnesian minerals in a contact metamorphosed limestone.
Furnished by: Dr. George C. Selfridge, Jr., Selfridge No. 4.
Reference: Beck, 1905, p. 592.

F–24

Name: Clinochrysotile (Globe-type). Amber, silky fibers ½ inch in length.
Locality: Turkey Mountain, near Montville, Morris County, N.J.
Geological occurrence: Class B. Hydrothermal vein deposits in metamorphosed limestone.
Furnished by: Dr. George C. Selfridge, Jr., Selfridge No. 75.
Reference: Merrill, 1888, Shannon, 1927.

F–25

Name: Chrysotile and lizardite, C>L (labeled retinalite). Light yellow, translucent, massive. Figures 6 and 7 are photomicrographs of similar material.
Locality: Turkey Mountain, near Montville, Morris County, N.J.
Geological occurrence: Class B. Hydrothermal alteration of diopside in metamorphosed limestone.
Furnished by: Dr. George C. Selfridge, Jr., Selfridge No. 77.
Reference: Merrill, 1888, Shannon, 1927.

F–26

Name: Clinochrysotile (Globe-type). Intimately mixed with stevensite (labeled deweylite). Amber, massive.
Locality: Texas, Lyles P. O., Fulton Township, Lancaster County, Pa.
Geological occurrence: Class A. Hydrothermal alteration of ultrabasic rocks.
Furnished by: Dr. George C. Selfridge, Jr., Selfridge No. 35.
Reference: Gordon, 1922.

F–40

Name: Clinochrysotile (labeled deweylite). White, shining luster, massive, small-chonchoidal fracture, adheres to the tongue.
Locality: Prairie Creek area of peridotite in T. 8 S., R. 25 W., 2½ miles south-southeast of Murfreesboro, Pike County, Ark.
Geological occurrence: Class A. Narrow seams in the altered peridotite. Hydrothermal alteration of ultrabasic rocks.
Furnished by: Collected by George T. Faust in 1943.
Reference: Miser and Ross, 1922; Faust, unpublished data.

F–41

Name: Clinochrysotile (Globe-type). (Labeled deweylite.) White to buff, granular, massive, adheres to the tongue.
Locality: Windous deposit, Currant Creek magnesite deposits, White Pine County, Nev.
Geological occurrence: Class B. Hydrothermal replacement of calcareous tuffs.
Furnished by: Eugene Callaghan and Charles J. Vitaliano.
Reference: Faust and Callaghan, 1948.

F–42

Name: Lizardite (labeled deweylite). Light-greenish brown, waxy luster, massive, pyrognomic.
Locality: Clark hallow on the southeast side of Lone Mountain, near Norris, Union County, Tenn.
Geological occurrence: Class A. Hydrothermal alteration of a mica-peridotite.
Furnished by: George M. Hall and Clarence S. Ross.
Reference: Hall and Amick, 1944.

F–43

Name: Lizardite (labeled deweylite). Greenish gray to brownish gray, shining luster, massive, small-conchoidal fracture, adheres to the tongue (fig. 10).
Locality: Crump's quarry, Mineral Hill, ¼ mile north of State Roads, about 1 mile west of Media, Middletown Township, Delaware County, Pa.
Geological occurrence: Class A. Hydrothermal alteration of ultrabasic rocks.
Furnished by: Collected by George T. Faust in 1924.
Reference: Gordon, 1922.

F–45

Name: Clinochrysotile (Globe-type). Intimately admixed with stevensite and dolomite (labeled deweylite). Amber colored, botryoidal, friable, massive. Resembles gum arabic.
Locality: Wood's chrome mine, Open Quarry, Little Britain Township, Lancaster County, Pa.
Geological occurrence: Class A. Hydrothermal alteration of ultrabasic rocks.
Furnished by: W. H. Tomlinson and W. T. Schaller.
Reference: Gordon, 1921.

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F–46

Name: Lizardite (labeled picrolite). The label on this specimen bears the statement "lithomarge(?)," a serpentine of the picrolite type. Only the powdered material of the original tube sample was available.
Locality: Near Bellows Falls, Windham County, Vt.
Geological occurrence: Class A. Hydrothermal alteration of ultrabasic rocks.
Furnished by: Clarence S. Ross.
Reference: Wells, 1937.
Note: The possibility that samples F–46 and F–47 are identical is suggested by (1) the similarity of the chemical and physical data of these two samples (2), the presence of sample F–47 in the collection of the U.S. National Museum, (3) the observation of our colleague, Alfred H. Chidester, U.S. Geological Survey, who knows of no such occurrence of serpentine near Bellows Falls, Vt.

F-47

Name: Lizardite (labeled picrolite). The label bears the statement "Carnat," a serpentine of the picrolite type. Only the powdered material of the original tube sample was available.
Locality: Tyrol, Austria.
Geological occurrence: Class A. No description available. Picrolites are, however, formed in hydrothermally altered ultrabasic rocks.
Furnished by: Clarence S. Ross; USNM R–4687.
Reference: Wells, 1937.

F-48

Name: Stevensite plus chrysotile (labeled deweylite). Amber, translucent, massive.
Locality: Mine Creek, Bakersville, Mitchell County, N.C.
Geological occurrence: Class A. Probably a hydrothermal alteration product of dunite.
Furnished by: Clarence S. Ross.
Reference: Ross, oral communication; Faust, Hathaway, and Millot (1959).

F-49

Name: Chrysotile (labeled deweylite, "white serpentine"). White, opaque, massive.
Locality: Wood's chrome mine, Open quarry, Little Britain Township, Lancaster County, Pa.
Geological occurrence: Class A. Hydrothermal alteration of ultrabasic rocks.
Furnished by: Collected by Wallace R. Griffitts.
Reference: Gordon, 1921.

F-50

Name: Clinochrysotile (labeled deweylite). Pale greenish gray, opaque, massive, adheres to the tongue. (Fig. 3).
Locality: Chrome mine near Moa, Oriente Province, Cuba.
Geological occurrence: Class A. Hydrothermal alteration product of ultrabasic rocks.
Furnished by: Collected by Clarence S. Ross.
Reference: Clarence S. Ross, oral communication.

F-51

Name: Clinochrysotile and Lizardite (labeled Serpentine). Dark green, resinous.
Locality: Nicaro, Oriente Province, Cuba.
Geological occurrence: Class A. Hydrothermal alteration of ultrabasic rocks.
Furnished by: Collected by Clarence S. Ross.
Reference: Clarence S. Ross, oral communication.

F-52

Name: Clinochrysotile (labeled deweylite). Brown, subtranslucent, massive with conchoidal fracture, adheres to the tongue.
Locality: Spar quarries, approximately 2 miles northwest of Sylmar, West Nottingham Township, Chester County, Pa.
Geological occurrence: Related to Class A. Hydrothermal replacement of albite in desilicated granitic pegmatites occurring within ultrabasic rocks, Gordon, 1922.
Furnished by: Samuel G. Gordon.
Reference: Gordon, 1922.

F-53

Name: Clinochrysotile (Globe-type). Golden brown fawn, silky fibers of 3 inches in length.
Locality: Asbestos deposits, beneath Grand View, about 11 miles southeast of El Tovar Hotel, Grand Canyon, Coconino County, Ariz.
Geological occurrence: Class B. Hydrothermal vein deposits in limestone.
Furnished by: Roger C. Wells, Wells *sample* 335, collected by J. S. Diller.
Reference: Diller, 1911, Laboratory notes of Roger C. Wells, 1913, Bateman, 1923, Stewart and Haury, 1947 Bromfield and Shride, 1956.

F-54

Name: Clinochrysotile. White, powder.
Locality: Synthetic product T-2-29C formed at 400°C and 1,000 atmospheres pressure.
Furnished by: Synthesized at the Geophysical Laboratory, Carnegie Institution, by Drs. N. L. Bowen and O. F. Tuttle.
Reference: Bowen and Tuttle, 1949.

F–56

Name: Clinochrysotile and orthochrysotile (labeled serpentine). Pale greenish gray, translucent, massive.

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Locality: Fifth level, at the shaft, Gouverneur Talc Co., ≈2,000 feet north of Balmat Corners, St. Lawrence County, N.Y.

Geological occurrence: Class B. "Se–2 (F–56) is serpentine replacing diopside in a diopsidic, calcitic marble. The diopside formed as the highest grade mineral in the marble, by reaction of sedimentary quartz and dolomite. Retrograde processes have removed the Mg (calcified the marble) and produced the stepwise assemblage anthophyllite⟶serpentine⟶talc."

Furnished by: Collected by Dr. Albert E. J. Engel.

Reference: A. E. J. Engel, written communication; Brown and Engel, 1956.

F–57

Name: Clinochrysotile and Lizardite (labeled serpentine). Yellow brown, opaque, massive.

Locality: Some 8 miles northeast of Se–2 (F–56) at the International (Freeman) Talc mine. The specimen came from the 2½ mine, 5th level, 1,600 feet west-southwest of shaft. Talcville, St. Lawrence County, N.Y.

Geological occurrence: Class B. "2½–5–16 (F–57) has an analogous origin to F–56."

Furnished by: Dr. Albert E. J. Engel, Engel No. 2½–5–16.

Reference: A. E. J. Engel, written communication; Brown and Engel, 1956.

F–58

Name: Clinochrysotile (labeled serpentine). Green, shining luster, subtranslucent, massive.

Locality: Canyon of Clear Creek, New Idria quadrangle, N½ sec. 12, T. 18 S., R. 11 E., San Benito County, Calif.

Geological occurrence: Class A. Highly sheared, and brecciated, lenticular masses of serpentine.

Furnished by: Dr. H. S. Yoder, Yoder No. J–33–1.

Reference: Yoder and Chesterman, 1951.

F–60

Name: Clinochrysotile. Artifically disaggregated bundles of white fibers.

Locality: Near Thetford, Megantic County, Quebec, Canada.

Geological occurrence: Class A. Hydrothermal replacement of ultrabasic rocks.

Furnished by: Dr. Bartholomew Nagy, Sample 1.

Reference: Cirkel, 1910; Dresser, 1913; Poitevin and Graham, 1918; Ross, J. G., 1931.

F–61

Name: Clinochrysotile. Part of specimen F–60, treated with 1*N* HCl.

Locality: Near Thetford, Megantic County, Quebec, Canada.

Furnished by: Dr. Bartholomew Nagy, Sample 1.

F–63

Name: Lizardite (labeled serpentine). Light green, opaque, massive but having a columnar aspect which causes the material to break as slablike fragments. (Fig. 11)

Locality: Staten Island, Richmond County, N.Y.

Geological occurrence: Class A. Hydrothermal alteration of ultrabasic rocks.

Furnished by: Professor Paul F. Kerr, Kerr No. 32.

Reference: Newland, 1901, Pough, 1938, Behm, 1954.

F–64

Name: Clinochrysotile and orthochrysotile (labeled "serpentine"). Amber, translucent, massive.

Locality: Turkey Mountain, Montville, Morris County, N.J.

Geological occurrence: Class B. Hydrothermal vein deposits in metamorphosed limestone.

Furnished by: Professor Paul F. Kerr.

Reference: Merrill, 1888, Shannon, 1927.

F–65

Name: Lizardite (labeled serpentine). Microscopic grains in a pencatite.

Locality: South end of the Organ Mountains, N. Mex., about 18 miles north of the Texas border.

Geological occurrence: Class B. Hydrothermal alteration of olivine in a pencatite (brucite-marble).

Furnished by: Professor Walter F. Hunt.

Reference: Hunt and Faust, 1937.

F–66

Name: Antigorite (labeled picrolite). Leek green, opaque, coarsely fibrous to lath shaped masses, some laths up to 1 inch in length.

Locality: Cyclops Mountains, Hollandia, Tanah Merah Bay, Dutch New Guinea.

Geological occurrence: Class A. Hydrothermal alteration of ultrabasic rocks.

Furnished by: Collected by Richard C. Erd.

Reference: van Bemmelen, 1949, p. 710.

F–67

Name: Antigorite.

Locality: North of Domodossola in Val Antigorio, Novara Province, Piedmont region, Italy. According to Bonney (p. 158)—But its occurrence *in situ* in the Val Antigorio itself is very doubtful. Thus the original specimen may have been obtained, either from an erratic in the lower part of the valley, or from an actual outcrop in a tributary one (such as the Val Devero or the Val Bognanco), to which the name of the main valley has been rather inaccurately attached.

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Geological occurrence: Class A. Hydrothermal alteration of an ultrabasic rock (augite-olivine rock).
Furnished by: Dr. Bartholomew Nagy, Sample 2.
Reference: Schweizer, 1840; Bonney, 1908; Brendler, 1912.

F–68

Name: Serpentinized phlogopite. Phlogopite with a small amount of chrysotile.
Locality: Verdolite quarry, River Road, 1 mile north of Easton, Forks Township, Northampton County, Pa.
Geological occurrence: Class B. Hydrothermal alteration of magnesian silicate minerals in metamorphosed limestone.
Furnished by: Collected by Professor W. S. Bayley.
Reference: Gordon, 1922; Bayley, 1941; Montgomery, 1955.

F–69

Name: Chrysotile and some lizardite (?) (labeled serpentine). Fresh, homogeneous, yellowish green, massive.
Locality: Nickel mine, Webster, Jackson County, N.C.
Geological occurrence: Class A. Hydrothermal alteration of ultrabasic rocks (dunite).
Furnished by: Clarence S. Ross.
Reference: Nutting, 1928; Ross, Shannon, and Gonyer, 1928.

F–70

Name: Clinochrysotile (labeled serpentine). Green, picrolite type.
Locality: Near Thetford, Megantic County, Quebec, Canada.
Geological occurrence: Class A. Hydrothermal alteration of ultrabasic rocks.
Furnished by: Dr. W. E. Richmond and Dr. P. G. Nutting.
Reference: Cirkel, 1910; Dresser, 1913; Poitevin and Graham, 1918; Ross, J. G., 1931.

F–71

Name: Lizardite plus clinochrysotile, L>C. Lemon yellow, translucent, massive (figs. 8, 9).
Locality: Snarum, Modum Canton, Parish of Buskerud, Norway.
Geological occurrence: Class A. A lenticular mass of serpentinized ultrabasic rock contained within gneissic rocks.
Furnished by: George T. Faust.
Reference: Böbert, 1838; Rose, 1851; Helland, 1873; Haraldsen, 1928 (Haraldsen's sample is referred to in this paper as H–1).

F–72

Name: Chrysotile plus lizardite *C>L*. Grayish green, opaque, massive.
Locality: Underground workings, New Almaden mine, Santa Clara County, Calif.
Geological occurrence: Class A. Completely serpentinized lherzolite, unsheared and completely fresh. Bailey, written communication, found 20 percent bastite, much microscopic chrysotile(?), and a few rather amorphous veins.
Furnished by: Edgar H. Bailey (NA–32).
Reference: Bailey, 1957, written communication.

F–73

Name: Chrysotile plus lizardite C>L. Greenish gray, opaque, massive.
Locality: Underground workings, New Almaden mine, Santa Clara County, Calif.
Geological occurrence: Class A. Completely serpentinized lherzolite, unsheared and completely fresh.
Furnished by: Edgar H. Bailey (NA–39).
Reference: Bailey, 1957, written communication.

F–74

Name: Clinochrysotile plus orthochrysotile. Grayish green, opaque, massive.
Locality: Underground workings, New Almaden mine, Santa Clara County, Calif.
Geological occurrence: Class A. Highly sheared serpentine, original nature cannot be stated, but probably is also a lherzolite. This rock is fresh in appearance.
Furnished by: Edgar H. Bailey (NA–33).
Reference: Bailey, 1957, written communication.

F–75

Name: Lizardite plus clinochrysotile, L>C. Opaque, massive. Locality: Campus of the Stevens Institute of Technology, Castle Point, Hoboken, Hudson County, N.J.
Geological occurrence: Class A. Serpentinization of ultrabasic rocks.
Furnished by: Collected by George T. Faust in 1947.
Reference: Newland, 1901.

F–76

Name: Lizardite plus clinochrysotile, L>C. Part of specimen F–75 treated at 20°C for 1 hour with cold dilute HCl (1:1).
Locality: Campus of the Stevens Institute of Technology, Castle Point, Hoboken, Hudson County, N.J.
Furnished by: Collected by George T. Faust in 1947.

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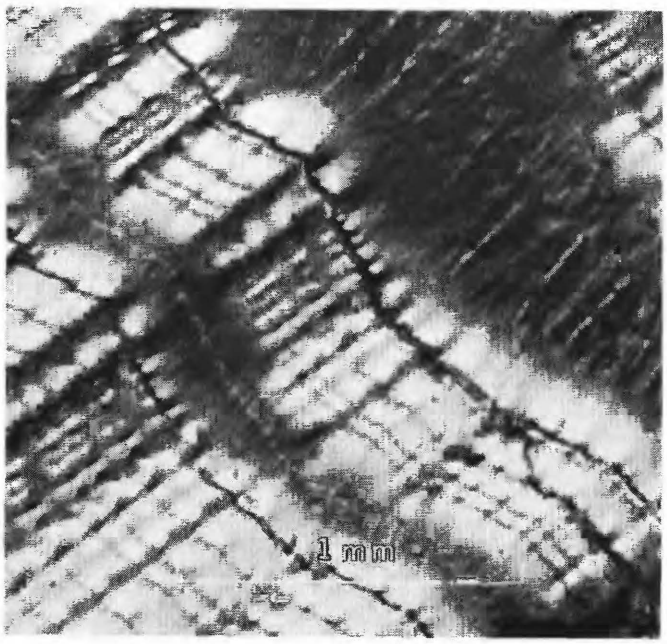


FIGURE 2.—Clinochrysotile (Globe-type), F-20A, asbestos deposits, Gila County, Ariz. Photomicrograph shows a pattern of closely mingled fibers, interrupted by bands of clinochrysotile in another orientation. Crossed polars.

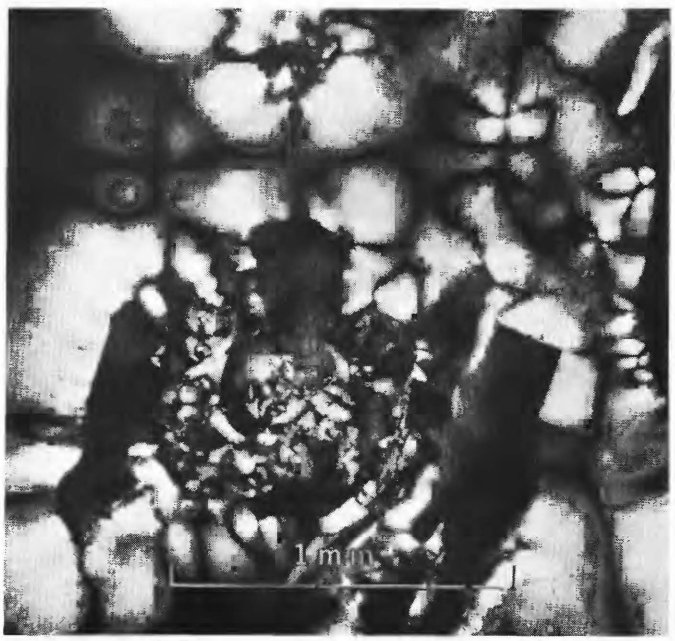


FIGURE 4.—Clinochrysotile (iron-bearing serpentine), 145, Stillwater County, Mont. Massive greenish material showing the character of a metacolloidal aggregate with numerous polarization crosses. Crossed polars.

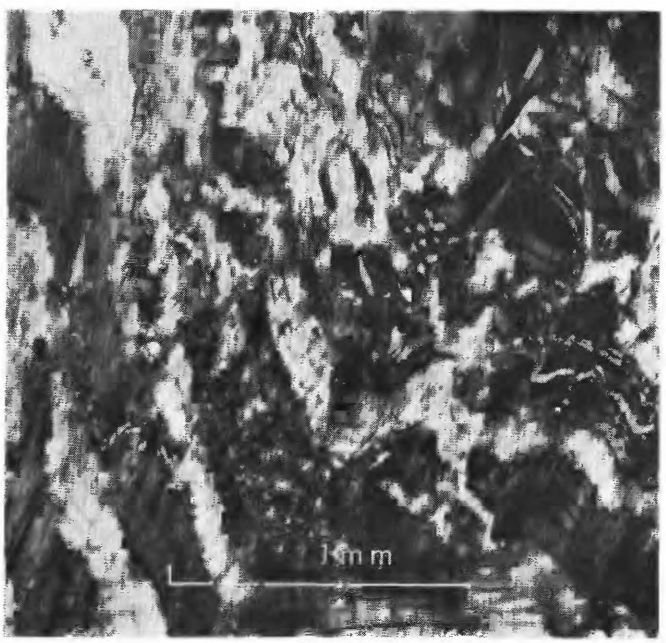


FIGURE 3.—Clinochrysotile (deweylite), F-50, near Moa, Cuba. Pale greenish gray material, massive in aspect but showing a pronounced fibration. Photomicrograph shows a pattern of closely mingled fibers crossed by crenulating bands. Crossed polars.

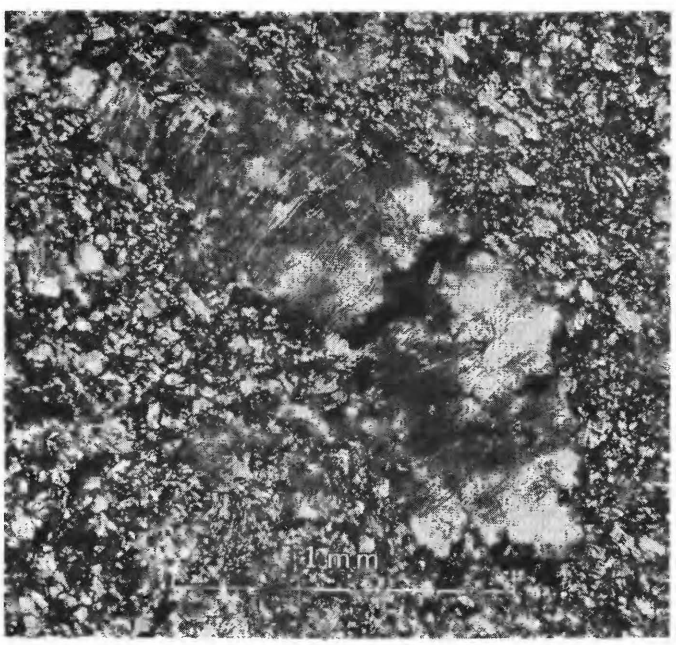


FIGURE 5.—Clinochrysotile and lizardite (deweylite), F-3, Forest Hill, Harford County, Md. Massive cream-colored material shows under the microscope a mass composed of plates of lizardite embedded in a matrix of clinochrysotile and platelets of lizardite. Crossed polars.

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FIGURE 6.—Clinochrysotile and lizardite, similar to F-25, Turkey Mountain, near Montville, Morris County, N.J. Photomicrograph shows flamboyant extinction in lizardite that was formed by the replacement of diopside. The associated grains showing a marked relief are diopside. Crossed polars.



FIGURE 8.—Lizardite plus clinochrysotile, F-71, Snarum, Norway. Lemon-yellow translucent masses show in thin section a mesh structure resulting from the replacement of olivine and also platy masses of lizardite. The platy lizardite shows anomalous brown polarization tints. Crossed polars.



FIGURE 7.—Clinochrysotile and lizardite. Same as figure 6. This specimen shows a variant form with shadowy extinction in the lizardite pseudomorphs after diopside. The pseudomorphs are embedded in a matrix of fine-grained clinochrysotile and lizardite. Crossed polars.

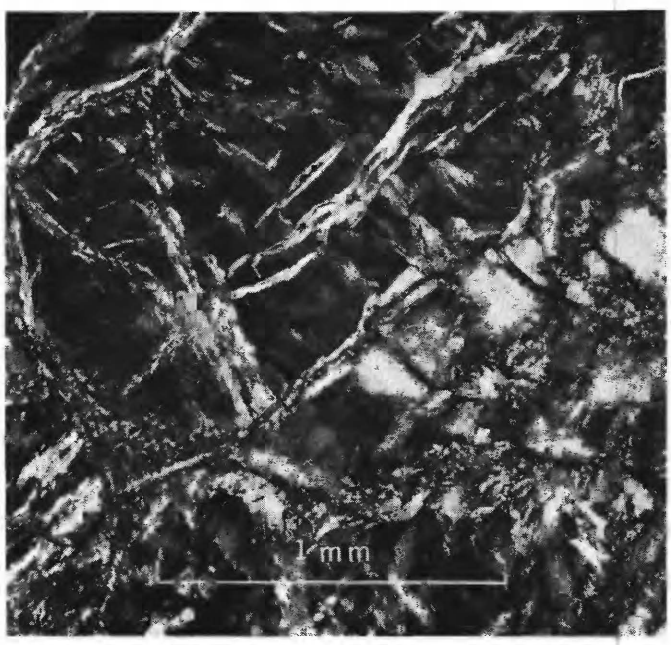


FIGURE 9.—Lizardite plus clinochrysotile, F-71, another part of the thin section shown in figure 8. Typical mesh structure of the serpentine made up of an admixture of these minerals. Crossed polars.

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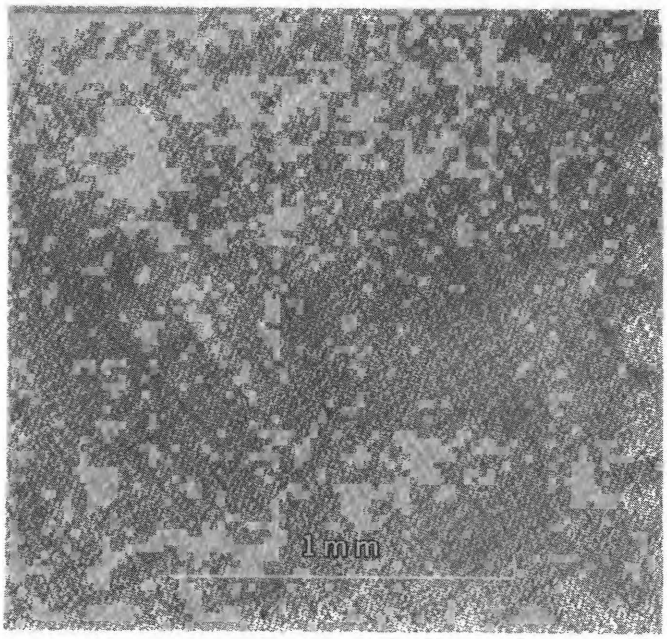


FIGURE 10.—Lizardite (deweylite), F–43, Mineral Hill, Delaware County, Pa. Photomicropgraph has a fabriclike aspect showing an apparent mat structure. Crossed polars.

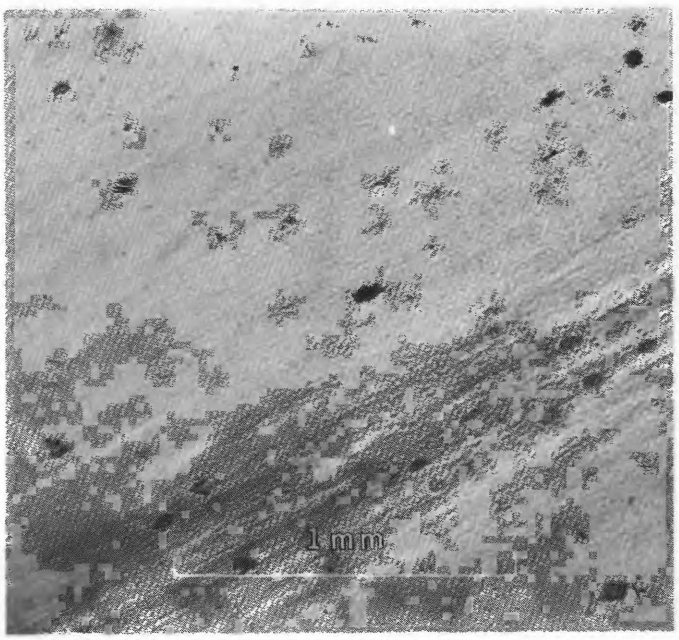


FIGURE 12.—Antigorite and chrysotile (baltimorite), F–19, Bare Hills, Baltimore County, Md. Photomicrograph shows fibrous habit which, in part, gives rise to a spindly pattern. Dark spots are small accumulations of iron oxides. Crossed polars.



FIGURE 11.—Lizardite, F–63, Staten Island, Richmond County, N.Y. Green slab-like fragments traversed by veins of white chrysotile fibers. Thin section shows cleavage traces, in lizardite, ostensibly basal {001}, and chrysotile bands cutting across the cleavage. Crossed polars.

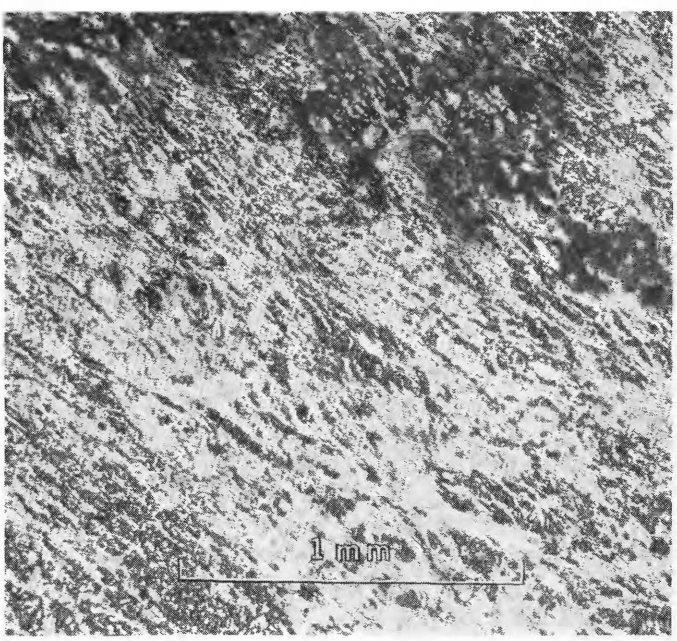


FIGURE 13.—Antigorite with minor amounts of chrysotile (Yu-Yen Shi stone), F–14, Liaoning Province, Manchuria. Photomicrograph shows fine scaly aggregates in several orientations but with a prevailing orientation. Crossed polars.

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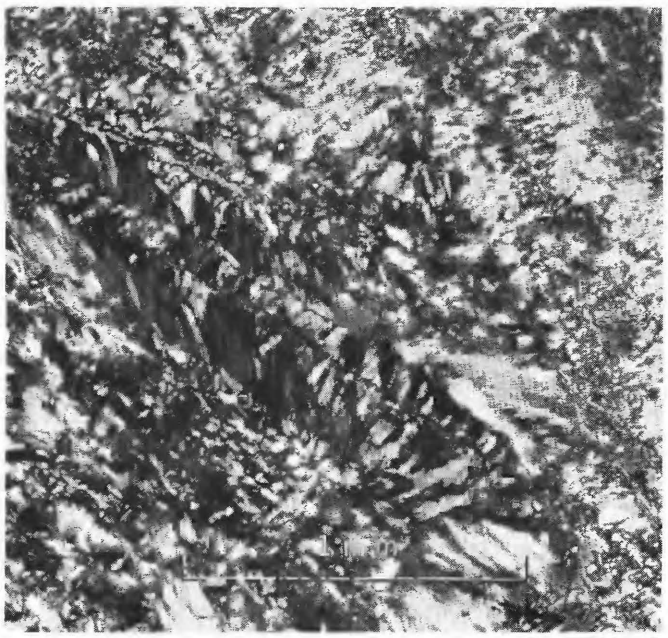


FIGURE 14.—Antigorite (williamsite), F–1, Low's mine, Lancaster County, Pa. Photomicrograph shows fine scaly aggregates, in part lamellar, in part divergent with a plumose character in the extinction relations. Crossed polars.



FIGURE 16.—Antigorite (from the type locality), similar to F–15 but a platy form. Photomicrograph shows several sets of oriented lamellae. Crossed polars.

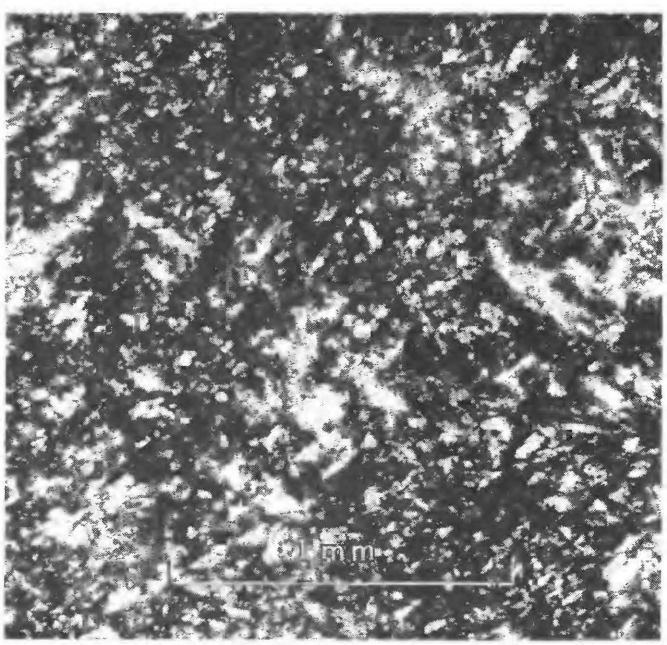


FIGURE 15.—Antigorite (from the type locality), F–15, north of Domodossola in Val Antigorio, Novara Province, Piedmont region, Italy. A typical schistose specimen which shows in thin section scaly laminar plates. Crossed polars.

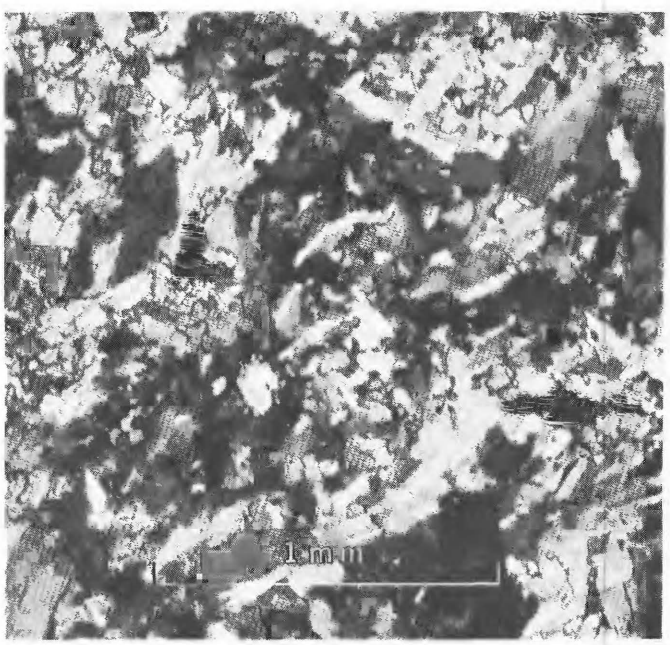


FIGURE 17.—Antigorite, 120, vicinity of Caracas, Venezuela, a portion of the material studied by Hess, Smith, and Dengo (1952). Basal cleavage {001} plates well developed and forming a confused aggregate. Crossed polars.

PREPARATION OF THE SAMPLES FOR STUDY

Most of the samples used in this study were prepared by carefully crushing large fragments down to the size where the serpentine-group mineral became unlocked from associated minerals. These grains were then handpicked under a binocular microscope or jeweller's loupe, and the purified samples crushed to a still finer size and reexamined. After the sample thus obtained was crushed to pass through a 100-mesh sieve, it was reexamined for impurities under the petrographic microscope. Almost all the samples thus prepared contained no detectable impurities, but in a few samples small specks of chromite so finely divided as to preclude further purification were present. In only one specimen did the Cr_2O_3 amount to as much as 0.22 percent. If we assume that all this Cr_2O_3 is present in chromite, and there are valid reasons to doubt this, then the maximum chromite content would have amounted to only 0.32 percent.

A few samples purified by the donors were studied by us without further purification so as to keep the samples intact. Almost all these samples were studied by DTA and X-ray methods, and this afforded additional checks on the purity of the samples. These techniques are particularly informative on the purity of very fine grained mixtures.

CHEMICAL STUDIES OF SERPENTINE AND RELATED MINERALS

METHODS OF CHEMICAL ANALYSIS

The chemical analyses were made on samples prepared from carefully hand-picked crushed material that was then ground to pass a 100-mesh sieve. The standard methods of rock analysis as outlined in "Applied Inorganic Analysis" by Hillebrand and Lundell (1929) were used. The SiO_2, R_2O_3, CaO, and MgO were determined on a 1-gram sample after fusion with Na_2CO_3. Total water was determined on half a gram by the Penfield method using one gram of anhydrous sodium tungstate as a flux. The alkalies when present were determined by the J. Lawrence Smith procedure.

ANALYSES STUDIED FOR THIS REPORT

Twenty-eight chemical analyses are given in tables 2, 3, and 4 of serpentine minerals that were studied by various techniques and are reported upon in this contribution. Some of them have been published previously in other studies. Analyses F–1, F–14, F–19, F–20 and F–40 are given in a paper by Nagy and Faust (1956); analyses F–46, F–47, and F–53 by Wells (1937), analysis F–68 by Bayley (1941) and analysis F–69 by Ross, Shannon, and Gonyer (1928). Unpublished analyses F–56 and F–57 are given with the kind permission of A. E. J. Engel; F–72, F–73, F–74 by our colleagues Edgar H. Bailey and Donald L. Everhart. Several of the analyses included here were made in connection with other studies for Clarence S. Ross, who generously made them available to us.

The analyses are divided into groups—class A and class B—based on their mode of origin, defined previously in the section dealing with the geological occurrence of the specimen studied.

Table 4 contains the analysis of a partially serpentinized phlogopite (eastonite) which is compared

TABLE 2.—*Chemical analyses of serpentine minerals formed by the reaction of hydrothermal solutions with ultrabasic rocks, Class A*

	F-1	F-43	F-42	F-47	F-46	F-40	F-3	F-19	F-15	F-26	F-48	F-72	F-73	F-74	F-51	F-69
SiO_2	44.50	43.31	41.66	40.97	39.92	44.25	41.74	43.53	41.50	46.20	47.0	35.98	35.98	37.36	36.62	35.56
Al_2O_3	1.41	.30	1.47	None	.44	.24	1.02	1.89	3.18	.14	-------	3.19	3.36	4.31	.54	2.46
Fe_2O_3	None	1.40	-------	5.55	5.68	1.34	.87	.49	1.81	.04	-------	6.36	5.49	4.42	3.81	4.62
FeO	.35	.17	.87	Tr.	Tr.	.60	.17	4.21	4.10	-------	5.5	1.72	2.29	.71	2.96	2.02
MgO	41.56	41.46	40.92	40.43	39.10	39.02	37.90	37.52	35.44	35.25	29.7	37.60	36.99	38.54	39.02	39.88
CaO	.02	.02	None	None	None	.02	None	None	.10	None	.2	None	None	None	.02	.10
Na_2O	None	-------	-------	-------	-------	-------	-------	None	-------	} .04	{-------	None	None	None	-------	-------
K_2O	None	-------	-------	-------	-------	-------	-------	None	-------		{-------	None	None	None	-------	-------
H_2O-	None	.80	} 14.57	{ n. d.	-------	2.06	4.85	.55	.80	4.82	} 17.7	14.16	15.00	13.50	{ 1.28	.88
H_2O+	12.36	12.92		{ 13.80	13.80	12.54	13.16	11.69	12.60	13.20					{ 15.80	15.04
TiO_2	None	.02	-------	None	None	.07	-------	None	-------	None	-------	None	None	None	None	-------
CO_2	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	.84	.54	.88	-------	-------
SO_3	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	.07	-------	-------
F	-------	-------	-------	-------	-------	-------	None	(1)	None	None	-------	-------	-------	-------	-------	-------
Cr_2O_3	.06	-------	-------	-------	-------	-------	None	.01	.28	-------	-------	.29	.32	.25	-------	-------
NiO	.095	-------	-------	-------	-------	-------	.06	.20	.16	-------	-------	-------	-------	-------	.22	.22
CoO	-------	-------	-------	-------	-------	-------	-------	None	-------	-------	-------	-------	-------	-------	-------	-------
MnO	None	None	-------	-------	-------	.02	01	.04	.09	.04	-------	.09	.09	.09	.08	-------
Σ	100.36	100.40	99.49	100.75	98.94	100.16	99.78	100.13	100.06	99.73	100.1	[2] 100.27	[3] 100.20	[4] 100.13	100.35	100.78

[1] Very weak test.
[2] No P_2O_5; S=0.04.
[3] No P_2O_5; S=0.14.
[4] No P_2O_5.

DESCRIPTION OF SAMPLES

Sample and locality	*Analyst*
F-1. State Line Pits, Low's mine, Pa	Joseph J. Fahey.
F-43. Mineral Hill, Delaware County, Pa	Joseph J. Fahey.
F-42. Near Norris, Tenn	Charles Milton.
F-47. Tyrol, Austria	John G. Fairchild
F-46. Near Bellows Falls, Vt	John G. Fairchild
F-40. Murfreesboro, Ark	Joseph J. Fahey.
F-3. Near Forest Hill, Md	K. J. Murata.
F-19. Bare Hills, Baltimore County, Md	K. J. Murata.
F-15. Val Antigorio, Piedmont, Italy	K. J. Murata.
F-26. Texas, Pa	Joseph J. Fahey.
F-48. Mine Creek, Bakersville, N.C	Charles Milton.
F-72. New Almaden mine, Santa Clara County, Calif	Forest A. Gonyer.
F-73. New Almaden mine, Santa Clara County, Calif	Forest A. Gonyer.
F-74. New Almaden mine, Santa Clara County, Calif	Forest A. Gonyer.
F-51. Nicaro, Oriente Province, Cuba	Marie L. Lindberg.
F-69. Nickel mine, Webster, N. C	Forest A. Gonyer.

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TABLE 3.—*Chemical analyses of serpentine minerals formed in calcareous or dolomitic rocks by the replacement of ferromagnesian minerals by hydrothermal solutions or by deposition by hydrothermal solutions, Class B*

[BaO was found to be absent in F-41]

	F-25	F-24	F-22	F-14	F-8	F-23	F-20	F-53	F-56	F-13	F-41	F-57
SiO_2	42.44	41.90	41.88	44.70	44.52	41.64	42.02	43.68	43.04	42.76	41.79	42.03
Al_2O_3	.64	None	.66	.50	None	.72	.52	.34	0	.96	.09	.35
Fe_2O_3	.19	.34	.26	.07	.12	1.96	.19	.51	.87	.23	.07	.26
FeO	.03	None	.09	.29	.07	.18	.11	----	.16	2.44	----	.06
MgO	42.76	42.58	42.18	42.05	41.88	41.55	41.44	40.64	40.64	39.31	38.33	39.95
CaO	None	None	None	.12	.64	None	None	.09	.85	.02	1.62	1.53
Na_2O	.06	----	.14	----	----	.10	----	.14	.07	None	----	----
K_2O	.08	----	None	----	----	None	----	.11	.01	.24	----	----
H_2O-	.50	.99	.70	.06	.06	.36	1.64	1.18	.41	.93	2.92	1.04
H_2O+	13.58	13.92	13.98	12.43	12.64	13.74	14.04	13.12	13.76	13.30	12.53	12.23
TiO_2	None	----	None	None	----	None	None	----	.02	None	.01	.16
CO_2	----	----	----	----	----	----	----	----	.74	----	2.87	1.13
F	None	None	None	None	.31	None	----	----	----	----	None	.55
Cr_2O_3	----	None	----	----	None	----	----	----	----	.005	----	.01
NiO	----	None	----	----	None	----	----	----	----	.002	----	----
MnO	.03	.04	.09	----	.002	.03	.03	.17	.15	.07	.003	.49
Cl	----	----	----	----	----	----	----	----	.05	----	----	.04
Σ	----	----	----	----	100.24	----	----	----	----	----	----	----
Less O=F	----	----	----	----	.13	----	----	----	----	----	----	----
Σ(cor.)	100.31	99.77	99.98	100.22	100.11	100.28	99.99	99.98	100.77	100.26	100.23	99.83

Description of samples

Sample and locality	Analyst
F-25. Montville, N.J	Joseph J. Fahey.
F-24. Montville, N.J	K. J. Murata.
F-22. Turkey Mountain, Montville, N.J	Joseph J. Fahey.
F-14. Manchuria	Joseph J. Fahey.
F-8. Smithfield, R.I	K. J. Murata.
F-23. Dognacska, Hungary	Joseph J. Fahey.
F-20. Gila County, Ariz	Joseph J. Fahey.
F-53. Grand Canyon, Ariz	Roger C. Wells.
F-56. Balmat Corners, N.Y	Margaret D. Foster.
F-13. Near Brewster Station, N.Y	Joseph J. Fahey.
F-41. White Pine County, Nev	Rollin E. Stevens.
F-57. Talcville, N.Y	Eileen K. Oslund.

with the calculated composition of a mixture of 50 percent phlogopite and 50 percent serpentine (Bayley, 1941).

ANALYSES TAKEN FROM THE LITERATURE

The collection of analyses of serpentine-group minerals from the literature is a sizable task, for they were amongst the earliest minerals to be analyzed. In order to bound the selection of analyses it was decided to take them as follows: For the older literature, the sources Dana (1892) and Gordon (1922); and for the recent literature, the papers by Jakob (1931), Selfridge (1936), Caillère (1936) Kouřimský and Šatava (1954), Pundsack (1955), Kalousek and Muttart (1957), and Brindley and Zussman (1957) were consulted. In so doing all duplications were eliminated and further analyses were found and a representative number of these are included herein. Asbestos is an important industrial mineral and it was more than desirable to include analyses of typical specimens. Merrill (1895), Becker and Haag (1928), Hall (1930), Ross (1931), Golding and Phaup (1936), Bowles (1955), Sinclair (1955), and Kalousek and Muttart (1957) were the chief sources. Sinclair's collection, obtained chiefly from the above references, was used as a check for coverage. It contains in addition some averaged analyses, prepared by averaging the data for different samples and some analyses from which minor constituents have been omitted. The collection in the 1928 edition of Becker and Haag likewise contains averaged analyses. Almost all the averaged analyses from the various sources have been excluded, and those which were known to be incomplete were verified and corrected.

A brief statement pertinent to each analysis includes, insofar as known, the name, variety, color, locality, analyst, source for the chemical analysis, and notes. In preparing the data on topographic mineralogy, free use was made of Brendler (1912), the Columbia Lippincott Gazetteer of the World (Seltzer, 1952), and Dana (1892).

TABLE 4.—*Chemical analysis of a partially serpentinized phlogopite (eastonite)*

[Sample F-68. Easton, Pa., John G. Fairchild, analyst. Calculated mixture Calculated composition of a mixture of 50 percent unaltered phlogopite and 50 percent pure serpentine. Calculated by W. S. Bayley]

	F-68	Mixture
SiO_2	46.20	42.8
Al_2O_3	5.59	5.5
Fe_2O_3	1.06	.3
MgO	33.95	36.5
CaO	None	None
Na_2O	.25	.15
K_2O	4.54	4.9
H_2O-	.24	0
H_2O+	5.72	7.5
CO_2	Present	----
F	.60	.55
Σ	98.15	98.20

LOCATION AND DESCRIPTION OF 219 SPECIMENS

[For analyses of these specimens, see table 5]

1. Metaxite. Reichenstein, Silesia. Robert B. Hare, 1879, analyst. Source: Caillère, 1936.

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2. Pyknotrope. Waldheim, Saxony. Fikenscher, analyst. Source: Kouřimský and Šatava, 1954.
3. Alumino-chrysotile. Hard, flattened, fibers. In the contact zone of granite and serpentinite. Markoopidj river basin, northern Caucasus, U.S.S.R. Dimitri Serdyuchenko, 1945, analyst. Source: Serdyuchenko, 1945.
4. Altered serpentine. Verdolite quarry, Easton, Northampton County, Pa. John Eyerman, 1911, analyst. Source: Gordon, 1922.
5. Serpentine. Ambindavato, Madagascar. S. Caillère, 1936, analyst. Source: Caillère, 1936.
6. Metaxite. Moncaup, Dept. Haute-Garonne, France. S. Caillère, 1936, analyst. Source: Caillère, 1936.
10. Antigorite. Sterzing, Tyrol, (Vipiteno) Bolzano Province, Italy. S. Caillère, 1936, analyst. Source: Caillère, 1936.
11. Picrosmine. Windisch-Matrei, East Tyrol, Austria. S. Caillère, 1936, analyst. Source: Caillère, 1936.
12. Antigorite. Zermatt, Canton Wallis, Switzerland. S. Caillère, 1936, analyst. Source: Caillère, 1936.
13. Dermatine. Waldheim, Saxony, Germany. S. Caillère, 1936, analyst. Source: Caillère, 1936.
14. Picrolite. North quarry, "Orphan's Luck Claims," Belingwe District, Southern Rhodesia. Ernest Golding, 1936, analyst. Source: Golding and Phaup, 1936, p. 96.
15. Antigorite. Rossa, Val Antigorio, Piedmont, Italy. USNM R–96917. William E. Smith, 1957, analyst. Source: Kalousek and Muttart, 1957.
16. Serpentine. Dense, gray "mother rock" of serpentine sample 121. Kaapsche Hoop, Barberton District, Transavaal, Union of South Africa. Johann Jakob, 1931, analyst. Source: Jakob, 1931.
17. Metaxite. Vallée de Comberousse near Saint Colomban-des-Villards, Savoy, France. S. Caillère, 1936, analyst. Source: Caillère, 1936.
18. Serpentine, green; adhering to chrysotile. Northern Joubertsdal, Barberton District, Transvaal, Union of South Africa. J. McCrae, 1930, analyst. Source: Hall, 1930, p. 113.
19. Serpentine, green. Northern Joubertsdal, Barberton District, Transvaal, Union of South Africa. J. McCrae, 1930, analyst. Source: Hall, 1930, p. 113.
20. Antigorite. North of Domodossola in Val Antigorio, Novara Province, Piedmont region, Italy. Sylvia Hillebrand, 1906, analyst. Source: Caillère, 1936.
21. Serpentine, green; containing stichtite. New Amianthus mine, Northern Joubertsdal, Barberton District, Transvaal, Union of South Africa. J. McCrae, 1930, analyst. Source: Hall, 1930, p. 113.
25. Antigorite. North of Domodossola in Val Antigorio, Novara Province, Piedmont region, Italy. S. Caillère, 1936, analyst. Source: Caillère, 1936.
26. Serpentine, precious. Easton, Northampton County, Pa. Thomas Thomson, 1828, analyst. Source: Gordon, 1922.
27. Serpentine, green. Altered gray pyroxene. Montville, Morris County, N.J. Charles Catlett, 1881, analyst. Source: Merrill, 1888.
28. Chrysotile. Slip fiber. Biltong Mine, Vukwe Mountains, Belingwe District, Southern Rhodesia. Ernest Golding, 1936, analyst. Source: Golding and Phaup, 1936, p. 96.
29. Antigorite. Villa Rosa, on the Po, Italy. Achille E. O. J. Delesse, 1848, analyst. Source: Delesse, 1848.
30. Antigorite. North of Domodossola, in Val Antigorio, Novara Province, Piedmont region, Italy. George J. Brush, 1857, analyst. Source: Brush, 1857.
31. Baltimorite. Bare Hills, Baltimore County, Md. Thomas Thomson, 1843, analyst. Source: Selfridge, 1936.
32. Serpentine, red-brown. Porthalla, Lizard, Cornwall, England. J. H. Collins, 1884, analyst. Source: Dana, 1892.
33. 6-layer orthoserpentine. No. 1 Massive. Nikka Vord chromite quarries, north of Baltasound, Unst, Shetland Islands. Oleg von Knorring, 1954, analyst. Source: Brindley and von Knorring, 1954.
34. Williamsite. Texas, Lancaster County, Pa. James Lawrence Smith and George J. Brush, 1853, analysts. Caillère, 1936.
35. Chrysotile. Shabani asbestos mine, Southern Rhodesia. Government Chemical Laboratory, Johannesburg, analyst not known. Source: Hall, 1930, p. 31.
36. Serpentine. Port Henry, Essex County, N.Y. Charles Catlett, 1889, analyst. Source: Dana, 1892.
37. Chrysotile. Fiber. Ethel mine, Lomagundi District, Southern Rhodesia. Ernest Golding, 1936, analyst. Source: Golding and Phaup, 1936, p. 94.
38. Serpentine, light. Sulphur Bank, on Clear Lake, Lake County, Calif. W. H. Melville, 1888, analyst. Source: Dana, 1892.

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39. Antigorite. Tilly Foster mine, near Brewster Station, N.Y. George W. Hawes, 1874, analyst. Source: Caillère, 1936.
40. Picrosmine. Pressnitz, Czechoslovakia. S. Caillère, 1936, analyst. Source: Caillère, 1936.
41. Serpentine. New Idria, San Benito County, Calif. W. H. Melville, 1888, analyst. Source: Dana, 1892.
42. Chrysotile. Province of Quebec, Canada. S. Caillère, 1936, analyst. Source: Caillère, 1936.
43. Picrolite. Val d'Aosta, Italy. S. Caillère, 1936, analyst. Source: Caillère, 1936.
44. Picrosmine. Greiner, Zemm Tal, Ziller-Tal, Austria. Schweizer, 1844, analyst. Source: Schweizer, 1844. Kouřimský and Šatava, 1954, find it to be antigorite.
45. Chrysotile. Silky. Transvaal, Union of South Africa. William A. Deer, 1957, analyst. Source: Brindley and Zussman, 1957.
46. Serpentine, precious. William's Bushkill quarry, Easton, Northampton County, Pa. John Eyerman, 1911, analyst. Source: Gordon, 1922.
47. Serpentine, variety steatoid. Dybingdale, north of a small lake called Dybingin, in the "Walde des Hofes Uhlen," Snarum, Modum Canton, Parish of Buskerud, Norway. Candidate Hartwall, in Prof. Berzelius' laboratory, 1838, analyst. Source: Böbert, 1838.
48. Serpentine, yellow. Altered white pyroxene. Montville, Morris County, N.J. Charles Catlett, 1888, analyst. Source: Merrill, 1888.
49. Antigorite, platy. Mikonui, New Zealand. Robert A. Howie, 1954, analyst. Source: Zussman, 1954.
50. Antigorite, green; from a kluft in dense serpentine, outermost zone of peridotite in contact with amphibolite. Valle di Capolo, left bank of the river Centovalli in Tessin (Ticino), Switzerland. Johann Jakob, 1931, analyst. Source: Jakob, 1931.
51. Chrysotile. About 8 miles from Tinaquillo, State of Cojedes; approximately 145 miles from Caracas, Venezuela. Analysis furnished by "Raybestos Manhattan" of New York. Source: Davey, 1947, confirmed by Donald O. Kennedy, U.S. Bur. Mines, written communication, April 24, 1959.
52. Chrysotile. Yellowish-white fibers with a silky luster. Montville, Morris County, N.J. Edwin L. Reakirt, 1854, analyst. Source: Dana, 1892.
53. Chrysotile, yellow. Shipton, Richmond County, Quebec Province, Canada. E. G. Smith, 1885, analyst. Source: Dana, 1892.
54. Chrysotile, light-green. Australia(?). Johann Jakob, 1931, analyst. Source: Jakob, 1931.
60. Serpentine, oil-green. Porthalla, Lizard, Cornwall, England. J. H. Collins, 1884, analyst. Source: Dana, 1892.
61. Metaxite. Reichenstein, Silesia. S. Caillère, 1936 analyst. Source: Caillère, 1936.
62. Serpentine. Snarum, Modum Canton, Parish of Buskerud, Norway. D. Fogy, 1906, analyst. Source: Selfridge, 1936.
63. Antigorite, green. Sils im Oberengadin, Grisons Canton, Switzerland. Johann Jakob, 1931, analyst. Source: Jakob, 1931.
64. Chrysotile. Fibers. Montville, Morris County, N.J. USNM R-4656. William E. Smith, 1957, analyst. Source: Kalousek and Muttart, 1957.
65. Chrysotile. Fibers. Middletown Township. Delaware County, Pa. USNM R–4658. William E. Smith, 1957, analyst. Source: Kalousek and Muttart, 1957.
66. Serpentine, dense, light-gray. Premier diamond pit, Cullinan, South-central Transvaal, Union of South Africa. Johann Jakob, 1931, analyst. Source: Jakob, 1931.
67. Chrysotile. Slip fiber. Biltong mine, Vukwe Mountains, Belingwe District, Southern Rhodesia. Ernest Golding, 1936, analyst. Source: Golding and Phaup, 1936, p. 96.
68. Serpentine. Matrix. Montville, Morris County, N.J. USNM R–4656. William E. Smith, 1957, analyst. Source: Kalousek and Muttart, 1957.
69. Serpentine. Matrix. Middletown Township, Delaware County, Pa. USNM R–4658. William E. Smith, 1957, analyst. Source: Kalousek and Muttart, 1957.
70. Chrysotile. Montville, Morris County, N.J. Sylvia Hillebrand, 1906, analyst. Source: Caillère, 1936.
71. Chrysotile, light-green. Reichenstein, Silesia. Johann Jakob, 1931, analyst. Source: Jakob, 1931.
72. Serpentine, precious. Niddister, Hillswick Ness, Shetland Island. Matthew F. Heddle, 1924, analyst. Source: Brindley and von Knorring, 1954.
73. Serpentine, gray. Tilly Foster mine, near Brewster Station, N.Y. C. A. Burt, 1873, analyst. Source: Dana, 1892.
75. Chrysotile. Long fiber, "Ribbon Line," New Amianthus mine, Barberton District, Transvaal, Union of South Africa. Government Chemical Laboratory, Johannesburg, analyst not known. Source: Hall, 1930, p. 31.
76. Chrysotile, pale-green. From the ancient mines on the southeast of Mount Troodos, Island of Cyprus, Mediterranean Sea. G. S. Blake, 1906, analyst. Source: Evans, 1906.

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77. Serpentine, black. Cadgwith, Lizard, Cornwall, England. W. H. Hudleston, 1877, analyst. Source: Dana, 1892.
78. Antigorite. North of Domodossola, in Val Antigorio, Novara Province, Piedmont region, Italy. Bergrath Stokar-Escher 1856, analyst. Source: Kenngott, 1856–57.
79. Black chrysotile. Bazhenovo, Ural Mountains, south of Sverdlovsk Oblast', U.S.S.R. A. V. Benevopenskoi, 1956, analyst. Source: Vertushkov and Yarosh, 1956.
80. Chrysotile. Fibrous serpentine, amianthus. Victoria, Province of British Columbia, Canada. George P. Merrill, 1895, analyst. Source: Merrill, 1895.
81. Pseudo-cubic serpentine. Tilly Foster mine, near Brewster Station, N.Y. Georges Friedel, 1891, analyst. Source: Dana, 1892.
82. Serpentine, dark-red. Lizard, Cornwall, England. J. A. Phillips, 1871, analyst. Source: Dana, 1892.
83. Bowenite. Kuttenberg, Bohemia; Kutna Hora, Czechoslovakia. A. Bukowsky, 1908, analyst. Source: Caillère, 1936.
84. Serpentine, fibrous; "Williamsite." 100 feet from road between Ethel mine and the Matoroshanga Pass, 1.8 miles south from south-center, beacon of the Umvukwe Ranch Extension, Umvukne Ranch, Southern Rhodesia. Ernest Golding, 1930, analyst. Source: Keep, 1930, p. 83.
85. Williamsite. Texas, Lancaster County, Pa. S. Caillère, 1936, analyst. Source: Caillère, 1936.
86. Chrysotile. Long fiber, "Grade IXL." From No. 4, main workings, Munnik-Mybirgh Asbestos Ltd., near Kaapsche Hoop deposits, Barberton District, Transvaal, Union of South Africa. H. G. Weall, 1930, analyst. Source: Hall, 1930, p. 31.
87. Serpentine. Matrix. Templeton Township, Papineau County, Quebec, Canada. Specimen from Prof. Charles U. Shepard, 1881. USNM 18879. William E. Smith, 1957, analyst. Source: Kalousek and Muttart, 1957.
88. Serpentine. Matrix. Aboutville, New York. Specimen from Prof. George J. Brush, 1874. USNM 9143. William E. Smith, 1957, analyst. Source: Kalousek and Muttart, 1957.
89. Chrysotile. Thetford, Megantic County, Quebec, Canada. J. T. Donald, Montreal, 1910, analyst. Source: Cirkel, 1910, p. 31.
90. Serpentine. Snarum, Modum Canton, Parish of Buskerud, Norway. Theodor Scheerer, 1846, analyst. Source: Rose, 1851.
91. Chrysotile. Fibers. Aboutville, N.Y. Specimen from George J. Brush, 1874. USNM 9143. William E. Smith, 1957, analyst. Source: Kalousek and Muttart, 1957.
92. Serpentine, dark. Sulphur Bank, Clear Lake, Lake County, Calif. W. H. Melville, 1888, analyst. Source: Dana, 1892.
93. White serpentine. Tilly Foster mine, near Brewster Station, Putnam County, N.Y. E. S. Breidenbaugh, 1873, analyst. Source: Dana, 1892.
94. Chrysotile. Southwark mine, Black Lake, 5 miles southwest of Thetford mines, Megantic County, Quebec, Canada. J. T. Donald, Montreal, 1910, analyst. Source: Cirkel, 1910, p. 31.
95. Serpentine, precious. Leslie's farm, Newlin, Chester County, Pa. John Eyerman, 1911, analyst. Source: Gordon, 1922.
96. Schweizerite. Zermatt, Canton Wallis, Switzerland. S. Caillère, 1936, analyst. Source: Caillère, 1936.
97. Chrysotile. Average of 11 analyses of typical and representative samples of chrysotile from the Province of Quebec, Canada. Primary data in Cirkel, 1910. Computed by Hall, 1930. Source: Hall, 1930, p. 31.
98. Serpentine, precious. Newburyport, Essex County, Mass. Th. Petersen, 1866, analyst. Source: Dana, 1892.
99. Thermophyllite. Delaware River quarry, Easton, Northampton County, Pa. John Eyerman, 1911, analyst. Source: Gordon, 1922.
100. Chrysotile. From the nickel mines at Petsamo, Finland. G. Bastien and A. Dikenstein, 1954, analysts. Source: Thoreau, 1954, p. 110.
101. Chrysotile. Templeton Township, Papineau County, Quebec, Canada. J. T. Donald, 1891, analyst. Source: Dana, 1892.
102. Antigorite. Tilly Foster mine, near Brewster Station, N.Y. S. Caillère, 1936, analyst. Source: Caillère, 1936.
110. Serpentine, green to grayish-black. Edward's quarry, Willistown, Chester County, Pa. John Eyerman, 1911, analyst. Source: Gordon, 1922.
111. Chrysotile. Fort Victoria, Southern Rhodesia. Government Chemical Laboratory, Johannesburg, analyst not known. Source: Hall, 1930, p. 31.
112. Orthoserpentine, 6-layer. No. 2, Nikka Vord chromite quarries, North of Baltasound, Unst, Shetland Islands. Oleg von Knorring, 1954, analyst. Source: Brindley and von Knorring, 1954.

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113. Thermophyllite. Hoponsuo, near Pitkaranta, Finland. Augustus B. Northcote, 1858, analyst. Source: Dana, 1892.
114. Precious serpentine. Dense. Snarum, Modum Canton, Parish of Buskerud, Norway. Johann Jakob, 1931, analyst. Source: Jakob, 1931.
115. Chrysotile. Amalgamated Asbestos Corp. B. C. quarries, Black Lake, 5 miles southwest of Thetford mines, Megantic County, Quebec, Canada. Milton Hershey, Montreal, 1910, analyst. Source: Cirkel, 1910, p. 31.
116. Serpentine. Snarum, Modum Canton, Parish of Buskerud, Norway. Haakon Haraldsen, 1928, analyst. Source: Haraldsen, 1928.
120. Antigorite (fig. 17). Vicinity of Caracas, Federal District, Venezuela. Lee C. Peck, 1952, analyst. Source: Hess, Smith, and Dengo, 1952.
121. Chrysotile, light-green. Kaapsche Hoop, Barberton District, Transvaal, Union of South Africa. Johann Jakob, 1931, analyst. Source: Jakob, 1931.
122. Serpentine, white. Easton, Northampton County, Pa. John Eyerman, 1911, analyst. Source: Gordon, 1922.
123. Porcellophite. Delaware River quarry, Easton, Northampton County, Pa. John Eyerman, 1911, analyst. Source: Gordon, 1922.
124. Deweylite, white. Optically pseudo-isotropic. Mladotice, near Ronow, (eastern Bohemia), Czechoslovakia. Jiri Konta, 1953, analyst. Source: Konta, 1953.
125. Marmolite. Hoboken, Hudson County, N.J. Franz von Kobell, 1874, analyst. Source: Selfridge, 1936.
126. Bowenite. Khotan, near the Yarkand, Chinese Turkestan, China. S. Caillère, 1936, analyst. Source: Caillère, 1936.
127. Antigorite. Muruhattan, Northern Sweden. Ragnar Blix, 1935, analyst. Source: Du Rietz, 1935.
128. Thermophyllite. Hoponsuo, near Pitkaranta, Finland. R. Hermann, 1858, analyst. Source: Selfridge, 1936.
129. Chrysotile. Gath Asbestos mines, Gath, Victoria Province, Southern Rhodesia. Government Chemical Laboratory, Johannesburg, analyst not known. Source: Hall, 1930, p. 31.
130. Serpentine. Corundum Hill, near Franklin on the Little Tennessee River, Macon County, N.C. Edward A. Schneider, 1890, analyst. Source: Dana, 1892.
131. Deweylite, grayish-green. Optically pseudo-isotropic. Mladotice, near Ronow, (Eastern Bohemia), Czechoslovakia. Jiri Konta, 1953, analyst. Source: Konta, 1953.
132. Antigorite. Zermatt, Canton Wallis, Switzerland. F. von Kobell, 1876, analyst. Source: Dana, 1892.
133. Schweizerite. Zermatt, Canton Wallis, Switzerland. Eduard Schweizer, 1884, analyst. Source: Selfridge, 1936.
134. Serpentine. Coleraine, southeast of Thetford, Megantic County, Quebec, Canada. B. J. Harrington, 1890, analyst. Source: Dana, 1892.
135. Serpentine, light-green. Cornwall, Lebanon County, Pa. John Eyerman, 1911, analyst. Source: Gordon, 1922.
136. Picrolite. Taberg, 12 km south of Jönköping, Lan Jönköping, Smålands, south Sweden. Nils W. Almroth, 1818, analyst. Source: Almroth, 1818. Kouřimský and Šatava, 1954, find it to be "sort of antigorite."
137. Serpentine, variety vorhauserite. Fassa-Tal, (Val di Fassa) Tyrol, Italy. Joseph Oellacher, 1857, analyst. Source: Kenngott, 1857. Not included in the analysis 0.96 percent apatite.
138. Chrysotile. Amelose bei Biedenkopf an der Lahn, Hesse-Nassau, Germany. R. Brauns, 1887, analyst. Source: Dana, 1892.
139. Picrolite. Florida, Berkshire County, Mass. W. H. Melville, 1879, analyst. Source: Dana, 1892.
140. Deweylite. The Hunt, Delaware County, Pa. John Eyerman, 1911, analyst. Source: Gordon, 1922.
145. Serpentine, iron-bearing (fig. 4). Stillwater Complex, Stillwater County, Montana. Alexander H. Phillips, analyst. Source: Harry H. Hess, written communication, 1957.
146. Lizardite. Kennack Cove, Lizard, England. L.J. Larner, 1951, analyst. Source: Midgley, 1951, p. 527.
147. Chrysotile. Radiated. Franklin, Hardyston Township, Sussex County, N.J. William F. Foshag, 1926, analyst. Source: Foshag, 1926.
148. Chrysotile. Médous, 2 kilometers from Bagnères-de-Bigorre, Hautes-Pyrénées, France. S. Caillère, 1936, analyst. Source: Caillère, 1936.
149. Chrysotile. Ambindavato, Madagascar. S. Caillère, 1936, analyst. Source: Caillère, 1936.
150. Bowenite. Bhèra, Shahpur district, Afghanistan. G. T. Prior, 1890, analyst. Source: Dana, 1892.
151. Porcellanous, resembling compact lithomarge. Middletown, Delaware County, Pa. Beverly S. Burton, 1868, analyst. Source: Gordon, 1922.

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152. Chrysotile. Type material. Reichenstein, Silesia. Franz von Kobell, 1834, analyst. Source: von Kobell, 1834.
153. Picrolite. Wood's mine, Lancaster County, Pa. W. H. Brewer, 1850, analyst. Source: Gordon, 1922.
154. Deweylite, brownish-red. Distinctly fibrous. Mladotice, near Ronow, (Eastern Bohemia), Czechoslovakia. Jiri Konta, 1953, analyst. Source: Konta, 1953.
155. Porcellophite. Middletown, Delaware County, Pa. Beverly S. Burton, 1868, analyst. Source: Selfridge, 1936.
156. Williamsite. Texas, Lancaster County, Pa. R. Hermann, 1851, analyst. Source: Selfridge, 1936.
157. Serpentine, yellowish. East Goshen, Chester County, Pa. S. B. Sharples, 1866, analyst. Source: Gordon, 1922.
158. Serpentine, slaty. Low's mine, Lancaster County, Pa. Benjamin Silliman, Jr., 1849, analyst. Source: Gordon, 1922.
159. Deweylite. Bare Hills, Baltimore County, Md. Thomas Thomson, 1843, analyst. Source: Selfridge, 1936.
160. Serpentine, light-green. Delaware River quarry, Easton, Northampton County, Pa. John Eyerman, 1911, analyst. Source: Gordon, 1922.
161. Chrysotile. Near New Haven, New Haven County, Conn. George J. Brush, 1854, analyst. Source: Dana, 1892.
162. Picrolite. Taberg, 12 km south of Jönköping, Lan Jönköping, Smålands, south Sweden. L. P. Lychnell, 1826, analyst. Source: Lychnell, 1826.
163. Bowenite. New Zealand. F. Berwerth, 1879, analyst. Source: Dana, 1892.
164. Chrysotile. "High-grade fiber," occurring in dolomite. Diepgezet east of Carolina, Transvaal, Union of South Africa. C. Gardthausen, 1930, analyst. Source: Hall, 1930, p. 31.
165. Deweylite. Baie d'Ouie, near Ia Peak, New Caledonia, Pacific Ocean. Auguste Terreil, analyst. Source: Lacroix, 1942–1943, p. 30.
166. "Meerschaum," serpentine. Middletown, Delaware County, Pa. John Eyerman, 1911, analyst. Source: Gordon, 1922.
170. Deweylite. Ruth's mine, Berks County, Pa. D. B. Brunner and Edgar F. Smith, 1883, analysts. Source: Gordon, 1922.
171. Deweylite. Baie d'Ouie, near Ia Peak, New Caledonia, Pacific Ocean. S. Caillère, 1936, analyst. Source: Caillère, 1936.
172. Webskyite. Between Mornshausen an der Dautphe and Amelose "in Hessische Hinterland," not far from Bindenkopf an der Lahn, Hesse-Nassau, Germany. Rheinhard Brauns, 1887, analyst. Source: Brauns, 1887. Kouřimský and Šatava, 1954, find it to be a mixture of antigorite and chrysotile where antigorite > chrysotile.
173. Williamsite. Texas, Lancaster County, Pa. Adolf Lindner, 1896, analyst. Source: Caillère, 1936.
174. Deweylite. Brownish, resinous botryoidal masses. Wood's mine, Lancaster County, Pa. George J. Brush, 1854, analyst. Source: Selfridge, 1936.
175. Serpentine, variety Karachaite. Yellow fibers, silky luster, hard. Asbestos deposits of Shaman-Beklegen, Karachi, northwest Caucasus, U.S.S.R. V. Krylova, 1936, analyst. Source: Efremov, 1936.
176. Deweylite. Baie d'Ouie, near Ia Peak, New Caledonia, Pacific Ocean. Stoyanoff, analyst. Source: Lacroix, 1942–1943, p. 30.
177. Aquacreptite. Yellowish-brown, amorphous masses, with conchoidal fracture. Strode's Mill, East Bradford, Chester County, Pa. J. H. Eaton, 1868, analyst. Source: Gordon, 1922.
178. Serpentine. Ambindavato, Madagascar. S. Caillère, 1936, analyst. Source: Caillère, 1936.
179. Aquacreptite. Strode's Mill, East Bradford, Chester County, Pa. C. U. Shepard, 1868, analyst. Source: Gordon, 1922.
180. Serpentine, blue-black. Northern Joubertsdal, Barberton District, Transvaal, Union of South Africa. J. McCrae, 1930, analyst. Source: Hall, 1930, p. 113. "Finely fibrous talcose or serpentine mineral replaced pale or colorless mineral."
181. Deweylite. Whitish and brownish resinous coatings with aragonite and serpentine. Ruth's mine, Berks County, Pa. D. B. Brunner and Edgar F. Smith, 1883, analysts. Source: Gordon, 1922.
182. Webskyite. Bottenhorn, 15 km northeast of Dillenburg, Hesse-Nassau, Germany. Rheinhard Brauns, 1887, analyst. Source: Brauns, 1887.
183. Williamsite. Low's mine, Lancaster County, Pa. George J. Brush, 1850, analyst. Source: Gordon, 1922.
185. Picrosmine. Pressnitz, Czechoslovakia. Guster Magnus, 1826, analyst. Source: Caillère, 1936.

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186. Neolite, green or yellow; massive or silky fibrous. Rose's quarry, Lower Merion, Montgomery County, Pa. Harry W. Jayne, 1875, analyst. Source: Gordon, 1922.
187. Picrosmine. Zwickau, Saxony, Germany. August Frenzel, 1880, analyst. Source: Caillère, 1936.
190. Picrolite. Val d'Aosta, Italy. Alfonso Cossa, 1878, analyst. Source: Caillère, 1936.
191. Picrolite. Val d'Aosta, Italy. Alfonso Cossa, 1878, analyst. Source: Caillère, 1936.
192. Serpentine. Dense "mother rock" associated with the chrysotile No. 202. Templeton, Templeton Township, Papineau County, Quebec, Canada. Johann Jakob, 1931, analyst. Source: Jakob, 1931.
193. Deweylite. Ruth's mine, Berks County, Pa. H. F. Keller, 1885, analyst. Source: Gordon, 1922.
194. Chrysotile. Montville, Morris County, N.J. S. Caillère, 1936, analyst. Source: Caillère, 1936.
195. Serpentine, dark oil green. Delaware River quarry, Easton, Northampton County, Pa. John Eyerman, 1911, analyst. Source: Gordon, 1922.
196. Chrysotile. Bell Asbestos mine, depth 130 ft., north side, Thetford, Megantic County, Quebec, Canada. E. A. Thompson, 1931, analyst. Source: Ross, 1931, p. 20.
197. Chrysotile, green. Wurlitz, 8 km southeast of Hof, Fichtelgebirge, Germany. Johann Jakob, 1931, analyst. Source: Jakob, 1931.
198. Serpentine. Wheatfield mine, Berks County, Pa. H. F. Keller, 1885, analyst. Source: Dana, 1892.
199. Schweizerite. Zermatt, Canton, Wallis, Switzerland. Viktor Merz, 1861, analyst. Source: Caillère, 1936.
200. Serpentine, fibrous, amianthus. Province of Quebec, Canada. James T. Donald, 1891, analyst. Source: Merrill, 1895.
201. Williamsite. Low's mine, Lancaster County, Pa. James Lawrence Smith and George J. Brush, 1853, analysts. Source: Gordon, 1922.
202. Chrysotile, light-yellow; almost colorless. Templeton, Templeton Township, Papineau County, Quebec, Canada. Johann Jakob, 1931, analyst. Source: Jakob, 1931.
203. Chrysotile, dark-green. Shipton, Richmond County, Quebec, Canada. E. G. Smith, 1885 analyst. Source: Dana, 1892.
204. Chrysotile. Goujot, Vosges, France. Achille E. J. Delesse, 1897, analyst. Source: Selfridge, 1936.
205. Chrysotile. Serpentine, fibrous, amianthus. "Alpine beds," Italy. J. T. Donald, Montreal, 1891, analyst. Source: Cirkel, 1910, p. 31.
206. Retinalite, pale wax-yellow. Calumet Islands on the Ottawa River, southwest Quebec, Canada. T. Sterry Hunt, 1883, analyst. Source: Dana, 1892.
207. Schweizerite. Zermatt, Canton Wallis, Switzerland. Adolf Lindner, 1896, analyst. Source: Caillère, 1936.
208. Bowenite. Smithfield, Providence County, R. I. James Lawrence Smith and George J. Brush, 1853, analysts. Source: Selfridge, 1936.
209. Bowenite. Smithfield, Providence County, R.I. James Lawrence Smith and George J. Brush, 1853, analysts. Source: Selfridge, 1936.
210. Serpentine. Light-green fibers. Shabani mine, Shabani, Southern Rhodesia. Johann Jakob, 1931, analyst. Source: Jakob, 1931.
211. Bowenite, yellow. Smithfield, Providence County, R.I. James Lawrence Smith and George J. Brush, 1853, analysts. Source: Dana, 1892.
212. Chrysotile. Broughton, Beauce County, Quebec, Canada. J. T. Donald, 1891, analyst. Source: Dana, 1892.
213. Serpentine, green. Tilly Foster mine, near Brewster Station, N.Y. C. A. Burt, 1873, analyst. Source: Dana, 1892.
214. Antillite. Havana, Havana Province, Cuba, West Indies. Charles U. Shepard, 1872, analyst. Source: Shepard, 1872.
215. Serpentine. Buckwheat mine, Franklin, Hardyston Township, Sussex County, N.J. Henry E. Merwin, 1937, analyst. Source: Palache, 1937. Note. Analysis recalculated to 100 percent after eliminating 3.63 percent carbonates.
216. Serpentine, dark oil-green. William's Delaware quarry, Easton, Northampton County, Pa. John Eyerman, 1911, analyst. Source: Gordon, 1922.
217. Chrysotile. Danville area, Richmond County, Quebec, Canada. Thomas Sopoci and Richard Wiley, 1955, analysts. Source: Pundsack, 1955.
218. Bowenite. Shigar, Ladakh District, East Kashmir, Kashmir State. C. A. McMahon, 1901, analyst. Source: Selfridge, 1936.
219. Serpentine. Ruth's mine, Berks County, Pa. H. F. Keller, 1885, analyst. Source: Dana, 1892.
220. Marmolite. Hoboken, Hudson County, N.J. Thomas H. Garrett, 1850, analyst. Source: Dana, 1892.
221. Serpentine. Snarum, Modum Canton, Parish of Buskerud, Norway. Amund Helland, 1873, analyst. Source: Dana, 1892.
222. Chrysotile. Fibers. Templeton Township, Papineau County, Quebec, Canada. Specimen

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from Prof. Charles U. Shepard, 1881. USNM. 18879. William E. Smith, 1957, analyst. Source: Kalousek and Muttart, 1957.

225. Chrysotile. Province of Quebec, Canada. S. Caillère, 1936, analyst. Source: Caillère, 1936.

226. Antigorite, ferriferous. From the nickel mines at Petsamo, Finland. G. Bastien and A. Dikenstein, 1954, analysts. Source: Thoreau, 1954, p. 110.

227. Serpentine, precious. Dense. Snarum, Modum Canton, Parish of Buskerud, Norway. Johann Jakob, 1931, analyst. Source: Jakob, 1931.

228. Chrysotile. Canada. Auguste Terreil, 1885, analyst. Source: Dana, 189?.

229. Chrysotile. Robertsonville, Thetford Township, Megantic County, Quebec, Canada. Analyst, not known. Source: Bryant, 1928 p. 10–14.

235. Jenkinsite. O'Neil mine Monroe, Orange County, N.Y. J. Lawrence Smith and George J. Brush, 1853, analysts. Source: Smith and Brush, 1853.

236. Jenkinsite. O'Neil mine, Monroe, Orange County, N.Y. J. Lawrence Smith and George J. Brush, 1853, analysts. Source: Smith and Brush, 1853.

237. Hydrophite. Taberg, Jönköping County, Smålands, south Sweden. Lars 2. Svanberg, 1839, analyst. Source: Svanberg, 1839.

238. Zincian serpentine. Occurs in dolomites. Almal'ik deposit, Uzbek, U.S.S.R. E. F. Kas'yanova, 1958, analyst. Source: Badalov, 1958.

239. Zincian serpentine. Occurs in dolomites. Almal'ik deposit, Uzbek, U.S.S.R. E. F. Kas'yanova, 1958, analyst. Source: Badalov, 1958.

240. Serpentine. Franklin, Hardyston Township, Sussex County, N.J. David Jenkins and Lawson H. Bauer, 1926, analysts. Source: Palache, 1937.

241. Serpentine. Franklin, Hardyston Township, Sussex County, N.J. George A. Koenig, 1886, analyst. Source: Palache, 1937. Note: Analysis corrected for 4.08 percent franklinite equivalent to the Fe_2O_3 found in the analysis.

242. Serpentine, manganiferous. Franklin, Hardyston Township, Sussex County, N.J. Earl V. Shannon, 1926, analyst. Source: Shannon and Larsen, 1926.

243. Antigorite. Blocklike masses. Snarum, Modum Canton, Parish of Buskerud, Norway. Ragner Blix, 1947, analyst. Source: Bøggild, 1947.

244. Serpentine. Valli dell Idice e del Sillaro, Italy. P. Gazzi, 1956, analyst. Source: Gazzi, 1956. Note: CaO is present as calcite so 0.39 percent CO^2 is deducted from ignition loss.

245. Serpentine with very little carbonates. Valli dell Idice e del Sillaro, Italy. P. Gazzi, 1956, analyst. Source: Gazzi, 1956. Note: CaO=5.41 percent is present as calcite so 4.24 percent CO_2 is subtracted from the ignition loss.

246. Chrysotile. Fibers. Globe, Gila County Ariz. USNM R–4654. William E. Smith, 1957, analyst. Source: Kalousek and Muttart, 1957, Note: The CaO represents calcite and is not used in the calculation.

247. Serpentine. Matrix, contains impurities. Globe, Gila County, Ariz. USNM R–4654. William E. Smith, 1957, analyst. Source: Kalousek and and Muttart, 1957. Note: The 21.00 percent CaO is probably present as calcite, so this constituent is not used in the calculation.

248. Chrysotile asbestos. Classified as soft fiber. Ash Creek mine, Ash Creek, Globe field, Ariz. R. E. Zimmerman, 1918, analyst. Source: Diller, 1922, p. 302.

249. Chrysotile. Harsh fiber. Ash Creek mine, Globe field, Gila County, Ariz. R. E. Zimmerman, 1918, analyst. Source: Diller, 1922.

250. Chrysotile. Soft fiber. Near the summit of Coon Creek Butte at the south end of the Sierra Ancha, Gila County, Ariz. R. E. Zimmerman, 1918, analyst. Source: Diller, 1922.

251. Chrysotile. Harsh fiber. Near the summit of Coon Creek Butte at the south end of the Sierra Ancha, Gila County, Ariz. R. E. Zimmerman, 1918, analyst. Source: Diller, 1922.

255. Bastite. Todtmoos im Wehra-Tal, Schwarzwald, Baden, Germany. W. Hetzer, analyst, in Weiss, 1863. Source: Dana, 1892.

256. Bastite. Massive material. Baste, Radau-Tal, near Harzburg, Harz, Germany. Friedrich Köhler, 1827, analyst. Source: Dana, 1892.

257. Bastite. Crystalline material. Baste, Radau-Tal, near Harzburg, Harz, Germany. Friedrich Köhler, 1827, analyst. Source: Dana, 1892.

258. Serpentine, dull-green. Formed by the alteration of pyroxene. Montville, Morris County, N.J. Edward A. Schneider, 1890, analyst. Source: Clarke and Schneider, 1890.

259. Serpentine, dark-green. Newburyport, Essex County, Mass. Edward A. Schneider, 1890, analyst. Source: Clarke and Schneider, 1890.

260. Chrysotile, silky, fibrous. Montville, Morris County, N.J. Edward A. Schneider, 1890, analyst. Source: Clarke and Schneider, 1890.

261. Deweylite(?), grayish-green. Corundum Hill, Macon County, N.C. Edward A. Schneider, 1890, analyst. Source: Clarke and Schneider, 1890.

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ANALYSIS OF 219 SPECIMENS

The collection of analyses, table 5, comprises 219 analyses of serpentine-group minerals and 42 analyses of specimens consisting chiefly of serpentine.

Harry H. Hess, Princeton University, kindly furnished us a copy of analysis 145 and material suitable for DTA and X-ray studies. (Fig. 4.) See Hess (1960).

INTERPRETATION OF THE CHEMICAL ANALYSIS

The structural formula for the minerals of the serpentine group is

$$[Mg_6Si_4O_{10}(OH)_8],$$

which represents the contents of the unit cell. It is assumed that the structural water in serpentine is that represented by the (OH) groups. The low-temperature water is ignored and considered to be either adsorbed or, in mixtures containing stevensite, to belong to that admixed species. The analytical determination of water in a mineral requires great skill and good judgment on the part of the chemist and the excellent agreement shown with the data of static thermal-analysis studies, table 12, is a testimony to their skill. Thermal-analysis studies, however, show conclusively that the determination of H_2O+ and H_2O- based on 100° or 110°C as fiducial points, no matter how accurately they are done, do not reveal the respective amounts of hydroxyl and adsorbed water. It is argued here that the uncertainty introduced by using total water (adsorbed water and hydroxyl water) in the calculation far outweighs the supposed advantage gained by including it (Bates, 1959). Moreover, from the results of thermal-analysis studies and other considerations it is concluded that its use leads (1) to a false sense of precision, (2) to the postulate that significant defects exist in the structurally equivalent positions of the large anions, a fact which has not been unequivocally demonstrated, and (3) to the assumption that the nonreporting of fluorine and chlorine by the chemist means that they are absent.

An examination of the analyses shows many in which H_2O+ and H_2O- have not been separated and some in which the water determination is in error. All these would be excluded, if a rigorous insistence on an "accurate" determination of H_2O+ and H_2O- were made as a provision for the acceptance of an analysis.

The method of calculation is similar to that given by Hendricks and Ross (1941). For purposes of calculation it is not necessary to recompute the analyses to 100 percent, or to a so-called dry basis, for the ratios of the constituents are maintained in the method. Table 6 gives the equivalent weights used in the calculations. In general, where the pairs of constituents K_2O and Na_2O, Fe_2O_3 and Al_2O_3, and FeO and Fe_2O_3 were reported together in an analysis, the equivalent weight used in the computation was the calculated mean of the two constituents; thus for $Fe_2O_3 + Al_2O_3$, the mean of 21.80 was used.

The procedure for calculation (see table below) is as follows:

1. It is assumed that the total negative valency is contributed by the 10 oxygen ions and the 8 hydroxyl groups giving a total negative valency of 28.
2. The analytically determined values of the metallic oxides are divided by their respective equivalent weights, and the quotients are labeled *e*.
3. The sum obtained by adding the various values of *e* in item 2 above is divided into 28 to yield a quotient called the factor *F*. This factor is used to adjust the total positive valency to 28 by multiplying each quotient in *e* the column labeled by *F*. The sum of these products (*e'*) should be exactly 28 and if it does not total 28 it should be adjusted to do so.
4. Each value of *e'* in item 3 is divided by the valence of the metal to give the data in column 4 from which the formula is written. The method of calculation is illustrated in the table below.

Sample F–1. Antigorite (labeled williamsite), State Line Pits

	Analysis (percent)	*e*	*e'* (= *e* × *F*)	Atomic ratios
SiO_2	44.50	2.964	16.117	4.044
Al_2O_3	1.41	.083	.453	.151
Fe_2O_3	None			
FeO	.35	.010	.054	.027
MgO	41.56	2.062	11.250	5.625
CaO	.02			
H_2O+	12.36			
Cr_2O_3	.06	.002	.011	.003
NiO	.095	.010	.055	.028
Σ	100.36	5.131	28.000	

Calculation:

$$F=\frac{28}{5.131}=5.4556$$

$$[Mg_{5.62}Fe^{2+}_{.03}Ni_{.03}Al_{.15}][Si_{4.04}]O_{10}(OH)_8$$

$$\Sigma_{oct}=5.83 \qquad \Sigma_{tet}=4.04$$

The collection of structural formulas computed from the chemical analyses is shown in tables 7, 8, and 9. The results bear out the precept given by Genth (1875, p. 120B) in reference to the montmorillonite mineral sauconite, to wit:

> Like all similar minerals, the composition is somewhat variable, owing in part to accidental admixture and a replacement of one isomorphous substance by another.

Genth's interpretation is just as valid today. It is the hope of the chemist that he is analyzing a pure sample free from "accidental admixture." It is the responsibility of the mineralogist and petrologist that the admixed substances are removed by one or several

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TABLE 5.—*Chemical analyses of 219 specimens of serpentine and related minerals*

[Analyses from the literature. For location and description of specimens, see p. 19–26]

	1	2	3	4	5	6	10	11	12	13	14	15	16	17	18	19	20
SiO_2	43.87	45.02	42.54	41.68	39.72	40.82	41.73	42.86	42.75	42.53	38.87	41.30	41.20	43.00	41.15	40 15	41.40
Al_2O_3	23.44	29.31	5.68	11.33	3.06	2.07	3.84	1.48	1.95	.35	7.91	1.59	1.26	.62	1.95	2.35	1.45
Fe_2O_3	5.37	-------	1.06	3.47	6.20	6.10	1.16	3.96	2.49	3.80	2.95	3.61	2.80	3.03	2.35	3.85	3.06
FeO	-------	.21	.74	.33	.91	1.00	3.58	2.03	3.07	.72	.43	4.51	.11	2.45	.25	.45	3.84
MgO	15.18	12.60	35.57	37.75	34.44	35.88	35.79	37.57	37.32	38.44	36.17	36.30	38.60	38.74	38.05	38.40	37.01
CaO	1.24	-------	.13	Tr.	.63	.50	.73	.46	.63	.98	Nil	.43	-------	.69	.05	.40	.72
Na_2O	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	.29	.04	.06	-------	.25	.25	-------
K_2O	-------	4.43	-------	-------	-------	-------	-------	-------	-------	-------	.15	.02	.13	-------	.10	.10	-------
TiO_2	-------	-------	-------	-------	-------	-------	-------	Tr.	-------	-------	-------	.15	.18	-------	-------	-------	-------
Cr_2O_3	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	.30	-------	-------	-------	-------	-------
NiO	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	.23	.26	-------	-------	.30	.30	-------
MnO	-------	-------	-------	.80	Tr.	-------	Tr.	-------	-------	-------	.04	.11	.21	-------	-------	-------	-------
ZnO	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
CuO	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
H_2O-	10.86	7.03	.38	4.55	1.51	.35	12.93	.31	.39	.86	1.26	n.d.	1.39	.01	16.05	14.35	13.27
H_2O+			13.26		13.28	13.26		11.56	11.88	12.50	11.68	11.19	14.14	11.97			
CO_2	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	.42	.03	-------	-------	-------	-------	-------
SO_3	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	.06	-------	-------	-------	-------	-------
Σ	99.96	98.60	99.36	99.91	99.75	99.98	99.76	100.23	100.48	100.18	[1] 100.40	99.90	100.08	100.51	[2] 100.90	100.60	100.75
Sp gr	-------	-------	-------	-------	-------	-------	-------	2.645	-------	-------	-------	-------	-------	-------	-------	-------	-------

	21	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
SiO_2	37.15	40.75	41.55	40.23	38.23	41.34	41.58	40.95	39.50	41.65	42.10	40.96	42.17	42.15	41.86	41.80	41.55
Al_2O_3	3.20	2.51	-------	2.18	3.49	3.22	2.60	1.50	5.08	.10	-------	1.70	.30	.58	.69	.95	.63
Fe_2O_3	7.70	3.47	3.90	4.02	6.53	-------	-------	-------	8.12	2.88	2.43	-------	1.57	1.45	-------	-------	3.35
FeO	-------	3.12	-------	Tr.	1.54	5.54	7.22	10.05		.16	-------	2.44	.64	.96	4.15	4.65	.52
MgO	36.20	36.94	40.15	39.46	37.33	37.61	36.80	34.70	34.65	41.06	41.50	38.73	41.33	40.76	38.63	38.55	40.77
CaO	-------	1.62	-------	-------	-------	-------	-------	-------	-------	None	-------	-------	-------	-------	-------	-------	.13
Na_2O	-------	-------	-------	-------	-------	-------	-------	-------	.10	-------	-------	.10	-------	-------	-------	-------	-------
K_2O	-------	-------	-------	-------	-------	-------	-------	-------		-------	-------		-------	-------	-------	-------	-------
TiO_2	-------	.06	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
Cr_2O_3	1.40	-------	-------	-------	-------	Tr.	-------	-------	-------	-------	-------	-------	-------	-------	.24	-------	-------
NiO	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	.45	-------	-------	.17	Tr.	-------	-------
MnO	-------	-------	-------	-------	.03	Tr.	-------	-------	-------	.05	-------	-------	-------	.10	.20	-------	-------
ZnO	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
CuO	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
H_2O-	15.10	.31	13.70	14.24	1.10	12.06	12.67	12.60	12.55	1.12	12.70	2.70	13.72	.92	14.16	13 95	.48
H_2O+		11.74			12.30					13.10		13.37		13.11			12.33
CO_2	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
SO_3	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
Σ	100.75	100.52	99.30	[3] 100.13	[4] 100.63	99.77	100.87	99.80	100.00	100.12	99.18	100.00	99.73	100.20	99.93	99.90	99.76
Sp gr	-------	2.550	3.39	-------	-------	2.644	-------	-------	2.545	-------	-------	-------	-------	-------	-------	-------	-------

	41	42	43	44	45	46	47	48	49	50	51	52	53	54	60	61	62
SiO_2	41.54	32.45	40.60	41.69	41.33	42.44	42.97	42.38	43.45	41.76	41.70	42.62	42.04	42.15	37.15	39.78	41.59
Al_2O_3	2.48	2.57	.30	1.56	.80	1.13	.87	.07	.81	.65	1.10	.38	-------	-------	5.60	.47	-------
Fe_2O_3	-------	17.61	3.63	-------	1.29	.26	-------	.97	.88	2.71	3.50	-------	-------	-------	1.10	2.61	2.43
FeO	1.37	1.30	.54	2.07	.08	1.69	2.48	.17	.69	.39	-------	.27	3.66	3.57	8.80	.53	-------
MgO	40.42	33.59	39.79	40.33	41.39	41.45	41.66	42.14	41.90	40.36	38.95	42.67	39.54	40.41	32.80	35.73	42.32
CaO	-------	.40	.79	-------	Tr.	.23	-------	-------	.04	-------	-------	-------	-------	-------	.10	6.77	-------
Na_2O	-------	-------	-------	-------	-------	-------	-------	-------	.05	.41	.14	-------	-------	-------	.29	-------	-------
K_2O	-------	-------	-------	-------	-------	-------	-------	-------	.02	.24	-------	-------	-------	-------		-------	-------
TiO_2	-------	-------	-------	-------	.02	-------	-------	-------	.02	.03	-------	-------	-------	-------	-------	-------	-------
Cr_2O_3	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
NiO	.04	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
MnO	-------	-------	-------	-------	.04	-------	-------	-------	-------	.02	-------	-------	-------	.03	-------	-------	-------
ZnO	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
CuO	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
H_2O-	14.17	.83	.98	12.82	1.57	12.70	12.02	14.12	.04	.33	1.07	14.25	14.31	1.24	14.16	.17	13.55
H_2O+		11.34	13.05		13.66				12.29	13.17	13.89			12.65		14.21	
CO_2	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
SO_3	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
Σ	100.02	100.09	99.68	98.47	100.18	99.90	100.00	[3] 99.85	100.19	100.07	100.35	100.19	99.55	100.05	100.00	100.27	99.89
Sp gr	-------	-------	-------	-------	-------	2.793	-------	-------	-------	-------	-------	-------	2.29	-------	2.56	-------	-------

See footnotes at end of table, p. 32.

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TABLE 5.—*Chemical analyses of 219 specimens of serpentine and related minerals*—Continued

	63	64	65	66	67	68	69	70	71	72	73	75	76	77	78	79
SiO_2	41.91	41.88	42.50	42.74	38.49	42.02	42.40	42.72	42.17	41.46	39.38	40.05	40.54	38.50	40.83	41.22
Al_2O_3	.49	.19	.32	.21	1.32	.49	.74	.20	-------	.01	1.56	1.90	1.09	1.02	3.20	.28
Fe_2O_3	1.90	.81	.50	1.22	3.29	1.50	.48	.68	-------	2.42	-------	1.60	-------	4.66	-------	1.07
FeO	.16	.05	.010	.43	.57	.057	.043	-------	3.33	1.16	13.87	.40	4.87	3.31	5.84	.39
MgO	41.36	41.38	42.50	41.20	37.80	42.05	42.70	43.38	40.54	41.76	32.25	38.35	39.02	36.40	36.62	41.98
CaO	-------	.47	.04	-------	1.41	.26	.01	-------	-------	-------	-------	.15	-------	1.97	-------	.12
Na_2O	.43	.06	.04	.44	-------	.02	.03	-------	-------	-------	} .17	{ .25	-------	-------	-------	-------
K_2O	.19	.023	.02	.25	-------	.014	.02	-------	-------	-------		{ .15	-------	-------	-------	-------
TiO_2	-------	.036	.021	-------	-------	.073	.070	-------	-------	-------	-------	-------	-------	-------	-------	-------
Cr_2O_3	-------	.005	.004	-------	-------	.001	.008	-------	-------	-------	-------	-------	-------	-------	-------	-------
NiO	-------	0	0	-------	-------	.002	0	-------	-------	-------	-------	-------	-------	.59	-------	-------
MnO	.02	.05	.02	.11	.49	.024	.02	-------	.09	.23	-------	-------	-------	-------	-------	.08
ZnO	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
CuO	-------	-------	.01	-------	-------	-------	.05	-------	-------	-------	-------	-------	-------	-------	-------	-------
H_2O-	.33	.60	.65	.22	.70	.32	.26	} 13.40	{ 2.53	} 12.43	11.90	16.60	{ 1.13	} 12.35	12.37	14.80
H_2O+	13.26	14.22	13.46	13.25	11.20	13.74	13.52		{ 11.40				{ 13.47			
CO_2	-------	.02	.14	-------	4.54	.06	.11	-------	-------	-------	-------	-------	-------	-------	-------	-------
SO_3	-------	.31	-------	-------	-------	.07	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
Σ	100.05	100.10	100.23	100.07	[5] 99.87	100.70	100.46	100.38	100.06	99.47	99.13	99.45	100.12	[6] 100.58	98.86	99.94
Sp gr	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	2.4	-------	-------	2.587	-------	2.48

	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96
SiO_2	41.95	41.98	38.86	40.06	41.33	41.96	40.75	41.52	41.80	39.05	40.71	41.80	39.64	42.28	39.22	40.23	40.70
Al_2O_3	-------	-------	2.95	2.36	2.11	.59	.90	.57	.19	3.67	2.39	.11	1.30	.86	3.64	1.01	.22
Fe_2O_3	-------	-------	1.86	-------	1.75	.93	1.30	.36	.93	} 2.41	{ -------	.68	-------	-------	} 2.26	{ 2.43	1.57
FeO	2.81	2.87	5.04	1.99	1.41	.54	.60	.06	.06		{ 2.43	.05	7.76	2.57		{ 3.50	.31
MgO	41.62	41.38	34.61	40.49	40.01	42.01	41.00	42.80	42.67	40.07	41.48	42.82	37.13	40.29	40.27	41.10	42.05
CaO	-------	-------	-------	-------	nil	1.15	-------	.11	.19	-------	-------	.10	-------	1.35	-------	-------	.82
Na_2O	-------	-------	} 1.10	{ -------	.34	-------	.35	.03	.02	-------	-------	.03	-------	.48	-------	-------	-------
K_2O	-------	-------		{ -------	.40	-------	Tr.	.02	.01	-------	-------	.01	-------	-------	-------	-------	-------
TiO_2	-------	-------	-------	-------	-------	Tr.	-------	.06	.10	-------	-------	.05	-------	-------	-------	-------	-------
Cr_2O_3	-------	-------	.08	-------	-------	-------	-------	.01	.003	-------	-------	.003	.29	-------	-------	-------	-------
NiO	-------	-------	.28	-------	.08	Tr.	-------	0	0	-------	-------	0	.33	-------	-------	-------	-------
MnO	-------	-------	-------	-------	.05	-------	-------	.04	.04	-------	-------	.04	.12	-------	-------	-------	-------
ZnO	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
CuO	-------	-------	-------	-------	-------	-------	-------	.05	-------	-------	-------	-------	-------	-------	-------	-------	-------
H_2O-	} 14.85	13.78	15.52	{ 1.78	.55	.17	1.90	.60	.24	n.d.	} 12.61	{ .28	} 13.81	12.52	{ n.d.	} 11.54	{ .38
H_2O+				{ 14.53	12.35	12.30	13.45	14.36	13.88	14.48		{ 14.04			{ 14.37		{ 13.63
CO_2	-------	-------	-------	-------	-------	-------	-------	-------	.04	-------	-------	.01	-------	-------	-------	-------	-------
SO_3	-------	-------	-------	-------	-------	-------	-------	.62	.08	-------	-------	.09	-------	-------	-------	-------	-------
Σ	101.23	100.01	100.30	101.21	100.38	99.65	100.25	100.61	100.25	99.68	99.62	100.11	100.38	100.35	99.76	99.81	99.68
Sp gr	-------	2.48	-------	-------	2.29	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

	97	98	99	100	101	102	110	111	112	113	114	115	116	120	121	122	123
SiO_2	40.49	41.76	39.83	40.08	40.52	39.13	36.59	38.58	38.40	41.48	38.62	39.36	37.39	43.60	42.25	44.21	42.87
Al_2O_3	1.27	Tr.	6.39	.15	2.10	-------	Tr.	3.21	.10	5.49	.20	-------	2.66	1.03	-------	2.72	.26
Fe_2O_3	} 2.53	{ -------	-------	2.82	-------	2.49	8.84	-------	3.42	-------	3.21	} 3.31	{ 2.63	.90	-------	-------	-------
FeO		{ 4.06	1.71	7.68	1.97	1.74	1.05	2.53	None	1.59	-------		{ 1.96	.81	1.70	.52	2.35
MgO	41.41	41.40	39.92	36.64	42.05	40.58	38.85	38.87	41.91	37.42	41.88	42.15	40.77	41.00	41.40	40.55	40.40
CaO	-------	-------	.07	1.31	-------	.50	-------	2.90	None	-------	-------	-------	.62	.05	-------	.26	1.04
Na_2O	-------	-------	1.11	Tr.	-------	-------	1.46	-------	-------	2.84	.30	-------	-------	.01	-------	-------	-------
K_2O	-------	-------	-------	.33	-------	-------	-------	-------	-------	-------	.42	-------	-------	.03	-------	-------	-------
TiO_2	-------	-------	-------	Tr.	-------	-------	-------	-------	None	-------	-------	-------	-------	.01	-------	-------	-------
Cr_2O_3	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	.02	-------	-------	-------
NiO	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	.16	-------	-------	-------
MnO	-------	-------	-------	-------	-------	-------	-------	-------	.05	-------	.04	-------	-------	.04	.02	-------	-------
ZnO	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
CuO	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
H_2O-	} 14.06	13.40	10.43	11.35	13.46	{ 2.80	} 13.41	14.10	{ 1.26	} 10.88	{ .29	n.d.	} 14.08	{ .08	.68	} 12.43	12.98
H_2O+						{ 13.19			{ 15.03		{ 15.09	14.50		{ 12.18	14.05		
CO_2	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
SO_3	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
Σ	99.76	100.62	99.46	[7] 100.36	100.10	100.43	100.20	100.19	100.17	99.70	100.05	99.32	100.11	99.92	100.10	100.69	99.90
Sp gr	-------	2.804	2.718	-------	-------	2.368	-------	-------	-------	2.61	-------	-------	-------	-------	-------	2.363	2.510

See footnotes at end of table, p. 32.

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TABLE 5.—*Chemical analyses of 219 specimens of serpentine and related minerals*—Continued

	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140
SiO_2	41.13	42.00	43.60	42.94	43.12	42.20	41.90	41.23	42.73	43.66	43.13	42.11	40.04	41.21	42.54	44.22	42.29
Al_2O_3	.55	.26	.03	.46	4.91	1.59	.71	.19	1.33	.64					3.78	.53	
Fe_2O_3	.51			1.56			.91	.31							4.75	6.61	1.92
FeO	.09	.90	.40	3.13	1.99	1.76	n.d.	.53	7.20	1.96	.37	5.47	8.28	1.72	5.57		
MgO	39.59	41.00	42.58	38.92	34.87	38.70	40.16	39.42	36.51	41.12	42.05	37.80	38.80	39.24	30.48	37.54	39.90
CaO	.21		.55	Tr.				.24				.68					
Na_2O					1.33	.16											
K_2O																	
TiO_2																	
Cr_2O_3				.08					Tr.								
NiO							.10		Tr.		Tr.						
MnO	.34			.07				.16			Tr.			.30			
ZnO																	
CuO																	
H_2O-	4.13	15.00	.90	.30	13.13	1.84	16.16	4.06	11.66	13.57	13.88	14.13	9.08	.41	13.13	.36	16.16
H_2O+	13.81		12.02	12.56		13.75		13.62					4.70	16.16		11.26	
CO_2																	
SO_3																	
Σ	100.36	99.16	100.08	100.02	99.35	100.00	99.94	99.76	99.43	100.95	99.43	100.19	100.90	99.04	100.25	100.52	100.27
Sp gr											2.514	2.559			2.604		

	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161
SiO_2	42.30	44.49	41.47	41.22	43.30	44.73	44.08	43.50	44.25	40.29	44.08	44.50	43.89	44.58	40.16	45.23	44.05
Al_2O_3	.59	2.26	.10	.90	.35	.32	.30	.40	4.90	.12	.30	.75		3.03	Tr.		
Fe_2O_3	4.54	.48		1.95	2.62					.86					1.16		
FeO	1.97		.90	3.60	.40	.33	1.17	2.08	3.67	.09	1.17	1.39	1.38	6.15		3.61	2.53
MgO	35.88	40.27	38.40	34.52	38.58	42.64	40.87	40.00	34.00	37.08	40.87	39.70	40.48	34.51	36.00	39.59	39.24
CaO	.05	.03	.83	1.27	.72	Tr.	.37			.20	.37				.80		
Na_2O			.42														
K_2O																	
TiO_2	0	.03			Tr.												
Cr_2O_3																	
NiO									.69			.90		Tr.			
MnO	.03		.71		Tr.					.31							
ZnO																	
CuO																	
H_2O-	1.30	12.80	2.31	4.70	1.66	12.21	13.70	13.80	12.32	7.02	13.70	12.75	13.45	12.38	21.60	11.60	13.49
H_2O+	13.12		14.51	11.55	12.91					14.23							
CO_2																	
SO_3																	
Σ	99.78	100.36	99.65	99.71	100.54	100.23	100.49	99.78	99.83	100.20	100.49	99.99	99.20	100.65	99.72	100.03	99.31
Sp gr						2.59	2.48									2.517	2.49

	162	163	164	165	166	170	171	172	173	174	175	176	177	178	179	180	181
SiO_2	40.98	44.77	41.90	41.81	44.58	42.34	43.16	34.96	45.01	43.15	47.12	44.56	43.03	44.85	41.00	50.75	45.65
Al_2O_3	.73				Tr.		.47	.49	.30	Tr.	2.82		5.56	1.31	4.00	3.40	
Fe_2O_3						1.39	.41	9.13	7.28		2.58		12.30	9.83	13.30	1.25	.20
FeO	8.72	3.35		1.36	2.13		.10	3.03				.50		.51		7.40	
MgO	33.44	39.17	36.30	37.38	39.55	36.77	37.69	21.97	34.62	35.95	30.90	36.30	19.58	26.70	17.60	28.80	34.38
CaO			.50			Tr.	.20				3.20			.75		.75	Tr.
Na_2O			2.71													.50	
K_2O																.15	
TiO_2																	
Cr_2O_3																	
NiO									.91								
MnO														Tr.			
ZnO																	
CuO																	
H_2O-	1.54	12.94	18.00	20.39	12.91	19.03	4.94	21.20	11.70	20.25	.76	18.00	17.40	5.78	23.00	6.75	19.49
H_2O+	12.86						13.58	9.84			13.48			10.61			
CO_2	1.73																
SO_3																	
Σ	100.00	100.23	99.41	100.94	99.17	99.53	100.55	100.62	99.82	99.35	100.86	99.36	97.87	100.34	98.90	99.75	99.72
Sp gr		2.61									2.20		2.05–2.08		2.05–2.08		2.3

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TABLE 5.—*Chemical analyses of 219 specimens of serpentine and related minerals*—Continued

	182	183	185	186	187	190	191	192	193	194	195	196	197	198	199	200	201
SiO_2	36.74	45.02	54.89	61.70	60.45	40.90	40.86	40.83	39.32	41.07	44.77	40.36	41.28	41.46	42.27	40.57	41.60
Al_2O_3		3.35	.79	6.85	.50	Tr.	Tr.					.21					Tr.
Fe_2O_3	11.52		1.40								.51	1.35				.90	
FeO	3.06				6.34	4.70	4.59	1.02	.51	1.05	4.77	.66	1.93	.99	1.88	2.81	3.24
MgO	17.38	37.75	33.55	27.95	26.01	41.31	41.37	42.94	41.14	42.33	45.09	43.86	42.00	44.68	43.10	41.50	41.11
CaO					1.25	.02	.03			.58							
Na_2O																	
K_2O																	
TiO_2																	
Cr_2O_3						.03	.02										
NiO						.08	.09										.50
MnO			.42					.04					.04				
ZnO																	
CuO																	
H_2O-	32.02	13.01	7.30	5.00	5.05	13.40	13.08	.70	18.41	.77	4.96	n.d.	.82	14.07	13.59	13.55	12.70
H_2O+								14.49		13.92		13.45	14.00				
CO_2																	
SO_3																	
Σ	100.72	99.13	98.35	101.50	99.60	100.44	100.04	100.02	99.38	99.72	100.10	99.89	100.07	101.20	100.84	99.33	99.15
Sp gr				2.77						2.498	2.417	2.55					

	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218
SiO_2	41.32	41.84	41.58	40.30	41.20	41.66	42.20	42.56	41.97	42.29	40.57	41.43	39.30	42.58	43.28	41.97	41.13
Al_2O_3			.42				Tr.	Tr.		Tr.	.90					.10	1.23
Fe_2O_3				2.27	.80											.38	
FeO	.58	2.23	1.69	.87		3.84	1.56	.95	2.14	1.21	2.81	2.10	6.79		2.50	1.57	1.49
MgO	42.16	41.99	42.61	43.37	43.52	40.50	42.50	43.15	41.90	42.29	41.50	40.18	36.12	43.48	42.55	42.50	43.65
CaO							Tr.	Tr.		.63		.95	Tr.		.23		.17
Na_2O																	
K_2O													Tr.			.08	
TiO_2																	
Cr_2O_3													Tr.				
NiO																	
MnO	.04								.02								
ZnO																	
CuO																	
H_2O-	1.40	14.28	13.70	12.72	15.40	13.19	13.28	12.84	.73	12.96	13.55	13.81	16.79	13.94	11.44		12.46
H_2O+	14.57								13.33							13.56	
CO_2																	
SO_3																	
Σ	100.07	100.34	100.00	99.53	100.92	[8] 99.82	99.54	99.50	100.09	99.38	99.33	98.47	99.00	100.00	100.00	100.16	100.13
Sp gr		2.14			2.381					2.57					2.487		

	219	220	221	222	225	226	227	228	229	235	236	237	238	239	240	241	242
SiO_2	42.14	42.32	42.72	41.70	28.76	23.28	35.31	37.10	30.18	37.42	38.97	36.19	40.88	41.38	39.62	43.65	41.32
Al_2O_3		.66		.24	.88	3.01	.38	Tr.	1.41	.98	.53	2.90	2.40	none	1.30		.65
Fe_2O_3				.30	5.37		3.08		5.81				1.64	1.94			
FeO	2.06	1.28	2.25	.05	2.02	28.00	.22	5.73		20.60	19.30	22.73			2.39		1.57
MgO	41.61	42.23	42.52	42.85	44.34	23.68	45.07	39.94	45.80	22.75	22.87	21.08	38.01	39.93	33.60	30.92	32.58
CaO				.05	.41	1.00									.37		.96
Na_2O				.07		.39	.38										
K_2O				.01		.52	.20										
TiO_2				.03		.38											
Cr_2O_3				.005													
NiO				0		4.66											
MnO				.02			.04			4.05	4.36	1.17	.08	.08	3.42	7.12	7.57
ZnO													1.64	2.60	4.14	3.62	.14
CuO				.02		.11											
H_2O-	14.20	13.80	13.39	.83	.88	10.55	.25	16.85	15.70	13.48	13.36	16.08	14.52	13.85	1.18	14.69	.94
H_2O+				14.23	16.86		15.13						.80	none	14.06		12.44
CO_2				.07													
SO_3				.02													
Σ	100.01	100.29	[9] 100.94	100.50	99.52	[10] 104.64	100.06	99.62	98.90	99.28	99.39	[11] 100.26	99.97	99.78	100.08	100.00	98.17
Sp gr			2.53					2.56				2.65					

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TABLE 5.—*Chemical analyses of 219 specimens of serpentine and related minerals*—Continued

	243	244	245	246	247	248	249	250	251	255	256	257	258	259	260	261
SiO_2	42.12	37.39	35.45	43.00	26.80	41.56	41.35	40.75	42.28	43.77	42.36	43.90	42.05	41.47	42.42	41.90
Al_2O_3		5.34	4.56	.27	.42	1.27	.91	1.82	1.07	6.10	2.18	1.50		1.73	.63	.71
Fe_2O_3	1.26	7.12	5.09	1.08	1.13								.30		.62	.91
FeO	.49	3.53	2.03	.17	.22	.64	.69	.74	.88	7.14	13.27	10.79	.10	.09	n.d.	n.d.
MgO	40.39	30.91	27.96	40.00	25.00	42.05	41.85	40.69	41.41	30.92	28.90	26.00	42.57	41.70	41.01	40.16
CaO	.85	.50	5.41	1.43	21.00	None	.07	None	.10	1.17	.63	2.70	.05	None	Tr.	
Na_2O		.51	.46	.03	.03											
K_2O		.37	.17	.02	.03											
TiO_2		.09	.35	.020	.022					Tr.						
Cr_2O_3				.005	.006					Tr.		2.37				
NiO				0	0										.23	.10
MnO	Tr.	.08	.05	.16	.12						.85	.55				
ZnO																
CuO				.03	.05											
H_2O-	.79	14.25	13.82	.53	.16	1.39	1.38	1.86	1.33	8.51	12.07	12.43	.96	1.20	2.04	2.26
H_2O+	12.51			13.17	14.85	12.92	11.96	12.65	12.23				13.70	13.86	13.60	13.90
CO_2	1.55	.39	4.24	.78	9.98					1.67						
SO_3				.01												
Σ	99.96	100.48	99.59	100.71	99.82	99.83	98.21	98.51	99.30	[12] 100.40	100.26	100.24	99.73	100.05	100.55	99.94
Sp gr																

[1] Cl = trace.
[2] Σ includes CoO = 0.40.
[3] Total H_2O reported as ignition loss.
[4] Σ includes CoO = 0.08.
[5] Σ includes P_2O_5 = 0.06.
[6] Σ includes FeS_2 (insoluble) = 1.78.
[7] No sulfur present.
[8] Σ includes 0.63 undetermined.
[9] Σ includes Mn_2O_3 = 0.06.
[10] Σ includes S = 9.06. Correction O for S = 4.53; corrected Σ = 100.11.
[11] Σ includes V_2O_5 = 0.11.
[12] Σ includes organic substance = 1.12.

methods of purification and that the final purity has been confirmed by examination under the polarizing microscope. For samples ranging from coarse grained to fine grained, it is usually possible to effect a purification. For fine-grained or stained samples it may not be possible to purify the sample or to detect the impurity by microscope methods alone, and resort to electron microscopy, DTA, and X-ray may be required. Faust (1951) demonstrated the hitherto unsuspected presence of halloysite in some very fine grained sauconites by several of the aforementioned techniques. The analyses of serpentine taken from the literature show clearly the validity of Genth's observation.

The calculated data for the analyzed samples studied in this research (table 7) are arranged first according to their geologic origin and then in the order in which they appear in tables 2 and 3. It will be observed that all the analyses when calculated on the basis of the structural formula show a full complement of ions in tetrahedral sites. Five analyses show a decided excess of ions in tetrahedral sites and a corresponding deficiency in octahedral sites; these are so-called deweylites, mixtures of serpentine-group minerals and stevensite. Ten of the analyses show only silicon atoms in tetrahedral coordination, six of them silicon and aluminum, four have silicon, aluminum, and trivalent iron, and two have silicon and trivalent iron in tetrahedral coordination. Samples F–72, F–73, and F–74 were derived from rocks known to contain magnetite, and the material analyzed probably contained some magnetite. Comparison of the data for these three samples with that calculated for a mixture of 90 percent serpentine and 10 percent magnetite indicates from the values for Fe^{2+} and Fe^{3+} that the contamination should not be great. The very low value for the number of silicon atoms in tetrahedral coordination is distinctly abnormal. These three samples, however, are not pure and they cannot be directly compared with the other samples studied by us. All analyses showing Fe^{3+} in tetrahedral coordination must be viewed with caution until the absence of significant amounts of magnetite are confirmed or a quantitative estimate of its abundance is determined.

TABLE 6.—*Equivalent weights used in the calculations*

Oxide	Equivalent weight	Oxide	Equivalent weight
SiO_2	15.02	TiO_2	19.98
Al_2O_3	16.99	Cr_2O_3	25.34
Fe_2O_3	26.62	NiO	37.36
FeO	35.92	MnO	35.47
MgO	20.16	ZnO	40.69
CaO	28.04	CoO	37.47
Na_2O	30.99	V_2O_5	18.19
K_2O	47.10		

The analyses in table 8 have been arranged, in general, first according to the number of ions in tetrahedral coordination, and then according to an increasing number of ions in octahedral coordination. Analyses 1 through 116, with the exception of analyses 80 and 81, all have exactly four calculated atoms in tetrahedral coordination and a range of ions in octahedral coordination from 4.76 to 6.19. Analyses 120 through 187 are arranged in order of increasing number of ions in tetrahedral coordination from 4.01 to 5.06. Analyses 190 through 222 are, with two exceptions (Nos. 198 and 218), arranged in order of ions in tetrahedral coordination from 3.89 to 3.99. Analyses 225 through 229, 243 through 251, and 255 through 261 represent special or regional collections and are grouped together. Table 9 contains the data

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TABLE 7.—*Relationship of the ions in octahedral and tetrahedral coordination as calculated from the chemical analyses of the specimens studied and listed in tables 2 and 3*

Sample	Locality	Ions in octahedral coordination													Ions in tetrahedral coordination			
		Mg	Fe^{2+}	Fe^{3+}	Al	Mn	Ni	Cr	Ti	Zn	Ca	Na	K	Σ oct	Si	Al	Fe^{3+}	Σ tet
Class A																		
F-1	State Line Pits, Pa	5.63	0.03		0.15		0.01	0.01						5.83	4.05			4.05
F-43	Delaware County, Pa	5.74	.01	0.10	.03									5.88	4.02			4.02
F-42	Near Norris, Tenn	5.78	.07		.12									5.97	3.95	0.05		4.00
F-47	Tyrol, Austria	5.68		.27										5.95	3.87		0.13	4.00
F-46	Near Bellows Falls, Vt	5.61		.31										5.92	3.85	.05	.10	4.00
F-40	Murfreesboro, Ark	5.45	.05	.09	.03				0.01					5.63	4.15			4.15
F-3	Near Forest Hill, Md	5.53	.02	.07	.12		.01							5.75	4.09			4.09
F-19	Bare Hills, Md	5.20	.38	.03	.21	0.01	.01							5.84	4.05			4.05
F-15	Antigorio, Italy	5.01	.33	.13	.30	.01	.01	.02			0.01			5.82	3.94	.06		4.00
F-26	Texas, Pa	5.06			.02	.01						0.01		5.10	4.45			4.45
F-48	North Carolina	4.33	.45								.02			4.80	4.60			4.60
F-72	Santa Clara County, Calif	5.50	.14	.37		.01		.02						6.04	3.53	.37	.10	4.00
F-73	do	5.45	.19	.36		.01		.03						6.04	3.56	.39	.05	4.00
F-74	do	5.57	.06	.32	.08	.01		.02						6.06	3.59	.41		4.00
F-51	Nicaro, Cuba	5.84	.25	.03			.02							6.14	3.68	.06	.26	4.00
F-69	Webster, N.C	5.85	.17	.14			.02				.01			6.19	3.51	.29	.20	4.00
Class B																		
F-25	Montville, N.J	5.94	0.01	0.01	0.03							0.01	0.01	6.01	3.96	0.04		4.00
F-24	do	6.01												6.01	3.97		0.03	4.00
F-22	do	5.93	.01	.02	.02	0.01						.03		6.02	3.95	.05		4.00
F-14	Manchuria	5.72	.02	.01	.05						0.01			5.81	4.08			4.08
F-8	Smithfield, R.I	5.73	.01	.01							.06			5.81	4.09			4.09
F-23	Dognacska, Hungary	5.82	.02	.14								.02		6.00	3.92	.08		4.00
F-20	Gila County, Ariz	5.88	.01	.01	.06									5.96	4.00			4.00
F-53	Grand Canyon, Ariz	5.67		.04	.04	.01					.01	.03	.01	5.81	4.09			4.09
F-56	Balmat, N.Y	5.69	.01	.06		.01					.08	.01		5.86	4.05			4.05
F-13	Brewster Station, N.Y	5.53	.19	.02	.11	.01							.03	5.89	4.04			4.04
F-41	White Pine County, Nev	5.54		.01	.01									5.56	4.22			4.22
F-57	Talcville, N.Y	5.75	.01	.02	.04	.04			0.01					5.87	4.05			4.05

for two special collections, the manganese-rich and zinc-rich species.

Serpentine-group minerals theoretically should have 6.00 ions in octahedral coordination and 4.00 ions in tetrahedral coordination. Assuming the material prepared for analysis to be 100 percent pure, the accuracy of the formula calculated for the mineral in expressing its true composition will depend chiefly on (1) the analytical skill of the chemist, (2) the quality of the methods used in the determinations, (3) the purity of the reagents, and (4) the completeness of the analysis.

The chemical analyses gathered from the literature were made over a long span of years, by various analysts, using many different procedures. There also has been some variation within this span of years in the values assigned to the atomic weights used in calculating the analysis. Lange (1952) gives a table showing the changes in atomic weights over the period 1894 to 1951. Indirect determinations that require that a factor be used to calculate the percentage of a constituent are affected by significant changes in the value of the atomic weight. For example, magnesium is commonly determined as magnesium pyrophosphate and calculated by means of a factor to MgO. Less obvious, but nonetheless frequently important, are those determinations that may be direct in themselves but are subject to correction because other constituents are present. Thus alumina is calculated from the value for the R_2O_3 group by subtracting from it the Fe_2O_3, TiO_2, or other oxide included in it. As the determination of iron involves the use of a conversion factor, calculation of Fe_2O_3 could introduce error.

Incompleteness of an analysis can introduce serious error into calculations of formulas. Washington (1919) has discussed such errors. He points out that failure to determine Fe_2O_3, Cr_2O_3, V_2O_3, TiO_2, ZrO_2, P_2O_5, MnO, and a little SiO_2, if they are present in significant amounts in the R_2O_3 precipitate, yields a figure for alumina which is too high. On the other hand, the nondetermination of those constituents which are precipitated and weighed with others and not otherwise determined leads to a low summation for the analysis. For the serpentines this includes chiefly NiO, MnO, and CO_2. NiO + MnO may be partially caught in the R_2O_3 precipitate.

Considering the calculation of the structural formula, it follows that the nondetermination of other constituents in the R_2O_3 group precipitate may result in a high value for aluminum ions. If considerable amounts of other constituents are present this may raise the total for the ions in octahedral coordination beyond $\Sigma = 6.00$.

The charge relationships for the octahedral and tetrahedral layers in the crystal structure of the minerals of the serpentine group will be discussed by Faust in a subsequent report on these minerals. Suffice it to say that most of the analyses reported on in this paper

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TABLE 8.—*Relationship of the ions in octahedral and tetrahedral coordination as calculated from the chemical analyses of serpentine-group minerals taken from the literature and listed in table 5*

Sample	Locality	Ions in octahedral coordination													Ions in tetrahedral coordination			
		Mg	Fe^{2+}	Fe^{3+}	Al	Mn	Ni	Cr	Ti	Zn	Ca	Na	K	Σ oct	Si	Al	Fe^{3+}	Σ tet
1	Silesia	1.98		0.36	2.28						0.14			4.76	3.85	0.15		4.00
2	Waldheim	1.61	0.02		2.81								0.48	4.92	3.85	.15		4.00
3	U.S.S.R	4.94	.06	.07	.59						.02			5.68	3.97	.03		4.00
4	Easton, Pa	4.79	.02	.22	.69	0.06								5.78	3.55	.45		4.00
5	Madagascar	4.96	.07	.45	.19						.08			5.75	3.84	.16		4.00
6	France	5.09	.08	.44	.12						.06			5.79	3.89	.11		4.00
10	Tyrol, Italy	5.01	.28	.08	.36						.09			5.82	3.93	.07		4.00
11	Tyrol, Austria	5.19	.16	.28	.13						.06			5.82	3.97	.03		4.00
12	Switzerland	5.16	.24	.17	.18						.08			5.83	3.97	.03		4.00
13	Waldheim	5.38	.06	.27	.03						.12			5.86	3.99	.01		4.00
14	Southern Rhodesia	5.03	.03	.21	.50		0.02					0.05	.02	5.86	3.63	.37		4.00
15	Antigorio, Italy	5.09	.36	.26	.06	.01	.02	0.02	0.01		0.4	.01		5.88	3.89	.11		4.00
16	Transvaal, Union of South Africa	5.51	.01	.20	.09	.02			.01			.01	.02	5.87	3.95	.05		4.00
17	France	5.34	.19	.21	.05						.08			5.87	3.98	.02		4.00
18	Transvaal, Union of South Africa	5.42	.02	.17	.16		.02	.02			.01	.06		5.88	3.94	.06		4.00
19	do	5.42	.04	.28	.07		.02					.06		5.89	3.81	.19		4.00
20	Antigorio, Italy	5.21	.30	.22	.07						.09			5.89	3.91	.09		4.00
21	Transvaal, Union of South Africa	5.24		.54				.11						5.89	3.61	.37	0.02	4.00
25	Antigorio, Italy	5.16	.25	.24	.10						.16			5.91	3.82	.18		4.00
26	Easton, Pa	5.69		.22										5.91	3.94		.06	4.00
27	Montville, N.J	5.57		.29	.06									5.92	3.82	.18		4.00
28	Southern Rhodesia	5.30	.12	.47	.04									5.93	3.65	.35		4.00
29	Villa Rosa, Italy	5.26	.43		.25									5.94	3.89	.11		4.00
30	Antigorio, Italy	5.16	.57		.21									5.94	3.92	.08		4.00
31	Bare Hills, Md	5.00	.81		.13									5.94	3.96	.04		4.00
32	Lizard, England	4.93	.65		.35							.02		5.95	3.78	.22		4.00
33	Shetland Islands	5.78	.02	.15										5.95	3.94	.01	.05	4.00
34	Texas, Pa	5.80		.12			.03							5.95	3.95		.05	4.00
35	Southern Rhodesia	5.58	.20	.15								.02		5.95	3.96	.04		4.00
36	Port Henry, N.Y	5.79	.05	.11										5.95	3.97	.03		4.00
37	Southern Rhodesia	5.72	.08	.10	.04		.01							5.95	3.98	.02		4.00
38	Sulphur Bank, Calif	5.50	.33		.08	.02		.02						5.95	4.00			4.00
39	Brewster Station, N.Y	5.48	.37		.10									5.95	4.00			4.00
40	Czechoslovakia	5.69	.04	.21							.02			5.96	3.90	.07	.03	4.00
41	New Idria, Calif	5.66	.11		.19									5.96	3.91	.09		4.00
42	Quebec	4.97	.11	.84							.05			5.97	3.22	.30	.48	4.00
43	Val d'Aosta, Italy	5.66	.04	.17							.10			5.97	3.88	.03	.09	4.00
44	Austria	5.68	.17		.12									5.97	3.95	.05		4.00
45	Transvaal, Union of South Africa	5.86	.01	.09	.02									5.98	3.93	.07		4.00
46	Easton, Pa	5.74	.13	.02	.06						.03			5.98	3.94	.06		4.00
47	Snarum, Norway	5.73	.19		.06									5.98	3.97	.03		4.00
48	Montville, N.J	5.90	.01	.07										5.98	3.99	.01		4.00
49	New Zealand	5.73	.05	.06	.08						.01	.01		5.94	3.99	.01		4.00
50	Switzerland	5.66	.04	.19								.07	.03	5.99	3.93	.07		4.00
51	Venezuela	5.50	.38		.08							.03		5.99	3.96	.04		4.00
52	Montville, N.J	5.94	.02		.03									5.99	3.99	.01		4.00
53	Quebec	5.59	.40											5.99	4.00			4.00
54	Australia	5.71	.28											5.99	4.00			4.00
60	Lizard, England	4.82	.73	.08	.31						.01	.05		6.00	3.66	.34		4.00
61	Silesia	5.16	.04	.10							.70			6.00	3.86	.05	.09	4.00
62	Snarum, Norway	5.92		.08										6.00	3.91		.09	4.00
63	Switzerland	5.78	.01	.11								.08	.02	6.00	3.93	.05	.02	4.00
64	Montville, N.J	5.86	.01	.06							.05	.02		6.00	3.98	.02		4.00
65	Delaware County, Pa	5.93		.04	.02							.01		6.00	3.98	.02		4.00
66	Transvaal, Union of South Africa	5.74	.03	.09	.02	.01						.08	.03	6.00	4.00			4.00
67	Southern Rhodesia	5.55	.05	.19		.04					.18			6.01	3.79	.15	.06	4.00
68	Montville, N.J	5.86	.01	.09					.01		.03	.01		6.01	3.93	.05	.02	4.00
69	Delaware County, Pa	5.92	.01	.04	.03							.01		6.01	3.95	.05		4.00
70	Montville, N.J	5.98		.03										6.01	3.96	.02	.02	4.00
71	Silesia	5.73	.27			.01								6.01	4.00			4.00
72	Shetland Island	5.84	.09	.07		.02								6.02	3.90		.10	4.00
73	Brewster Station, N.Y	4.76	1.15		.08							.03		6.02	3.90	.10		4.00
75	Transvaal, Union of South Africa	5.58	.03	.18	.13						.02	.08		6.02	3.91	.09		4.00
76	Cyprus	5.60	.39		.03									6.02	3.91	.09		4.00
77	Lizard, England	5.29	.27	.21			.05				.21			6.03	3.75	.12	.13	4.00
78	Antigorio, Italy	5.20	.47		.26									5.93	3.90	.10		4.00
79	Urals, U.S.S.R	5.95	.03	.03		.01					.01			6.03	3.92	.03	.05	4.00
80	British Columbia	5.85	.22											6.07	3.96			3.96
81	Brewster Station, N.Y	5.83	.23											6.06	3.97			3.97
82	Lizard, England	5.08	.41	.14	.17		.02		.01			.21		6.04	3.83	.17		4.00
83	Czechoslovakia	5.77	.16		.11									6.04	3.84	.16		4.00
84	Southern Rhodesia	5.57	.11	.12	.09		.01					.14		6.04	3.86	.14		4.00
85	Texas, Pa	5.82	.04	.04							.14			6.04	3.90	.07	.03	4.00
86	Transvaal, Union of South Africa	5.84	.05	.09								.06		6.04	3.90	.10		4.00
87	Quebec	6.01	.01								.01	.01		6.04	3.91	.06	.03	4.00
88	Aboutville, N.Y	5.98	.01	.02							.02	.01		6.04	3.93	.02	.05	4.00
89	Thetford, Canada	5.71	.19		.15									6.05	3.74	.26		4.00
90	Snarum, Norway	5.79	.19		.07									6.05	3.81	.19		4.00
91	Aboutville, N.Y	6.01	.01								.02	.01		6.05	3.94	.01	.05	4.00
92	California	5.37	.63			.01	.03	.02						6.06	3.85	.15		4.00
93	Brewster Station, N.Y	5.60	.20		.04						.14	.08		6.06	3.94	.06		4.00
94	Thetford, Canada	5.69	.25		.13									6.07	3.72	.28		4.00
95	Chester County, Pa	5.76	.24	.07										6.07	3.79	.11	.10	4.00
96	Switzerland	5.94	.03								.10			6.07	3.86	.03	.11	4.00
97	Quebec, Canada	5.87	.20											6.07	3.86	.14		4.00
98	Massachusetts	5.81	.26											6.07	3.94		.06	4.00
99	Easton, Pa	5.40	.13		.34						.01	.20		6.08	3.65	.35		4.00
100	Finland	5.22	.61	.05							.16		.04	6.08	3.83	.02	.15	4.00
101	Qubec, Canada	5.89	.16		.04									6.09	3.81	.19		4.00
102	Brewster Station, N.Y	5.89	.14								.07			6.10	3.82		.18	4.00
110	Chester County, Pa	5.65	.09	.23								.14		6.11	3.58		.42	4.00
111	Southern Rhodesia	5.55	.20		.06						.30			6.11	3.70	.30		4.00
112	Shetland Islands	6.10		.01										6.11	3.75	.01	.24	4.00
113	Finland	5.12	.12		.40							.51		6.15	3.81	.19		4.00
114	Snarum, Norway	6.05		.01								.05	.06	6.17	3.75	.02	.23	4.00

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TABLE 8.—*Relationship of the ions in octahedral and tetrahedral coordination as calculated from the chemical analyses of serpentine-group minerals taken from the literature and listed in table 5*—Continued

Sample	Locality	Ions in octahedral coordination													Ions in tetrahedral coordination			
		Mg	Fe^{2+}	Fe^{3+}	Al	Mn	Ni	Cr	Ti	Zn	Ca	Na	K	Σ oct	Si	Al	Fe^{3+}	Σ tet
115	Thetford, Canada	6.09	.10											6.19	3.82		.18	4.00
116	Snarum, Norway	5.84	.16	.09							.06			6.15	3.60	.30	.10	4.00
120	Venezuela	5.62	.06	.06	.11		.01		.01		.01			5.88	4.01			4.01
121	Transvaal, Union of South Africa	5.85	.14											5.99	4.01			4.01
122	Easton, Pa	5.48	.04		.29						.03			5.84	4.01			4.01
123	do	5.63	.18		.03						.13			5.97	4.01			4.01
124	Czechoslovakia	5.76	.01	.04	.06	.03					.03			5.93	4.02			4.02
125	Hoboken, N.J	5.85	.07		.03									5.95	4.02			4.02
126	China	5.85	.03		.01						.07			5.96	4.02			4.02
127	Sweden	5.44	.25	.11		.01		.01						5.82	4.03			4.03
128	Finland	4.85	.16									.24		5.25	4.93			4.03
129	Southern Rhodesia	5.51	.14		.18							.02		5.85	4.03			4.03
130	North Carolina	5.74		.07	.08									5.89	4.02			4.02
131	Czechoslovakia	5.76	.04	.02	.02	.01					.03			5.88	4.04			4.04
132	Switzerland	5.14	.57		.15									5.86	4.04			4.04
133	do	5.67	.15		.07									5.89	4.04			4.04
134	Thetford, Canada	5.88	.03											5.91	4.04			4.04
135	Cornwall, Pa	5.40	.44								.09			5.93	4.04			4.04
136	Sweden	5.20	.70											5.90	4.05			4.05
137	Tyrol, Italy	5.74	.14			.02								5.90	4.05			4.05
138	Hesse-Nassau	4.32	.44	.34	.42									5.52	4.05			4.05
139	Massachusetts	5.12		.46	.06									5.64	4.05			4.05
140	Delaware County, Pa	5.69		.14										5.83	4.05			4.05
145	Montana	5.13	.16	.33	.07						.01			5.70	4.06			4.06
146	Lizard, England	5.47		.04	.24									5.75	4.06			4.06
147	Franklin, N.J	5.59	.07		.01	.06					.11	.08		5.92	4.06			4.06
148	France	5.07	.30	.14	.10						.13			5.74	4.07			4.07
149	Madagascar	5.40	.03	.18	.04						.09			5.74	4.07			4.07
150	Afghanistan	5.78	.02		.04									5.84	4.07			4.07
151	Delaware County, Pa	5.64	.09		.03						.04			5.80	4.09			4.09
152	Silesia	5.60	.16		.05									5.81	4.09			4.09
153	Wood's mine, Pa	4.68	.28		.53		.05							5.54	4.09			4.09
154	Czechoslovakia	5.62	.01	.07	.01	.03					.03			5.77	4.10			4.10
155	Delaware County, Pa	5.64	.09		.03						.02			5.78	4.10			4.10
156	Texas, Pa	5.47	.11		.08		.07							5.73	4.12			4.12
157	Chester County, Pa	5.66	.11											5.77	4.12			4.12
158	Lancaster County, Pa	4.76	.48		.33									5.57	4.13			4.13
159	Bare Hills, Md	5.52		.07							.11			5.70	4.14			4.14
160	Easton, Pa	5.41	.28											5.69	4.15			4.15
161	Conneticut	5.50	.20											5.70	4.15			4.15
162	Sweden	4.81	.74		.09									5.64	4.16			4.16
163	New Zealand	5.42	.26											5.68	4.16			4.16
164	Transvaal, Union of South Africa	5.36									.07	.52		5.95	4.16			4.16
165	New Caledonia	5.55	.11											5.66	4.17			4.17
166	Delaware County, Pa	5.50	.17											5.67	4.17			4.17
170	Berks County, Pa	5.44		.10										5.54	4.20			4.20
171	New Caledonia	5.45	.01	.03	.06						.03			5.58	4.20			4.20
172	Hesse-Nassau, Germany	3.94	.30	.83	.07									5.14	4.20			4.20
173	Texas, Pa	4.85		.57	.04		.07							5.53	4.23			4.23
174	do	5.40												5.40	4.32			4.32
175	U.S.S.R.	4.23		.18	.31						.38			5.10	4.33			4.33
176	New Caledonia	5.27	.04											5.31	4.34			4.34
177	Chester County, Pa	2.94		.93	.66									4.53	4.34			4.34
178	Madagascar	3.86	.04	.72	.16						.10			4.88	4.35			4.35
179	Chester County, Pa	2.82		1.08	.51									4.41	4.41			4.41
180	Transvaal, Union of South Africa	3.76	.54	.08	.35						.09	.11		4.93	4.45			4.45
181	Berks County, Pa	5.02		.02										5.04	4.48			4.48
182	Hesse-Nassau	3.15	.31	1.05										4.51	4.48			4.48
183	Lancaster County, Pa	4.21			.40									4.61	4.59			4.59
185	Czechoslovakia	4.29		.09	.08	.03								4.49	4.71			4.71
186	Montgomery County, Pa	3.34			.50									3.84	4.96			4.96
187	Saxony, Germany	3.24	.45		.05						.11			3.85	5.06			5.06
190	Italy	5.84	.37				.01							6.22	3.89			3.89
191	do	5.86	.37				.01							6.24	3.88			3.88
192	Quebec, Canada	6.11	.08											6.19	3.90			3.90
193	Berks County, Pa	6.11	.04											6.15	3.92			3.92
194	Montville, N.J	6.10	.08								.07			6.16	3.92			3.92
195	Easton, Pa	5.83	.35											6.18	3.89		.03	3.92
196	Thetford	6.16	.05											6.21	3.81	.02	.10	3.93
197	Germany	5.97	.15											6.12	3.94			3.94
198	Berks County, Pa	6.20	.08											6.28	3.86			3.86
199	Switzerland	5.98	.15											6.13	3.94			3.94
200	Canada	5.91	.22											6.13	3.88		.07	3.95
201	Lancaster County, Pa	5.81	.26				.04							6.11	3.95			3.95
202	Quebec, Canada	6.02	.05											6.07	3.96			3.96
203	do	5.91	.18											6.09	3.96			3.96
204	France	5.97	.13											6.10	3.91	.05		3.96
205	Italy	6.09	.07											6.16	3.80		.16	3.96
206	Quebec, Canada	6.12												6.12	3.90		.06	3.96
207	Switzerland	5.75	.30											6.05	3.97			3.97
208	Rhode Island	5.95	.12											6.07	3.97			3.97
209	do	6.00	.07											6.07	3.97			3.97
210	Southern Rhodesia	5.90	.17											6.07	3.97			3.97
211	Rhode Island	5.91	.10								.06			6.07	3.97			3.97
212	Quebec, Canada	5.89	.22											6.11	3.87	.10		3.97
213	Brewster Station, N.Y	5.76	.17								.10			6.03	3.98			3.98
214	Cuba	5.46	.58											6.04	3.98			3.98
215	Franklin, N.J	6.05												6.05	3.98			3.98
216	Easton, Pa	5.83	.19								.03			6.05	3.98			3.98
217	Quebec, Canada	5.94	.12										.01	6.07	3.94	.01	.03	3.98
218	Kashmir	6.03	.11								.02			6.16	3.82	.13		3.95
219	Berks County, Pa	5.83	.16											5.99	3.99			3.99
220	Hoboken, N.J	5.92	.10											6.02	3.98	.01		3.99
221	Snarum, Norway	5.88	.12											6.00	3.97		.01	3.98
222	Quebec, Canada	6.03	.01								.01	.01		6.06	3.94	.03	.02	3.99

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TABLE 8.—*Relationship of the ions in octahedral and tetrahedral coordination as calculated from the chemical analyses of serpentine group minerals taken from the literature and listed in table 5*—Continued

Sample	Locality	Ions in octahedral coordination													Ions in tetrahedral coordination			
		Mg	Fe^{2+}	Fe^{3+}	Al	Mn	Ni	Cr	Ti	Zn	Ca	Na	K	Σ oct	Si	Al	Fe^{3+}	Σ tet
225	Quebec, Canada	6.93	.18	-----	-----	-----	-----	-----	-----	-----	.06	-----	-----	7.17	3.02	.11	.42	3.55
226	Finland	4.74	1.93	-----	-----	-----	-----	-----	.08	-----	.17	.10	.09	7.11	3.13	.48	-----	3.61
227	Snarum, Norway	6.59	.02	-----	-----	-----	-----	-----	-----	-----	-----	.02	.07	6.70	3.47	.04	.23	3.74
228	Canada	6.01	.50	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	6.51	3.75	-----	-----	3.75
229	do	7.03	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	7.03	3.11	.17	.50	3.78
243	Norway	5.69	0.04	0.09	-----	-----	-----	-----	-----	-----	-----	-----	-----	5.82	4.06	-----	-----	4.06
244	Italy	4.53	.29	.53	.30	0.01	-----	-----	0.01	-----	-----	0.10	0.07	5.84	3.68	0.32	-----	4.00
245	do	4.51	.19	.41	.42	-----	-----	-----	.03	-----	-----	.10	.03	5.69	3.84	.16	-----	4.00
246	Globe, Ariz	5.65	.01	.08	.03	.01	-----	-----	-----	-----	-----	.01	-----	5.79	4.07	-----	-----	4.07
247	do	5.59	.03	.13	.08	.01	-----	-----	-----	-----	-----	.01	-----	5.85	4.03	-----	-----	4.03
248	Arizona	5.90	.05	-----	.06	-----	-----	-----	-----	-----	-----	-----	-----	6.01	3.92	.08	-----	4.00
249	do	5.92	.05	-----	.03	-----	-----	-----	-----	-----	0.01	-----	-----	6.01	3.93	.07	-----	4.00
250	do	5.81	.06	-----	.12	-----	-----	-----	-----	-----	-----	-----	-----	5.99	3.91	.09	-----	4.00
251	do	5.80	.07	-----	.09	-----	-----	-----	-----	-----	.01	-----	-----	5.97	3.97	.03	-----	4.00
255	Schwarzwald, Germany	4.29	.56	-----	.67	-----	-----	-----	-----	-----	-----	-----	-----	5.52	4.08	-----	-----	4.08
256	Baste, Harz	4.18	1.08	-----	.25	.07	-----	-----	-----	-----	.06	-----	-----	5.64	4.12	-----	-----	4.12
257	do	3.76	.87	-----	.17	.04	-----	0.18	-----	-----	.28	-----	-----	5.30	4.25	-----	-----	4.25
258	Montville, N.J	6.00	-----	.01	-----	-----	-----	-----	-----	-----	-----	-----	-----	6.01	3.98	-----	.02	4.00
259	Massachusetts	5.89	.01	.09	-----	-----	-----	-----	-----	-----	-----	-----	-----	5.99	3.94	-----	.06	4.00
260	Montville, N.J	5.78	-----	.06	.07	-----	.02	-----	-----	-----	-----	-----	-----	5.93	4.02	-----	-----	4.02
261	North Carolina	5.74	-----	.07	.08	-----	.01	-----	-----	-----	-----	-----	-----	5.90	4.02	-----	-----	4.02

yield formulas which are either neutral or have a charge excess or deficiency of ±0.02. This value is well within the limit of analytical error plus the error of rounding off to the second decimal place.

To assess the effect for any particular ion, it is necessary to take into consideration the equivalent weights for the ions concerned. In one of the analyses 0.29 percent Cr_2O_3 was accidentally included with the Al_2O_3. This leads to the formula

$$[Mg_{5.37}Fe^{2+}_{.63}Ni_{.03}Mn_{.01}Al_{.05}][Si_{3.87}Al_{.13}]O_{10}(OH)_8$$
$$\Sigma_{oct}=6.09 \text{ ions} \qquad \Sigma_{tet}=4.00 \text{ ions}$$

Recalculations on the basis of the determined value of Cr_2O_3 gives

$$[Mg_{5.37}Fe^{2+}_{.63}Ni_{.03}Mn_{.01}Cr_{.02}][Si_{3.85}Al_{.15}]O_{10}(OH)_8$$
$$\Sigma_{oct}=6.06 \text{ ions} \qquad \Sigma_{tet}=4.00 \text{ ions}$$

In another analysis a similarly small amount, 0.24 percent Cr_2O_3, was included with the Al_2O_3 and computed as Al_2O_3 to give

$$[Mg_{5.49}Fe^{2+}_{.33}Mn_{.02}Al_{.11}][Si_{4.00}]O_{10}(OH)_8$$
$$\Sigma_{oct}=5.95 \text{ ions}$$

With correction for Cr_2O_3 there results

$$[Mg_{5.50}Fe^{2+}_{.33}Mn_{.02}Cr_{.02}Al_{.08}][Si_{4.00}]O_{10}(OH)_8$$
$$\Sigma_{oct}=5.95 \text{ ions}$$

An error in the analytically determined value of silica and alumina may lead to one of several conditions. If some alumina is reported as silica, the value of silicon in tetrahedral coordination may appear too high, or failing to exceed Σ=4.00 ions it will mask the fact that a small but definite number of aluminum ions is in tetrahedral coordination. If some silica is reported as alumina, a deficiency of silicon ions in tetrahedral coordination may be reported.

From studies of the micas, montmorillonites, and other layer lattice minerals, it now appears to be established that ferric iron may replace silica to a limited extent in sites in tetrahedral coordination. This

TABLE 9.—*Relationship of the ions in octahedral and tetrahedral coordination as calculated from the chemical analyses of Jenkinsite hydrophite, and zincian serpentine*

Sample	Locality	Ions in octahedral coordination								Ions in tetrahedral coordination			
		Mg	Fe^{2+}	Fe^{3+}	Al	Mn	Zn	Ca	Σ oct	Si	Al	Fe^{3+}	Σ tet
	Jenkinsite and hydrophite												
235	Orange County, N.Y	3.62	1.84	-----	0.12	0.37	-----	-----	5.95	4.00	-----	-----	4.00
236	do	3.59	1.70	-----	.07	.39	-----	-----	5.75	4.11	-----	-----	4.11
237	Sweden	3.41	2.06	-----	.30	.11	-----	-----	5.88	3.93	0.07	-----	4.00
	Zincian serpentine												
238	Uzbek, U.S.S.R	5.44	-----	0.12	0.20	0.01	0.12	-----	5.89	3.93	0.07	-----	4.00
239	do	5.69	-----	10	-----	.01	.18	-----	5.98	3.96	-----	0.04	4.00
240	Franklin, N.J	5.00	.20	-----	.11	.29	.31	0.05	5.96	3.96	.04	-----	4.00
241	do	4.54	-----	-----	-----	.60	.26	-----	5.40	4.30	-----	-----	4.30
242	do	4.81	.13	-----	.08	.63	.01	.13	5.79	4.09	-----	-----	4.09

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appears to be true in the serpentines. It is therefore particularly desirable, if iron is present in significant amounts, to determine both Fe_2O_3 and FeO. Failure to do so may introduce error into the calculated formula. Thus considering all iron to be bivalent could lead to a deficiency in the number of ions in tetrahedral coordination. It will be noted in table 8 that some of the analyses of serpentines deficient in ions in tetrahedral positions report only bivalent iron, whereas some of it is probably trivalent and if it were reported as such, a sufficient amount could be assigned to tetrahedral sites. The absence of magnetite, usually easily proven by running a strong hand magnet over the crushed powder should, however, be demonstrated.

Nickel, cobalt, zinc, and manganese, referred to as the zinc group, are precipitated together with ammonium sulfide after the iron, aluminum, and other ions have been removed as hydroxides by ammonium hydroxide. If they are present in significant amounts in the sample being analyzed, but are not determined, they will cause the analysis to have a low summation and the structural formula to show deficiency in octahedral sites filled.

INTERPRETATION OF THE CALCULATED STRUCTURAL FORMULAS OF THE SAMPLES REPORTED IN THIS STUDY

A graphical method was used to evaluate our chemical analyses. A plot was made using the sum of the ions in tetrahedral coordination ($\underset{tet}{\Sigma}$) and the sum of the ions in octahedral coordination ($\underset{oct}{\Sigma}$) as coordinate axes (figs. 18 and 19). It was found that most of the analyses fall within a rectangle having the coordinates ($\underset{tet}{\Sigma}$=4.00–4.10) and ($\underset{oct}{\Sigma}$=5.80–6.04). Two of the analyses which fall outside this rectangle have their full complement of tetrahedral sites but show some excess of ions in octahedral coordination. These chemical analyses—F–51, a specimen from Nicaro, Cuba; and F–69, from Webster, N.C.—represent serpentinized ultrabasic rocks. Ross, Shannon, and Gonyer (1928), commenting on anaysis F–69, imply the presence of unaltered olivine, an observation which is in accord with our graphical study. A similar interpretation is suggested for sample F–51.

Five other specimens have calculated formulas that lie outside the rectangle defined above. These samples have all been called deweylite. Only one specimen whose calculated formula lies within the rectangle, F–43, has been described as a deweylite. It had been observed in the DTA and X-ray studies that these same deweylite specimens were natural mixtures of serpentine and the magnesium end-member of the montmorillonite group, stevensite. In earlier studies such as that of Selfridge (1936), stevensite had been regarded as a member of the serpentine group. In order to check the experimentally determined mixed-phase concept of deweylite by the graphical relation outlined above, the chemical analysis of theoretical stevensite was treated as a serpentine, calculated to yield the postulated formula below,

$$[Mg_{3.82}][Si_{5.09}]O_{10}[OH]_8$$

and plotted as such on the diagram (fig. 19). A straight line connecting the positions of theoretical serpentine and theoretical stevensite (calculated as a serpentine-group mineral) shows that the five analyses F–3, F–40, F–41, F–26, and F–48 all lie astride it or close to it. Sample F–40 is known to contain some carbonate mineral as an impurity.

Twenty samples are included within the rectangle and even though this is a small number of analyses, there does appear to be a tendency for the antigorites to be set apart from the chrysotiles and lizardites. Only one sample, F–13, from the Tilly Foster mine, Brewster Station, N.Y., considered to be a mixture by other studies, is not associated with its congeners. The antigorites lie within a subrectangle with the coordinates $\underset{oct}{\Sigma}$=5.80 to 5.84 and $\underset{tet}{\Sigma}$=4.00 to 4.10. This compositional difference between the antigorites and the chrysotiles and lizardite is in accord with the crystal structure relationships. Zussman (1954, p. 510) describes it as follows:

> The crystal structure proposed involves 8½ repeats of the subcell[1] in the tetrahedral layer, i.e. 34 Si atoms per cell. It may also be noted that the "rectified wave" model clearly implies a deficiency of Mg and (OH) ions, since at the junction of neighbouring "arches" there is insufficient room for an extra half subcell in the octahedral layer. Moreover, the two (OH) ions at the top of the tetrahedral layer in positions marked *A* (fig. 4) would be unduly close to one another and would probably also be omitted. Allowing for these deficiencies, the numbers of atoms in successive planes would be as follows: 51(O), 34Si, 34(O) and 15(OH), 48 Mg, 48(OH). The structural model is thus in accord with the chemical data and with the observed density, within the limits of experimental error.

Kunze (1956, 1958) has made a comprehensive study of the crystal structure of antigorite and his results show (1956, p. 82) that,

> The chemical formula of chrysotile, $Mg_3(OH)_4Si_2O_5$, is not valid for antigorite, the reason is a so-called "coincidence" deficiency of electroneutral atom groups. This deficiency is repeated along the crystallographical *a* axis with exactly defined (superperiod) distance. In the resulting superstructure of antigorite (which is a so-called "double half-wave" structure), we find two "half-waves" alternately connected by means of Mg-bridges. In contrast to the monoclinic chrysotile, here we find a larger interaction in the form of hydrogen bonds between two layers along the direction of the layer period *c*.

and (1958, p. 319)

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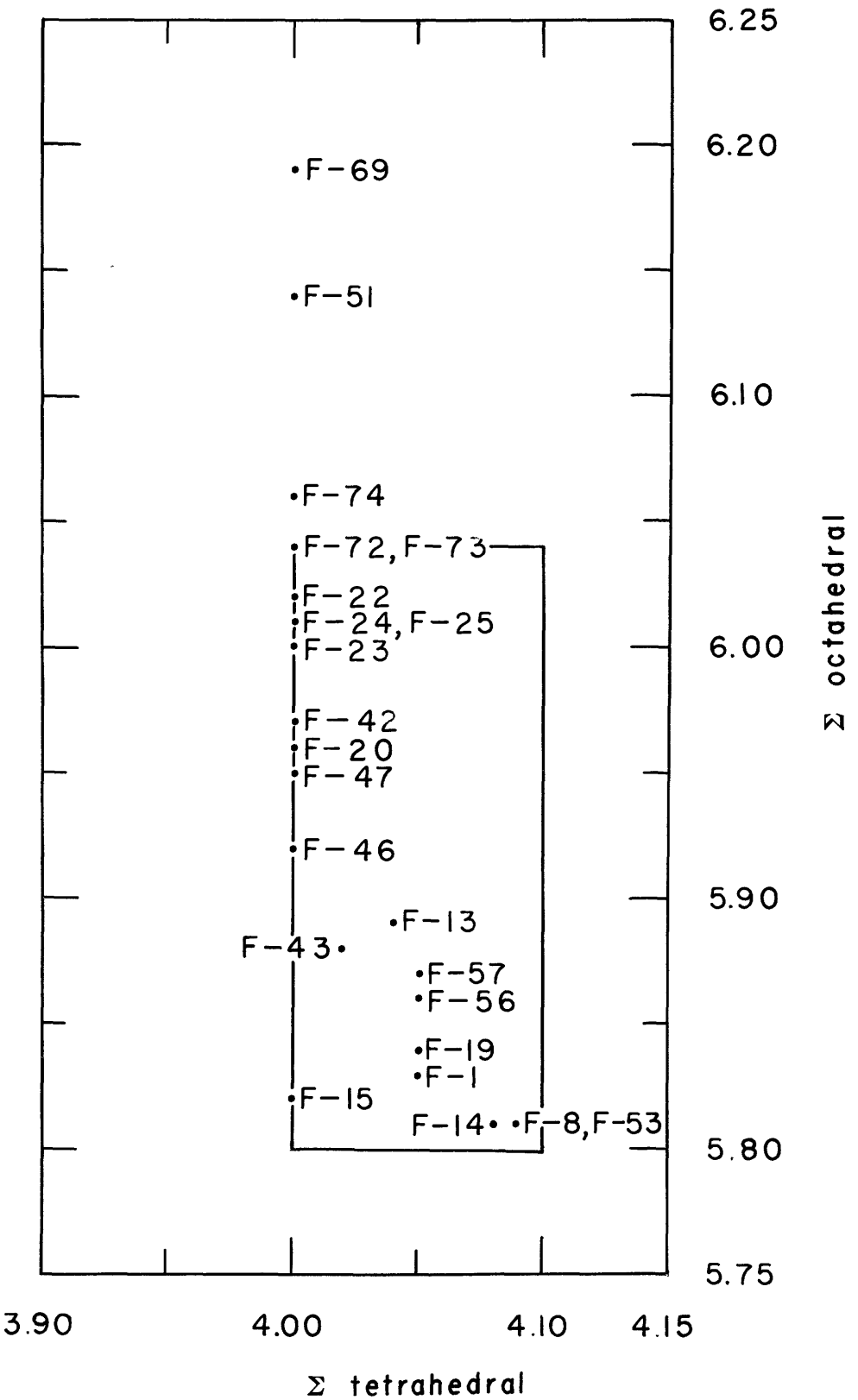


FIGURE 18.—The relation between the ions in octahedral coordination $\left(\Sigma_{oct}\right)$ and the ions in tetrahedral coordination $\left(\Sigma_{tet}\right)$, calculated from the analyses reported in this study. Rectangle outlines compositions of typical serpentine-group minerals.

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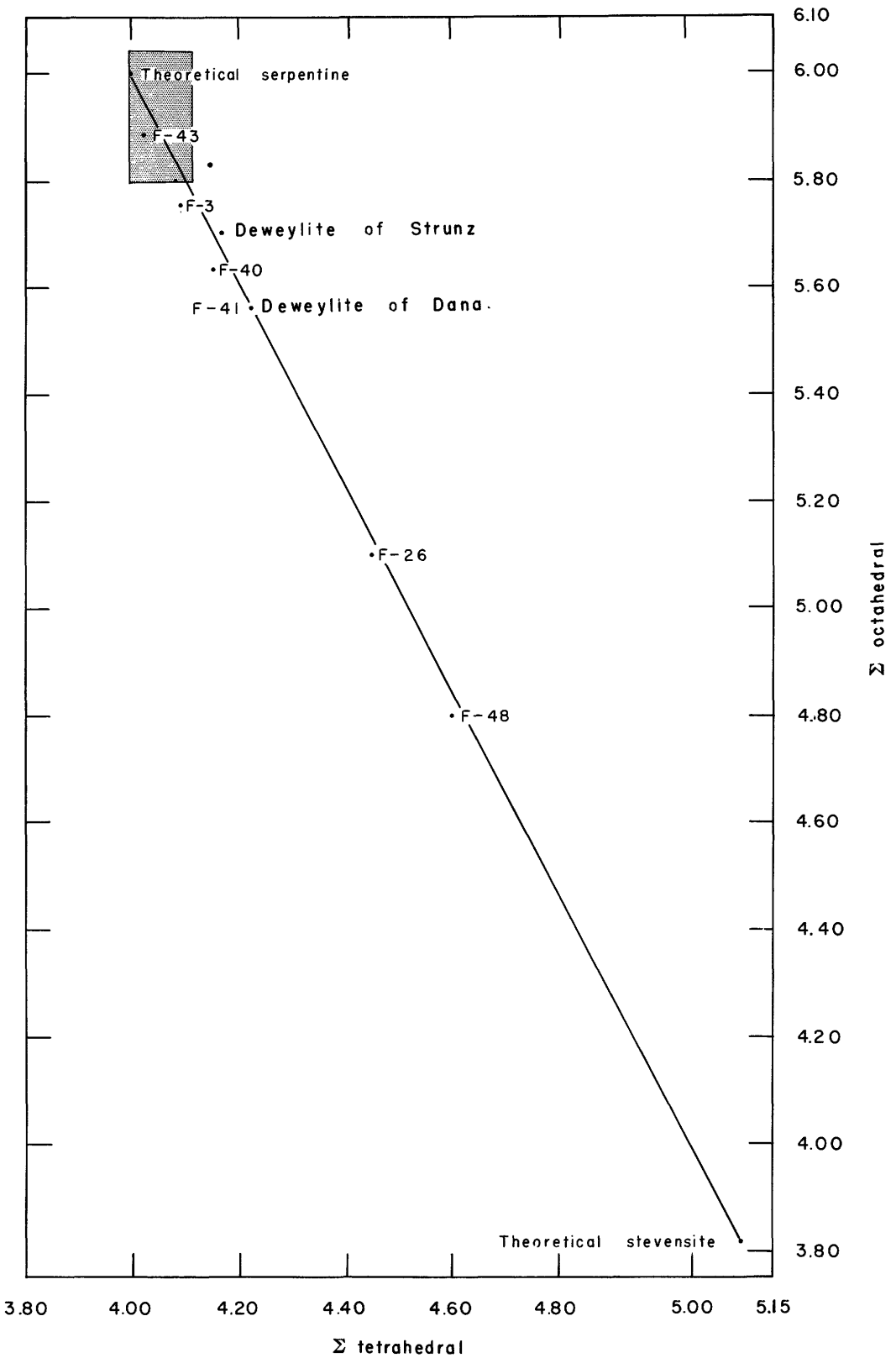


FIGURE 19.—The relation between the ions in octahedral coordination $\left(\Sigma_{oct}\right)$ and the ions in tetrahedral coordination $\left(\Sigma_{tet}\right)$, calculated from the chemical analyses of samples called deweylite and reported in this study. Section along the tieline theoretical serpentine to theoretical stevensite. Shaded area outlines compositions of typical serpentine-group minerals, as in figure 18.

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To be sure the chemical formula of antigorite $[Mg_{2.813}][Si_2]O_5(OH)_{3.647}$ has less MgO and H_2O than chrysotile $[Mg_3][Si_2]O_5(OH)_4$. . . .

Antigorite and chrysotile have (1) different but related crystal structures, (2) different but related chemical composition, and (3) different densities, so that we are posed with a dilemma. According to the phase rule we can regard them as separate phases. Furthermore, they appear to differ enough so that, strictly speaking they are not polymorphs. However, for the purpose of this study we have included them in the general term "serpentine group."

The structural formulas of the antigorites reported on in this study, tables 2 and 3, have been computed to the requirements of the crystal-structure data for Zussman (1954) and Kunze (1956, 1958) and are given in table 10.

Calculation of the analysis of the so-called serpentinized phlogopite F–68, and of the theoretical composition of the mixture, into the structural formula used in this paper gives the following: for the natural mixture F–68

$$[Mg_{4.51}Al_{.59}Fe^{3+}_{.07}Na_{.04}K_{.52}][Si_{4.12}]O_{10}(OH)_8,$$
$$\Sigma_{oct}=5.73 \qquad \Sigma_{tet}=4.12$$

for Bayley's (1941) theoretical mixture of 50 percent phlogopite + 50 percent serpentine

$$[Mg_{4.97}Al_{.50}Fe^{3+}_{.02}Na_{.03}K_{.57}][Si_{3.91}Al_{.09}]O_{10}(OH)_8$$
$$\Sigma_{oct}=6.09 \qquad \Sigma_{tet}=4.00$$

These formulas suggest that sample F–68 is a natural admixture of serpentine, stevensite, and phlogopite. This observation is concordant with the interpretation of the analyses of other serpentine group minerals from Easton, Pa., taken from the literature (fig. 24).

INTERPRETATION OF THE STRUCTURAL FORMULAS CALCULATED FROM ANALYSES OBTAINED FROM THE LITERATURE

The data obtained from the chemical analyses of the serpentine group minerals taken from the literature are plotted in figures 20 and 21. Because some of these samples obviously are impure, it is desirable to know just how certain impurities (fig. 22) will affect the calculated structural formulas. In order to bring this out clearly, it is useful to treat the various admixed phases as if they were serpentine and calculate their formula in terms of the formula $X_6Y_4O_{10}(OH)_8$. This yields the following postulated structural formulas.

MINERALS

Forsterite	$[Mg_{7.00}][Si_{3.50}]O_{10}(OH)_8$
Fayalite	$[Fe_{7.00}][Si_{3.50}]O_{10}(OH)_8$
Diopside	$[Mg_{2.33}Ca_{2.33}][Si_{4.67}]O_{10}(OH)_8$
Tremolite	$[Mg_{3.04}Ca_{1.20}][Si_{4.87}]O_{10}(OH)_8$
Enstatite	$[Mg_{4.67}][Si_{4.67}]O_{10}(OH)_8$
Stevensite	$[Mg_{3.82}][Si_{5.09}]O_{10}(OH)_8$
Sepiolite (Dana)	$[Mg_{3.50}][Si_{5.25}]O_{10}(OH)_8$
Sepiolite (Strunz)	$[Mg_{3.82}][Si_{5.09}]O_{10}(OH)_8$
Spadaite (Dana)	$[Mg_{4.00}Fe^{2+}_{.07}Al_{.07}][Si_{4.91}]O_{10}(OH)_8$
Talc	$[Mg_{3.82}][Si_{5.09}]O_{10}(OH)_8$
Deweylite (Dana)	$[Mg_{5.60}][Si_{4.20}]O_{10}(OH)_8$
Deweylite (Strunz)	$[Mg_{5.70}][Si_{4.15}]O_{10}(OH)_8$

MIXTURES

80 percent serpentine 20 percent brucite	$[Mg_{7.16}][Si_{3.42}]O_{10}(OH)_8$
95 percent serpentine 5 percent quartz	$[Mg_{5.61}][Si_{4.20}]O_{10}(OH)_8$
90 percent serpentine 10 percent quartz	$[Mg_{5.22}][Si_{4.39}]O_{10}(OH)_8$
90 percent serpentine 10 percent Fe_2O_3	$[Mg_{5.54}Fe^{3+}_{.71}][Si_{3.69}]O_{10}(OH)_8$
95 percent serpentine 5 percent Fe_2O_3	$[Mg_{5.77}Fe^{3+}_{.25}][Si_{3.85}]O_{10}(OH)_8$
90 percent serpentine 10 percent calcite (aragonite)	$[Mg_{5.74}Ca_{.59}][Si_{3.83}O_{10}(OH)_8$
90 percent serpentine 10 percent magnesite	$[Mg_{6.39}][Si_{3.80}]O_{10}(OH)_8$
90 percent serpentine 10 percent dolomite	$[Mg_{6.04}Ca_{.31}][Si_{3.82}]O_{10}(OH)_8$
90 percent serpentine 10 percent magnetite	$[Mg_{5.57}Fe^{2+}_{.25}Fe^{3+}_{.21}][Si_{3.72}Fe^{3+}_{.28}]O_{10}(OH)_8$

These postulated formulas are plotted on figures 20 and 21 and allow interpretation of the data to be made. It would be desirable to be able to check the suspected impurities in the samples studied, but this cannot be done and we have to base our interpretations on such other data as are available.

The mixtures of the carbonate mineral and serpentine are calculated on the assumption that an analyst did not determine carbon dioxide directly and the carbon dioxide percentage is included with the "loss on ignition" or as part of the H_2O+.

The following calculated formulas illustrate the magnitude of the change in the calculated formula for a sample containing 5.33 percent dolomite and 0.64 percent magnesite.

No allowance made for the carbonates:

$$[Mg_{5.60}Fe^{3+}_{.01}Al_{.01}Ca_{.17}][Si_{4.10}]O_{10}(OH)_8$$
$$\Sigma_{oct}=5.79 \text{ ions} \qquad \Sigma_{tet}=4.10 \text{ ions}$$

Analysis corrected for 5.33 percent dolomite and 0.64 percent magnesite based on the determined amount of CO_2 and on mineralogical data:

$$[Mg_{5.54}Fe^{3+}_{.01}Al_{.01}][Si_{4.22}]O_{10}(OH)_8$$
$$\Sigma_{oct}=5.56 \qquad \Sigma_{tet}=4.22$$

It will be observed that the second corrected formula clearly shows that this sample is a deweylite.

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TABLE 10.—*Relationship of the ions in octahedral and tetrahedral coordination as calculated from the chemical analyses of antigorites studied and listed in tables 2 and 3*

	According to Zussman (1954)			According to Kunze (1956, 1958)		
	Ions in lattice	Σ oct	Σ tet	Ions in lattice	Σ oct	Σ tet
Theoretical formula	$Mg_{5.65}Si_4O_{10}(OH)_{7.41}$	5. 65	4. 00	$Mg_{5.626}Si_4O_{10}(OH)_{7.294}$	5. 626	4. 00
Calculated formula for sample—						
F–1	$[Mg_{5.51}Fe^{2+}_{.03}Al_{.11}Ni_{.01}][Si_{3.96}Al_{.04}]O_{10}(OH)_{7.41}$	5. 66	4. 00	$[Mg_{5.49}Fe^{2+}_{.03}Al_{.10}Ni_{.01}][Si_{3.95}Al_{.05}]O_{10}(OH)_{7.29}$	5. 63	4. 00
F–8	$[Mg_{5.61}Fe^{2+}_{.01}Fe^{3+}_{.01}Ca_{.06}][Si_{4.00}]O_{10}(OH)_{7.41}$	5. 69	4. 00	$[Mg_{5.59}Fe^{2+}_{.01}Ca_{.06}][Si_{3.99}Fe^{3+}_{.01}]O_{10}(OH)_{7.29}$	5. 66	4. 00
F–13	$[Mg_{5.41}Fe^{2+}_{.19}Fe^{3+}_{.02}Al_{.06}Mn_{.01}K_{.03}][Si_{3.95}Al_{.05}]O_{10}(OH)_{7.41}$	5. 72	4. 00	$[Mg_{5.39}Fe^{2+}_{.19}Fe^{3+}_{.05}Al_{.04}Mn_{.01}K_{.03}][Si_{3.93}Al_{.07}]O_{10}(OH)_{7.29}$	5. 68	4. 00
F–14	$[Mg_{5.60}Fe^{2+}_{.02}Fe^{3+}_{.01}Al_{.05}Ca_{.01}][Si_{4.00}]O_{10}(OH)_{7.41}$	5. 69	4. 00	$[Mg_{5.57}Fe^{2+}_{.02}Fe^{3+}_{.01}Al_{.03}Ca_{.01}][Si_{3.98}Al_{.02}]O_{10}(OH)_{7.29}$	5. 64	4. 00
F–15	$[Mg_{4.90}Fe^{2+}_{.32}Fe^{3+}_{.13}Al_{.21}Cr_{.02}Ni_{.01}Mn_{.01}Ca_{.01}][Si_{3.86}Al_{.14}]O_{10}(OH)_{7.41}$	5. 61	4. 00	$[Mg_{4.88}Fe^{2+}_{.32}Fe^{3+}_{.13}Al_{.19}Cr_{.02}Ni_{.01}Mn_{.01}Ca_{.01}][Si_{3.84}Al_{.16}]O_{10}(OH)_{7.29}$	5. 57	4. 00
F–19	$[Mg_{5.09}Fe^{2+}_{.32}Fe^{3+}_{.03}Al_{.16}Ni_{.01}][Si_{3.96}Al_{.04}]O_{10}(OH)_{7.41}$	5. 61	4. 00	$[Mg_{5.07}Fe^{2+}_{.32}Fe^{3+}_{.03}Al_{.15}Ni_{.01}][Si_{3.95}Al_{.05}]O_{10}(OH)_{7.29}$	5. 58	4. 00

The Serpentine-Group Minerals (1962)
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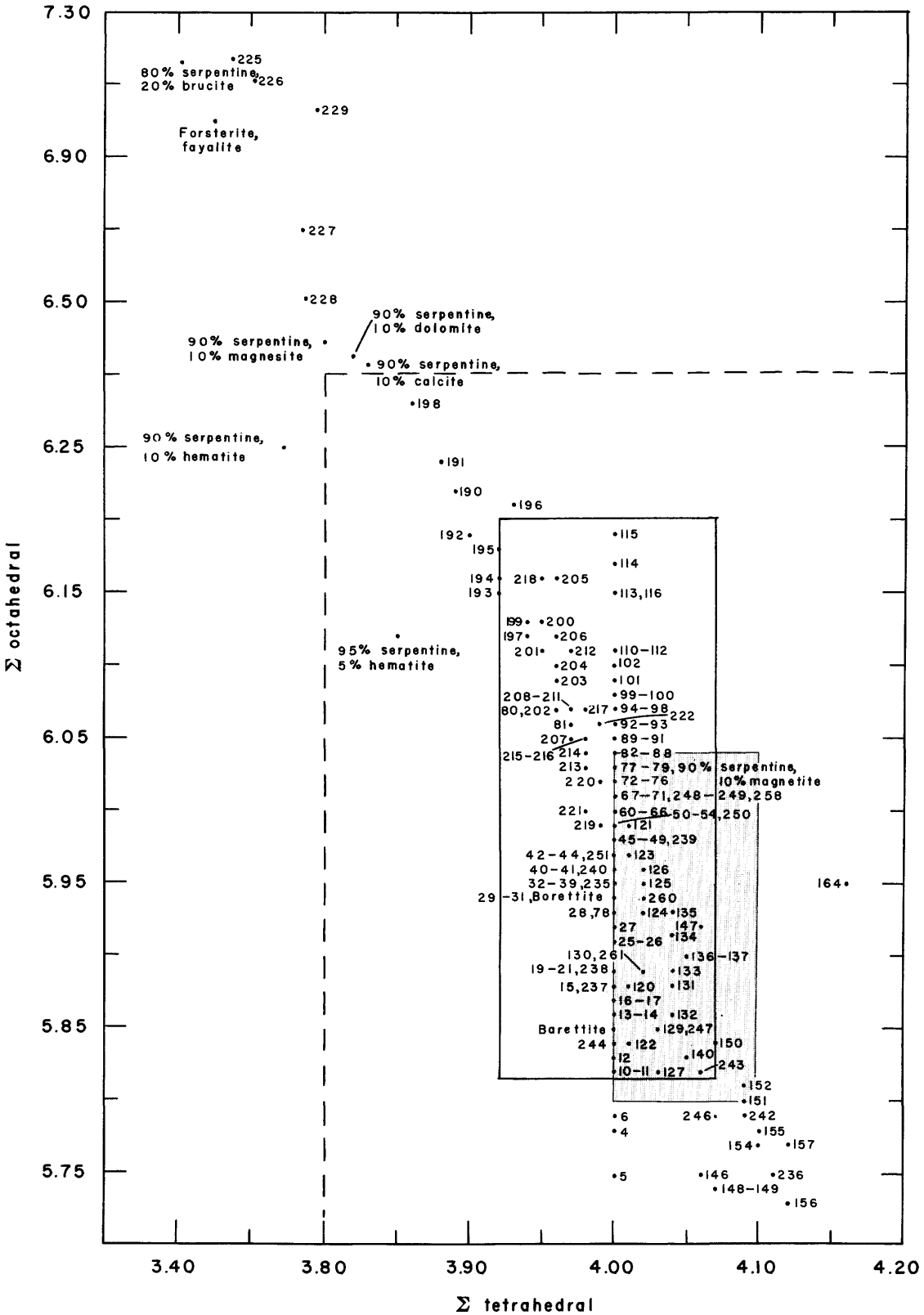


FIGURE 20.—The relation between the ions in octahedral coordination $\left(\Sigma_{oct}\right)$ and the ions in tetrahedral coordination $\left(\Sigma_{tet}\right)$ calculated from the chemical analyses taken from the literature; large rectangle encloses serpentine analyses. Shaded rectangle is the same as figure 18.

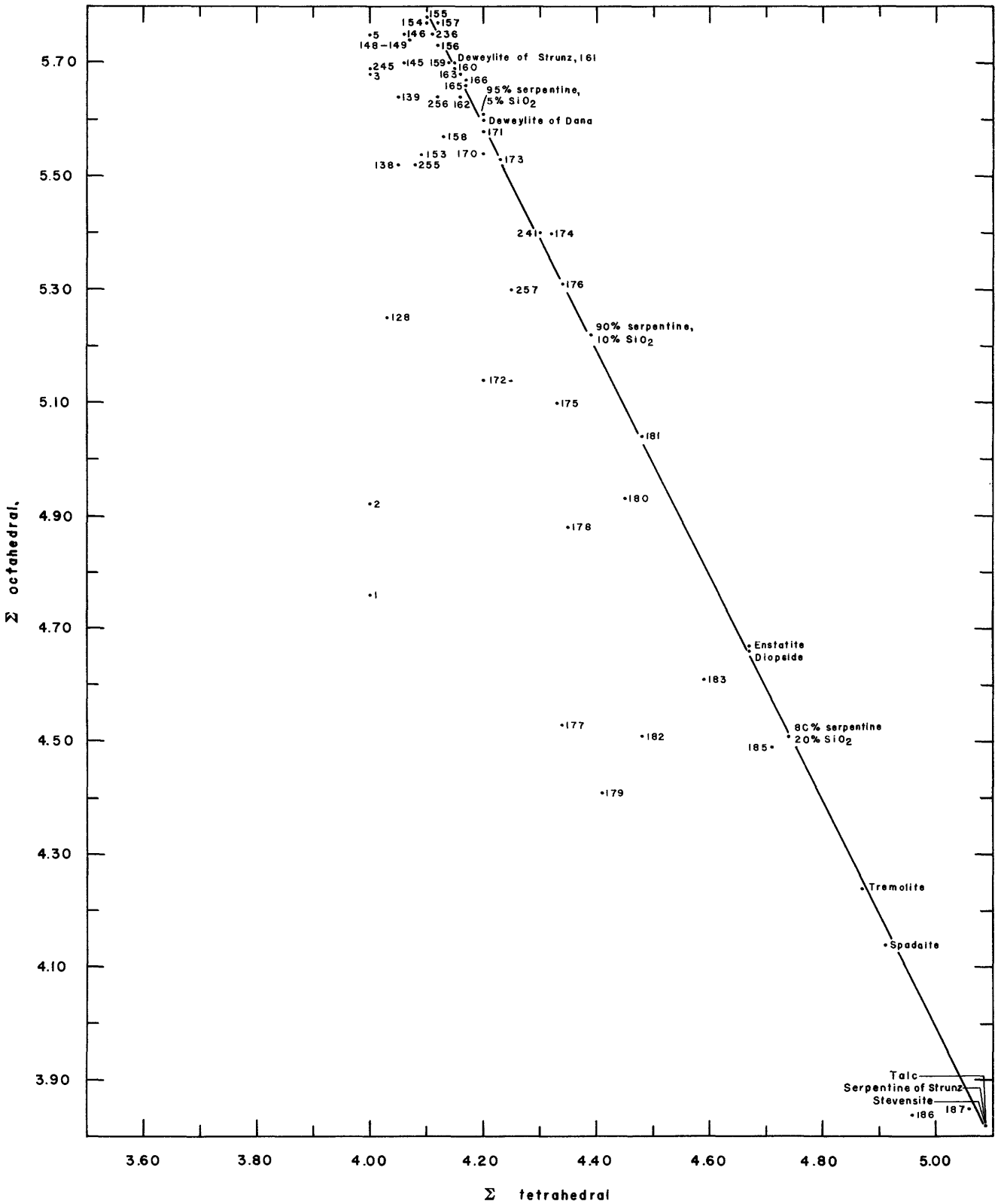


FIGURE 21.—The relation between the ions in octahedral coordination $\left(\frac{\Sigma}{oct}\right)$ and the ions in tetrahedral coordination $\left(\frac{\Sigma}{tet}\right)$ calculated from the chemical analyses taken from the literature. Section along the tieline theoretical serpentine to theoretical stevensite.

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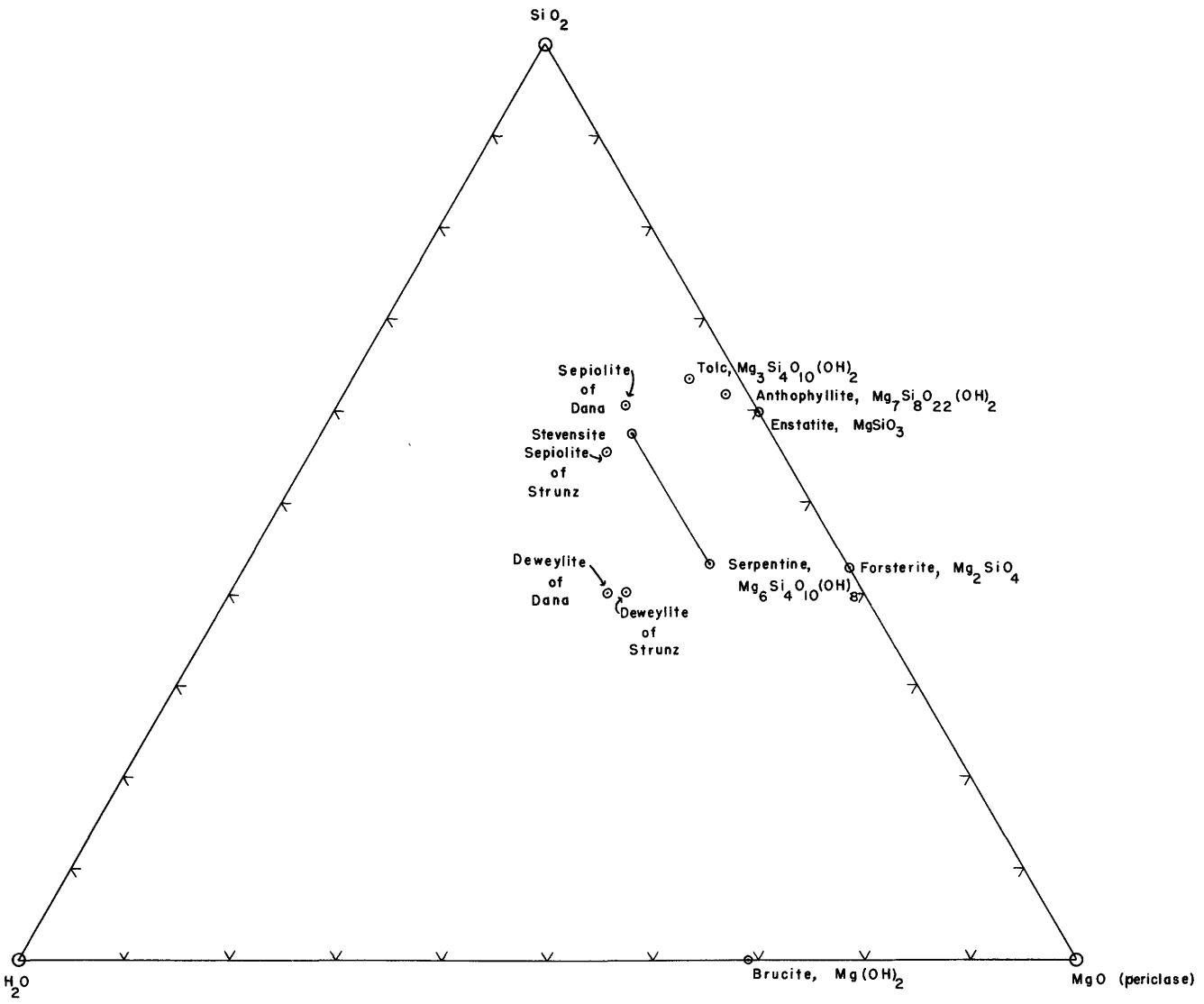


FIGURE 22.—Natural phases in the ternary system MgO–SiO$_2$–H$_2$O.

Some of the minerals of the chlorite group have compositions closely similar, if not identical, with the minerals of the serpentine group so that it will be very difficult if not impossible to detect them by this graphical treatment. They are easily detected by experimental techniques and consequently are not likely to be present as contaminants.

The rectangle outlined by the coordinates $\Sigma_{oct}=3.92$, $\Sigma_{tet}=5.82$; $\Sigma_{oct}=3.92$, $\Sigma_{tet}=6.20$; $\Sigma_{oct}=4.05$, $\Sigma_{tet}=5.82$; and $\Sigma_{oct}=4.05$, $\Sigma_{tet}=6.20$ contains most of the analyses of substances reported to be serpentine-group minerals. With the aid of the postulated formulas for possible admixed substances, the likely impurities may be disclosed. Olivine (forsterite and fayalite), brucite, calcite, magnesite, or dolomite as admixtures with serpentine will displace the calculated formula towards a higher value of ions in octahedral coordination. Analyses 225, 226, 227, 228, and 229 may be suspected of such admixtures. Small amounts of enstatite, diopside, or tremolite will displace the formula towards the corner of the rectangle with coordinates $\Sigma_{oct}=4.05$ and $\Sigma_{tet}=5.82$.

Mixtures of 5 or 10 percent of hematite with serpentine will displace the formula away from the theoretical composition toward the corner with coordinates $\Sigma_{oct}=3.92$ and $\Sigma_{tet}=6.20$ but with a much lower slope than the admixtures of olivine and other admixtures mentioned above.

The tieline (fig. 21) connecting the composition of theoretical serpentine with theoretical stevensite, cal-

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culated on the basis of the serpentine formula, contains quite a number of analyses. Many, if not all, of these points represent analyses of admixtures of stevensite and serpentine. The deweylites of Dana and Strunz lie along this tieline, together with the various deweylite analyses from the literature. The composition of spadaite lies on this tieline and it has been found by other studies to consist chiefly of stevensite.

Analyses 1 and 2 are definitely not serpentine-group minerals, although they may contain some admixed serpentine. They probably represent altered minerals.

Analyses 177 and 179 have been called acquacreptite; Nos. 172 and 182, webskyite; and these together with No. 178 are characterized by a considerable quantity of Fe_2O_3 in their analyses. The values of Fe_2O_3 are as follows: Analysis 177, 12.30 percent; No. 179, 13.30 percent; No. 172, 9.13 percent; No. 182, 11.52 percent; and No. 178, 9.83 percent. They are probably mixtures of a montmorillonite-group mineral and serpentine. A mixture similar to these has been found to consist of serpentine and a montmorillonite-group mineral and does not contain any free iron oxide mineral.

The heavy concentration of points along the coordinate axis $\Sigma_{tet}=4.00$ is at once apparent. This arises, in part, from the method of calculation wherein Σ_{tet} is adjusted to 4.00. The deviation of a point from $\Sigma_{oct}=6.00$ represents either (a) deficiency of ions in the structure in octahedral coordination, as in the antigorites, (b) analytical error, (c) a small amount of contamination by admixed impurities, or (d) a combination chiefly of (b) and (c). The effect of an inaccurate analytical value for silica will, in general, shift Σ_{oct} to values less than 6.00 ions.

The areal trends for a given type of occurrence are given in figures 23 and 24. Serpentines of class A are represented by analyses from Texas, Pa.; Quebec, Canada; Transvaal, Union of South Africa; Southern Rhodesia; Val Antigorio, Italy; Lizard, England; and Snarum, Norway. Serpentines of class B are represented by analyses from Easton, Pa.; Gila County, Ariz.; Montville, N.J.; and Tilly Foster mine, Brewster Station, N.Y.

The samples from Texas, Pa., all lie on or near the tieline theoretical serpentine to theoretical stevensite. Most of them are so-called deweylites. The plot of the analyses of the serpentines from Quebec suggests that some of them contain admixed brucite or olivine. Mineralogical studies suggest that the most likely admixed phase is brucite. The analyses of the samples from the Transvaal, Union of South Africa, indicate that most of the samples are nearly pure. One of the specimens is a so-called deweylite. The analyses of the specimens from southern Rhodesia cluster about theoretical serpentine. The analyses of samples from Val Antigorio, Italy, cluster about and slightly above the theoretical value for antigorites, namely $\Sigma_{oct}=5.88$ and $\Sigma_{tet}=4.00$. The analyses of the specimens from the Lizard, England, cluster about theoretical serpentine. One analysis is a so-called deweylite. The analyses of the specimens from Snarum, Norway, in general, cluster about theoretical serpentine. One analysis suggests admixture with olivine.

The analyses of the specimens from Easton, Pa., range over a fairly large interval for Σ_{oct}—namely, from $\Sigma_{oct}=5.78$ to $\Sigma_{oct}=6.08$. One specimen appears to be contaminated with an iron oxide mineral. The analyses of the chrysotiles from Gila County, Ariz., show a tendency to group around theoretical serpentine. Two of the analyses depart from this and each is known, from the literature, to contain impurities. The analyses of the samples from Montville, N.J., are, with one exception, close to theoretical serpentine in composition. The analysis with $\Sigma_{oct}=6.16$ and $\Sigma_{tet}=3.92$ is probably contaminated with the pyroxene from which the serpentine is derived. The analyses of specimens from Tilly Foster mine, Brewster Station, N.Y., suggest that they are antigorites contaminated with chrysotile.

Manganoan serpentine minerals have been known for a long time. Kenngott (1856–57) reported 0.30 percent MnO in the serpentine from the Fleimstal, Monzoni, in the Italian Tyrol, which he named vorhauserite (analysis 137). Serpentine-group minerals containing sufficient MnO to appear in the structural formulas in table 7 are as follows: F–13, F–15, F–19, F–22, F–26, F–53, F–56, F–57, F–72, F–73, and F–74. In 10 of these formulas, Mn amounts to 0.01 ions in octahedral coordination, and in only one (F–57) does it reach 0.04 ions. In table 8, which contains a wide selection of data from the literature, serpentine samples reported to have sufficient MnO to appear in the structural formulas are as follows: analyses 15, 66, 71, 79, 92, 127, 131, 244, 246, and 247 show 0.01 ions in octahedral coordination; analyses 16, 38, 72, and 137 show 0.02 ions; analyses 124, 154, and 185 show 0.03 ions; analyses 67 and 257 show 0.04 ions; and analyses 4 and 147 show 0.06 ions; analysis 256 shows 0.07 ions in octahedral coordination. Spectrographic studies of serpentines suggest that bivalent manganese is very commonly present in small amounts.

Although the quantity of bivalent manganese is low in most serpentine minerals and generally of no importance in the crystal structure, its presence is significant because of the common occurrence of these minerals.

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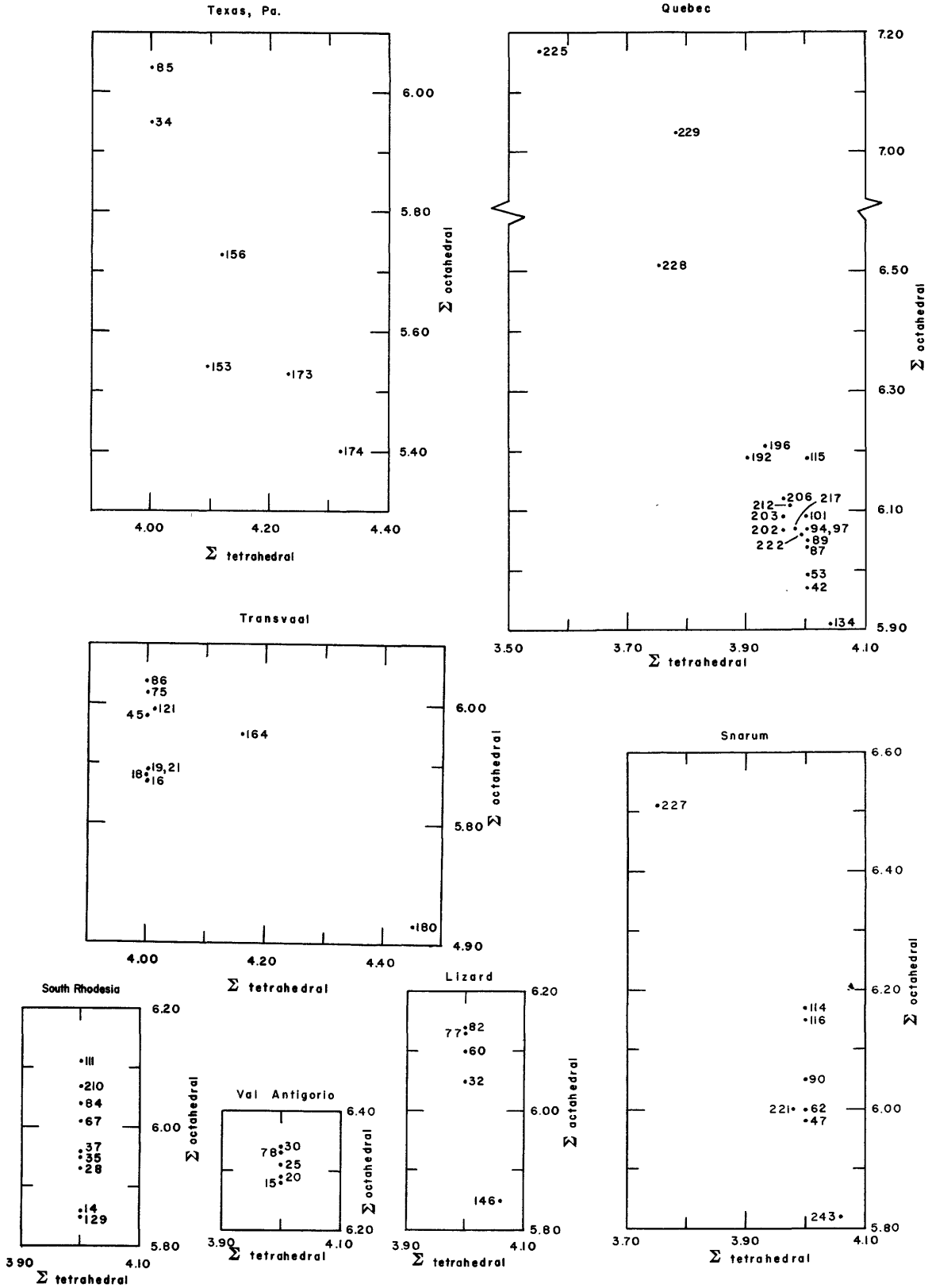


FIGURE 23.—Graphs of the relation Σ_{oct} versus Σ_{tet} for serpentines of Class A from Texas, Pa.; Quebec, Canada; Transvaal, Union of South Africa; Southern Rhodesia; Val Antigorio, Italy; Lizard, England; and Snarum, Norway.

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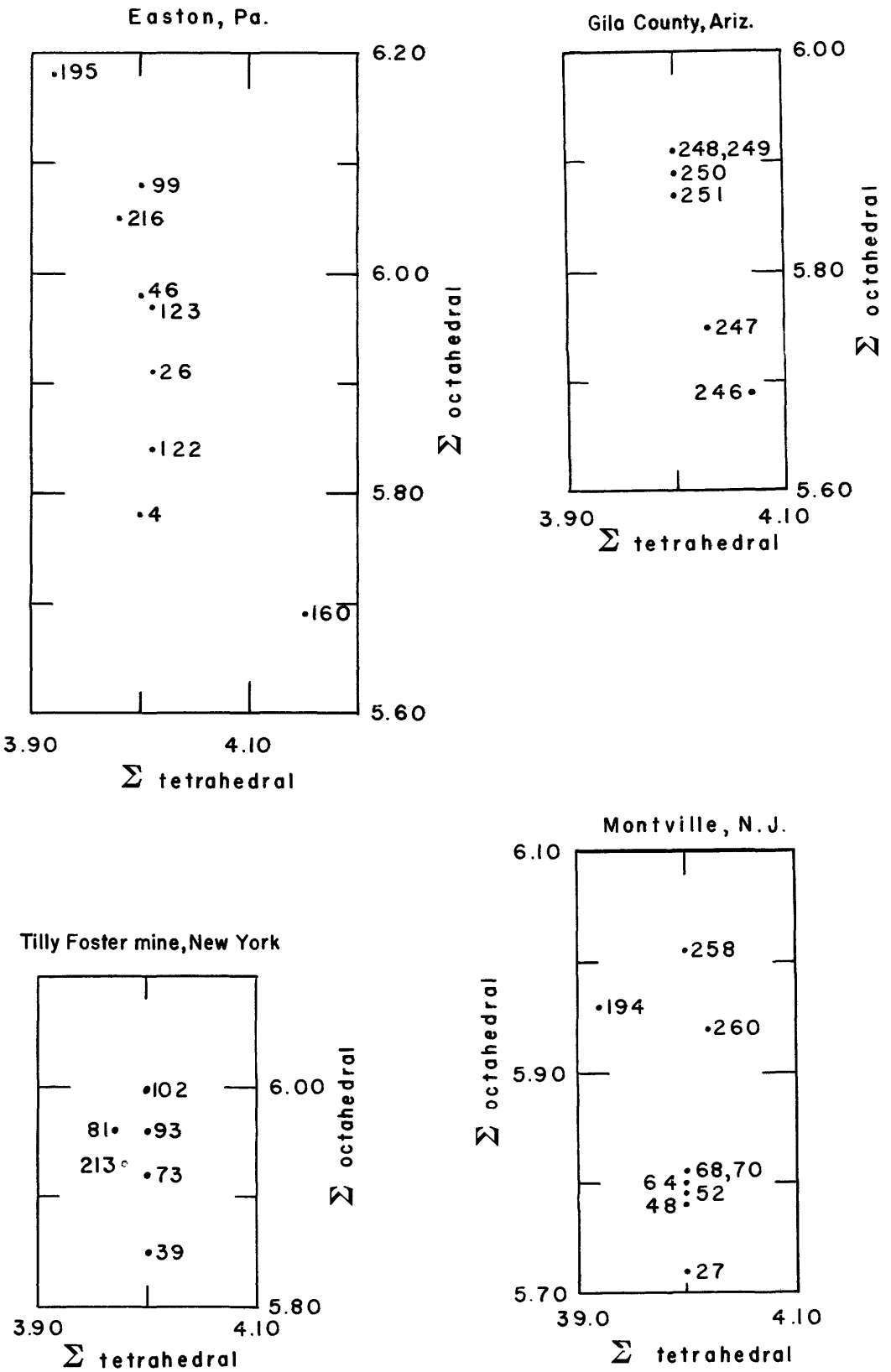


FIGURE 24.—Graphs of the relation Σ_{oct} versus Σ_{tet} for serpentines of Class B from Easton, Pa.; Gila County, Ariz.; Montville, N.J.; and Tilly Foster mine, Brewster Station, N.Y.

The cobaltian wads (asbolan, asbolite) of New Caledonia, described by La Croix (1942–43) show that the content of manganese may be significantly concentrated in the decomposition and weathering of serpentine minerals.

Larger amounts of bivalent manganese appear in the iron-rich serpentine minerals jenkinsite and hydrophite, which contain 0.37–0.39 ions and 0.11 ions, respectively, in octahedral coordination (table 9). The zincian serpentine minerals (table 9) commonly contain large amounts of manganese, the three specimens from Franklin, N.J., showing 0.29, 0.60, and 0.63 ions in octahedral coordination. Manganoan serpentine minerals are probaly more abundant than the reported data show. They should be looked for at pyrometasomatic zinc deposits where the pyroxenes johannsenite $CaMnSi_2O_6$ and its solid solutions with diopside and hedenbergite occur and have been altered by later hydrothermal solutions.

Zincian serpentine minerals were observed in the mineral assemblage at Franklin, N.J., by Koeing (1886) Shannon and Larsen (1926), and David Jenkins and Lawson H. Bauer, 1926, quoted in Plaache (1937). (See table 9, specimens 240, 241, and 242.) Recently Badalov (1958) has described zincian serpentine minerals from Uzbek, U.S.S.R. (See table 9, specimens 238 and 239.)

The hydrous nickel-magnesium silicates (the garnierite group), including genthite, nickeloan stevensite, pimelite (nickeloan saponite), nickeloan deweylites, and nickeloan serpentines have also been studied and the results of this work will be published later. The observation is significant that a plot of the data for more than 50 analyses of these minerals gathered from the literature shows many of them to be admixtures of the nickeloan serpentine minerals and nickeloan stevensite and to lie along the tieline connecting these two phases, so that the plot is similar in appearance to figure 21.

THERMAL-ANALYSIS STUDIES

STATIC (DEHYDRATION) METHOD

The static method of thermal-analysis consists of heating a sample at a given temperature until it attains "constancy" in weight. This operation is repeated at successively higher temperatures until the sample has lost all its water. The system is commonly investigated from room temperature up to 1,000°C. The graph resulting from a plot of the data showing the loss in weight of the sample as a function of the temperature is called a dehydration curve. There are various experimental methods for obtaining the data. The methods used in this study have been described by Nutting (1943). The crucible containing the sample is suspended from the bottom of the pan of an analytical balance by means of a platinum wire and hangs in the "hot-spot" of the furnace. The sample is always in the furnace and the heating process is continuous. The water is lost from the specimen; therefore, the process is irreversible and the system investigated is not in equilibrium.

Dehydration curves are very useful because a given mineral species gives a characteristic curve, which, when taken together with other data, permits indentifications to be made. These curves also show the manner in which the water is lost from the mineral in the particular heating process used in the experiment.

Many dehydration studies have been made on minerals of the serpentine group. Some of these studies have been made an pure minerals, but very few of the dehydration studies have been accompanied by chemical analyses of the purified minerals.

Rammelsberg (1869) was probably the first to make dehydration studies on serpentine He studied a light-green serpentine from Texas, Lancaster County, Pa. Clarke and Schneider (1890) made dehydration studies at 105°, 250°, 383°–412°, and 498°–527°C, and red heat and white heat on five analyzed serpentine minerals. These were:

A. Dull-green serpentine from Montville, N.J. (altered pyroxene), analysis 258.
B. Dark-green serpentine from Newburyport, Massachusetts, analysis 259.
C. Silky fibrous chrysotile from Montville, N.J., analysis 260.
D. Grayish-green picrolite from Buck Creek, N.C., analysis 130.
E. Massive serpentine (deweylite) from Corundum Hill, N.C., analysis 261.

On the basis of the data in their paper and results on similar material in this paper, it is suggested that sample A is chiefly chrysotile with possibly some lizardite; sample C is chiefly clinochrysotile; and sample D is chiefly antigorite with some chrysotile. Zambonini (1910, referred in some publications as 1908, the date of oral presentation) included three serpentine minerals in his studies on dehydration phenomenon: chrysotile from the type locality at Reichenstein, Province of Silesia, analysis 152; noble serpentine from the Peninsula of Eyre, South Australia; and bowenite from New Zealand. The chrysotile from Reichenstein is probably chiefly clinochrysotile. Kurnakov and Chernykh (1926), and Chernykh (1933) in connection with their studies of magnesium carbonates and silicates made automatic recordings of the dehydration curves of various members of the serpentine group. Bianchi and Carpanese (1928) made

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dehydration studies on "precious serpentine" from Snarum, Norway, and antigorite from Valsavaranche, Aosta, Italy.

Thermal dehydration data for six analyzed specimens and two unanalyzed specimens are given in table 11 and the graphs in figures 25 and 26. Joseph J. Fahey made the dehydration studies on F–1 and F–13 and the others were studied by Perley G. Nutting. The shapes of these curves fall into two groups. In one class F–1, F–13, F–14, F–19, and F–70 each sample shows a single "shoulder" in the temperature range of 550° to 650°C; in the other class F–41a, F–43, and F–69 each sample shows in addition a "shoulder" corresponding to the loss of "low-temperature" water.

The correspondence between the water, H_2O+ and H_2O-, as determined in the chemical analysis and as obtained at similar temperatures in the thermal-dehydration studies, is given in table 12. The agreement between these two methods is excellent. Those samples having significant amounts of ferrous iron need to be corrected for the small increase in weight in the dehydration experiments arising from the oxidation to Fe_2O_3. Specimen F–41, on which the chemical analysis was made, and F–41a, used in the dehydration study, were not from the same specimen; F–41a apparently contains a greater proportion of fine-grained carbonate minerals.

The curves for three of these serpentine specimens show an additional "shoulder" at low temperatures. Such a relationship is to be expected for specimens

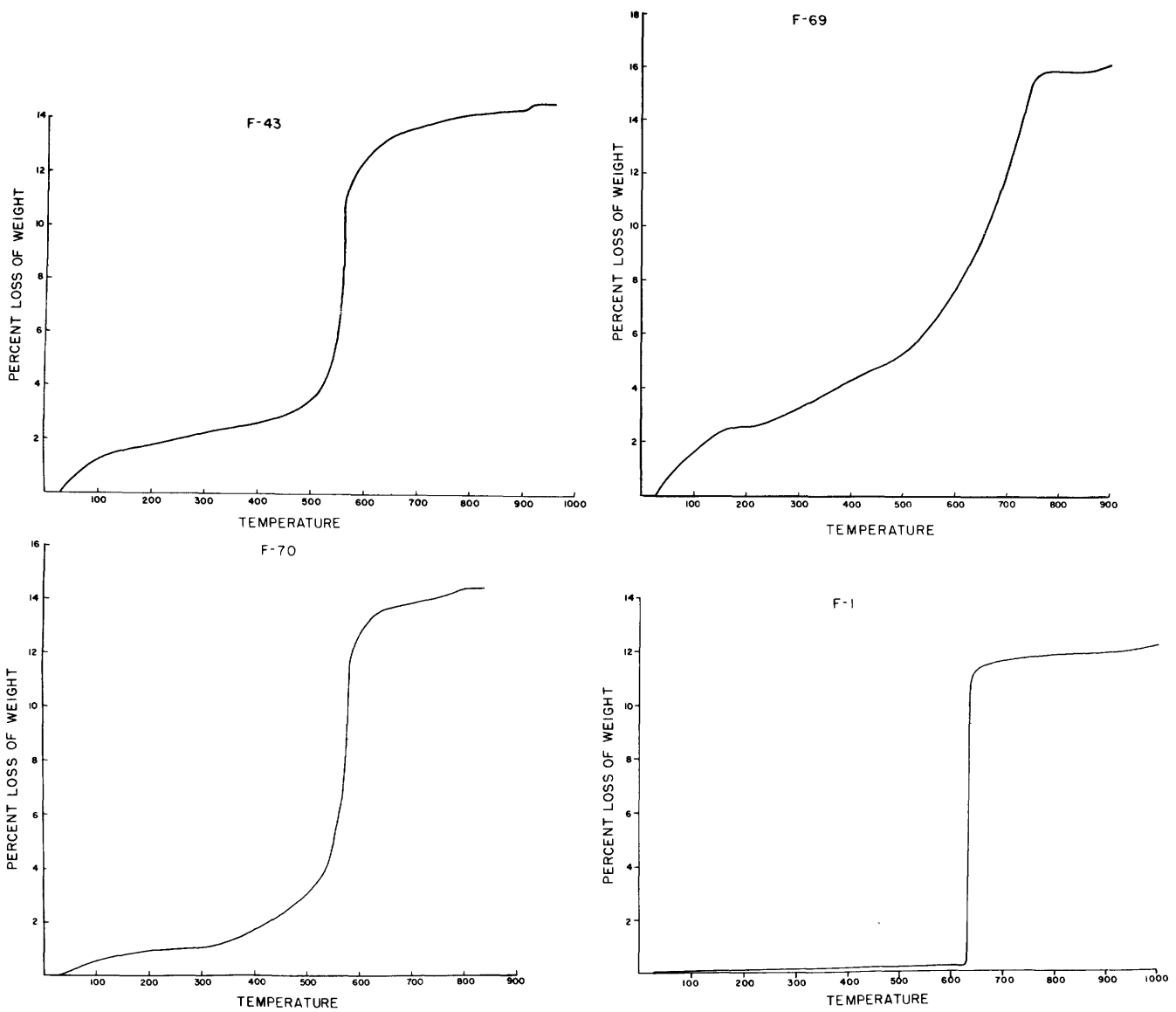


FIGURE 25.—Thermal-analysis curves of serpentine-group minerals obtained by the static method. Temperature expressed in degrees Centigrade. F–43, lizardite, Mineral Hill, Delaware County, Pa.; F–69, chrysotile and some lizardite(?), Webster, N.C.; F–70, clinochrysotile, Thetford, Quebec; F–1, antigorite, State Line Pits, Low's mine, Lancaster County, Pa.

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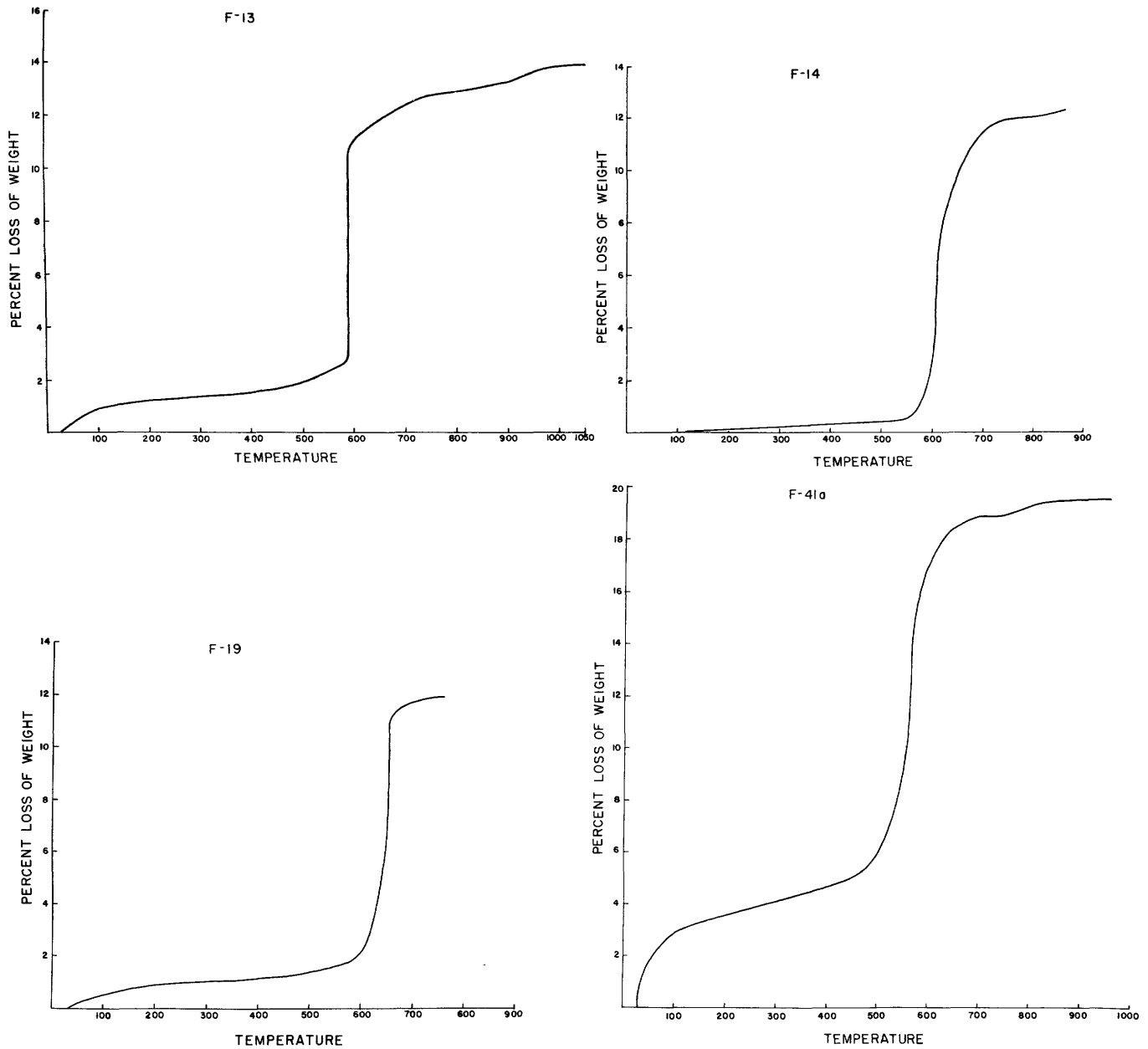


FIGURE 26.—Thermal-analysis curves of serpentine-group minerals obtained by the static method. Temperature expressed in degrees Centigrade. F–13, chiefly antigorite, Tilly Foster iron mine, near Brewster Station, N.Y.; F–14, chiefly antigorite, "Yu-Yen stone", Manchuria; F–19, antigorite, and some chrysotile, Bare Hills, Baltimore County, Md.; F–41a clinochrysotile (Globe-type), Currant Creek, Nev.

F–41a and F–43, which are typical of the variety deweylite. Chemical-solution studies by Nutting (1928) suggest that specimen F–69 consists of chrysotile and some lizardite. Nutting (1928) studied the absorption of water vapor by specimen F–69 at 26°, 36°, and 46°C and at humidities ranging from 0 to 100 percent saturation. Specimen F–69 was placed in a desiccator at a humidity of 80 percent saturation at 26°C before thermal analyses. Under these conditions a gram of this material could adsorb as much as 1.59 percent of its weight in water. This pretreatment accounts for the anomalous behavior of specimen F–69. It should be noted that insufficiently dried specimens of the related mineral kaolinite will behave similarly.

A graphical study (figs. 25 and 26) of these data shows that the high-temperature "shoulder" in curves for the specimens composed entirely or chiefly of antigorite—F–1, F–13, F–14, and F–19—is found at a higher temperature than the corresponding shoulder in curves for specimens consisting entirely or chiefly of clinochrysotile, F–41a and F–70, or lizardite, F–43, or of the inferred mixture, F–69. This trend is to be

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TABLE 11.—*Thermal-analysis data obtained by the static method on minerals of the serpentine group*

[Specimen numbers in the table are described in section on the description of the minerals]

F-1 Antigorite		F-13 Chiefly antigorite		F-14 Chiefly antigorite		F-19 Antigorite and some chrysotile		F-41a Clinochrysotile (Globe-type) (labeled deweylite)		F-43 Lizardite (labeled deweylite)		F-69 Chrysotile and some lizardite(?)		F-70 Clinochrysotile		H-1 Lizardite(?) Data of Haraldsen (1928)	
Temperature (° C)	Loss in weight (percent)	Temperature (° C)	Loss in weight (percent)	Temperature (° C)	Loss in weight (percent)	Temperature (° C)	Loss in weight (percent)	Temperature (° C)	Loss in weight (percent)	Temperature (° C)	Loss in weight (percent)	Temperature (° C)	Loss in weight (percent)	Temperature (° C)	Loss in weight (percent)	Temperature (° C)	Loss in weight (percent)
30	None	26	---	28	---	27	---	28	---	30	None	26	---	28	---	20	0
110	None	70	0.63	95	0.11	65	0.38	95	2.80	91	1.14	50	0.70	100	0.54	110	.60
380	0.08	106	.93	125	.12	102	.54	145	3.23	118	1.32	75	1.19	155	.74	500	4.18
480	.13	140	1.05	145	.12	160	.62	190	3.47	181	1.64	100	1.57	195	.84	600	12.26
628	.18	175	1.15	245	.18	220	.84	235	3.75	230	1.80	150	2.16	260	1.00	700	13.30
630	.52	200	1.23	310	.26	325	1.05	270	3.96	262	2.21	200	2.58	305	1.06	800	13.52
637	10.93	275	1.33	375	.29	370	1.14	285	4.06	305	2.30	300	3.30	338	1.41	1000	13.77
645	11.32	340	1.41	420	.33	460	1.26	345	4.44	350	2.48	400	4.16	405	2.07	1200	13.94
690	11.62	420	1.57	470	.38	485	1.36	395	4.66	395	2.63	500	5.33	432	2.31	1300	13.86
760	11.82	442	1.66	555	.51	515	1.48	440	4.97	450	2.96	550	6.21	480	2.55		
830	11.83	477	1.82	610	6.32	585	1.83	480	5.39	478	3.38	600	7.61	532	3.40		
850	11.97	494	1.89	655	10.40	655	11.13	545	8.65	517	3.80	650	11.16	585	11.93		
860	11.99	504	2.08	700	11.61	695	11.70	565	13.17	565	10.55	700	11.45	626	13.39		
1000	12.22	539	2.30	760	12.01	760	11.97	620	18.06	630	13.08	750	15.50	657	13.54		
		562	2.43	765	12.06			655	18.68	650	13.31	800	15.83	712	13.86		
		576	2.55	860	12.31			710	18.98	705	13.60	900	16.17	777	14.09		
		583	2.65					750	19.16	790	14.10			795	14.34		
		588	4.12					815	19.54	885	14.58			837	14.34		
		590	10.98					880	19.66	925	14.62						
		593	10.98					950	19.70	960	14.62						
		598	11.15														
		610	11.30														
		623	11.44														
		630	11.84														
		666	12.00														
		678	12.19														
		683	12.25														
		688	12.38														
		700	12.50														
		717	12.63														
		760	12.87														
		800	13.01														
		900	13.39														
		940	13.68														
		1050	14.11														

found also in the data of others, in particular, Bianchi and Carpanese (1928) and Epprecht (1947). It is also in agreement with the results of DTA studies on serpentines.

The results of thermal dehydration studies of minerals of the serpentine-group show that these minerals give characteristic curves which are very similar to those of kaolinite and halloysite. Specimens of antigorite tend to give curves which have a relatively well-developed "flat" shoulder, and these shoulders occur at slightly higher temperatures than those in curves for chrysotile or lizardite.

Curve H–1 (fig. 27) is taken from the work of Haraldsen (1928) and represents a study of the behavior of serpentine from Snarum, Norway—probably dominant lizardite with some clinochrysotile—at temperatures up to 1,300°C and demonstrates the monotonic character of the curve after dehydration has taken place.

DYNAMIC (DIFFERENTIAL-THERMAL-ANALYSIS) METHOD

The apparatus for differential thermal analysis (DTA) as used in this study is a modification of that described by Alexander, Hendricks, and Nelson (1939). The technique used is given in two papers by Faust (1948,

TABLE 12.—*Correspondence between* H_2O *reported in chemical analysis and that found by dehydration studies*

	F-1 Antigorite		F-13 Chiefly antigorite		F-14 Chiefly antigorite		F-19 Antigorite and some chrysotile		F-41 F-41a [1] Clinochrysotile (Globe-type—labeled deweylite)		F-43 Lizardite (labeled deweylite)		F-69 Chrysotile and some lizardite	
	H_2O-	H_2O+	H_2O-	H_2O+	H_2O-	H_2O+	H_2O-	H_2O+	H_2O-	H_2O+	H_2O-	H_2O+	H_2O-	H_2O+
From chemical analysis [2]	0	12.36	0.93	13.30	0.06	12.43	0.55	11.69	2.92	12.53	0.80	12.92	0.88	15.04
From dehydration studies	0 (110°C)	12.22	.93 (106°C)	13.18	.11 (95°C)	12.20	.54 (102°C)	11.43	2.80 (95°C)	16.90	1.32 (118°C)	13.30	1.57	14.60

[1] Chemical analysis and dehydration study were not made on the same tube sample.
[2] Water determined in chemical analysis is stated as H_2O+ and H_2O- referred to 110°C.

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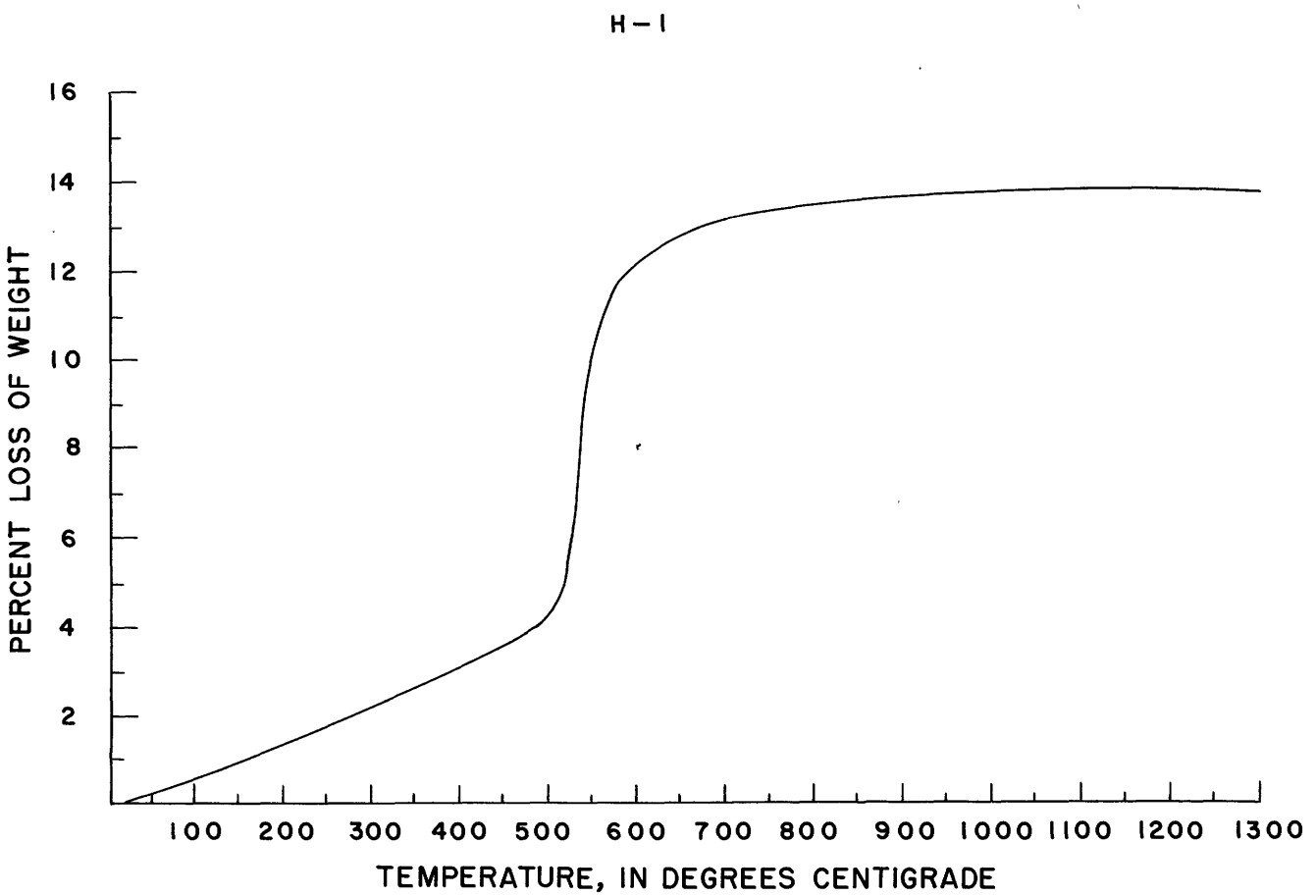


FIGURE 27.—Thermal-analysis curve of sample H–1, lizardite, Snarum, Norway, obtained by the static method. Data of Haraldsen, 1928.

1950). The samples were heated at the rate of 12°C per minute. The records were obtained as photographs.

PREVIOUS DTA STUDIES ON SERPENTINE-GROUP MINERALS

Caillère (1933) divided the serpentine-group minerals into two subgroups on the basis of DTA studies. Group I (p. 135) includes those minerals whose curve is characterized by an endothermic inflection corresponding to a sudden loss of water at 650°C and prolonged up to 750°C; and by an exothermic peak, which follows immediately, at 750° to 825°C. The minerals of Group II (p. 137) yield a curve presenting only an endothermic inflection at 650°C which corresponds to a sudden dehydration of the substance. Caillère (1934a) introduced the names α-antigorites for Group I and β-antigorites for Group II. In her comprehensive paper (Caillère, 1936) covering the serpentine minerals, she has followed this nomenclature and states (p. 224) that the β-antigorite is the most abundant and that, in general, the bowenites, williamsites, and chrysotiles are β-antigorites. She further concludes [2] that, in general, all specimens of altered serpentines—friable, bright green, rich in adsorbed water—belong to the group of α-antigorites, whereas the dark-green rocks, poor in hygroscopic water, are made up of β-antigorites. It appears that the α variety most generally arises by the superficial alteration of the β form. This hypothesis she finds to be in accord with her observation that intimate mixtures of these two antigorites in the same rock are extremely rare.

Efremov (1939, 1940) characterized the DTA curves of the serpentine-group minerals as an endothermic reaction in the range 600° to 700°C followed by an exothermic effect.

Caillère and Henin (1945) observed that bowenite from Khotan, Chinese Turkestan, a β-antigorite treated with solutions of sodium, magnesium, or calcium salts behaved as an α-antigorite in DTA tests. Faust, in Bowen and Tuttle, 1949, identified by DTA methods their synthetic mineral as chrysotile. A summary of the unpublished DTA studies by Faust of nickel-bearing serpentine and related minerals found in garnierite is given in the paper by Pecora, Hobbs, and Murata (1949, p. 20, 22). Kauffman and Dilling (1950) included DTA curves for five serpentine specimens in

[2] Caillère, 1936, p. 232–233. Literal translation by George T. Faust.

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their study of the DTA method. Midgley (1951) presented a DTA curve for an unusual serpentine mineral from Kennack Cove, Lizard, Cornwall, England. This mineral he considered to be a polymorph of normal antigorite.

Kiefer (1950–51, 1951) made DTA studies on three serpentines. In addition he ground three different serpentines in water, or solutions of acids or alkalies, for 40 hours, obtained DTA curves, and noted in each experiment that he had converted the β-antigorite to α-antigorite. He concluded that his results, indicating that the α-antigorites were more stable than the β-antigorites, were at variance with those of Simonne Caillère but preferred to use the same designations for the "antigorites" rather than introduce confusion into the literature. Kiefer also observed that the endothermic trough occurs at higher temperatures for β-antigorite than α-antigorite.

Hess, Smith, and Dengo (1952) published a DTA curve for antigorite from Caracas, Venezuela. Sudo and others (1952) published two curves of serpentine minerals from Japan. Faust and Murata (1953) published DTA curves for the synthetic chrysotile made by Bowen and Tuttle and for antigorite from the type locality, Antigorio Valley, Italy. Nagy (1953) published portions of his DTA curves for acid-heated antigorite and chrysotile. Schmidt and Heystek (1953) published DTA curves for antigorite and chrysotile specimens from South Africa. Vermaas (1953) published DTA curves for antigorite specimens from the Transvaal, the type antigorite from Antigorio, Italy, and chrysotile specimens from the Transvaal. Kalousek and Mui (1954) made DTA studies on reaction products in the system H_2O-MgO-SiO_2, synthesized in the temperature range of 75° to 350°C, and they identified by the DTA curves a substance they called "chrysotile-like." Pundsack (1955) published a DTA curve of chrysotile from the Danville area, Quebec, Canada (No. 1 crude grade of fiber). Eckhardt (1956) gives DTA curves for chrysotile from Yugoslavia and schweizerite from Findelengletscher, near Zermatt, Wallis, Switzerland. Nagy and Faust (1956) give DTA curves for natural and synthetic chrysotile, natural antigorite, and a natural mixture of chrysotile and antigorite.

A detailed study of the minerals of the serpentine-group was made by Kouřimský and Šatava (1954) in which DTA methods were extensively used in identifying the minerals.

The work cited above is not all of equal quality. This arises in part from the scope of the study and from the experimental details. Those scientists interested in the bulk of the specimens are content to use impure materials, and this has its field of application in economic geology.

PRESENT DTA STUDIES

The DTA curves for the serpentine group of minerals given in this paper were all made over the temperature range 25° to 1,100°C. A word should be said about the accuracy of the temperature measurements. No attempt at accurate thermometry is implied in the temperature data ascribed to a particular point on a DTA curve. The curves were calibrated using quartz as a standard (Faust, 1948) and corrections were made for the cold junctions. Maxima and minima for sharp curves are easy to measure and are at least within ±2°C of their true values. Gently curved or rounded peaks and troughs are measured by erecting a tangent line to the curve parallel to the baseline and passing a perpendicular line through the point of tangency. Such curves have a wide latitude of error, sometimes as much as ±4°C. The precision of the measurements is much more uncertain, because the dissociation of serpentine, minerals, in DTA, is an inequilibrium process. The data for the synthetic clinochrysotile (specimen F–54, curves C–488 and C–489 in table 13) represent a very favorable comparison. The DTA patterns of the chrysotiles and lizardites are so similar in morphology and temperature of the various peaks and troughs that they are grouped together. These have been divided into six subgroups: *A*, clinochrysotile; *B*, clinochrysotile of the Globe type; *C*, clinochrysotile plus orthochrysotile; *D*, chrysotile plus lizardite, where $C>L$; *E*, lizardite plus clinochrysotile, where $L>C$; and F, lizardite. The basis for the classification is chiefly from the X-ray powder diffraction studies but DTA, solution studies, and other techniques have also been used in the placement of a given specimen in a given subgroup. The data are given in table 13.

INTERPRETATION OF THE DTA CURVES

A TYPICAL CLINOCHRYSOTILE CURVE

The synthetic preparation, specimen F–54, of Bowen and Tuttle (1949) yields a simple clinochrysotile type pattern which is shown in curves C–488 and C–489 in figure 28. These curves show a very shallow endothermic trough in the temperature range 100° to 175°C which arises from the loss of adsorbed water. On record C–488, between 175°C and approximately 525°C, the curve has a very slight upward bow. At approximately 525°C the curve begins its descent into the trough and reaches a minimum at 665°C. This endothermic trough is unsymmetrical and is wider than it is deep. Broad troughs of this type are characteristic of very fine grained substances. After the expulsion of the water from this clinochrysotile, the curve returns to the baseline at about 700°C and continues along until approximately 785°C where an exothermic reaction begins and reaches a maximum

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TABLE 13.—*Observations of the differential-thermal-analysis curves of chrysotiles and lizardites*

[Principal endotherms marked (EN); principal exotherms marked (EX)]

Specimen	Curve	Temperature (°C) of thermal phenomena for indicated range						
		85°–200°C	200°–400°C	400°–600°C	600°–700°C	700°–800°C	800°–900°C	900°–1000°C
A. Clinochrysotile								
F–54	C–488	(1)			665 (EN)		803 (EX)	
F–54	C–489	(1)			670 (EN)		805 (EX)	
F–52	C–501	104		426	676 (EN)	790	801 (EX)	
		135 (EN)						
F–22	C–122	130	393		692 (EN)	796	820 (EX)	900
F–40	C–91	121			696 (EN)		817 (EX)	
F–50	C–470	117				701 (EN)	805 (EX)	
						788 (?)		
F–58	C–655	131				710 (EN)	807 (EX)	
F–70	C–746	120				[2] 706 (EN)	806 (EX)	
						[2] 721 (EN)		
F–60	C–680	160	384			705 (EN)	814 (EX)	
F–61 [3]	C–681	57			690		819	
		87						
B. Clinochrysotile (Globe-type)								
F–20	C–84		292	433		710 (EN)	824 (EX)	
F–20A	C–817		(1)		690 (EN)		825 (EX)	[4] 923
F–53	C–731	94	(1)		647	712 (EN)	[5] 802 (EX)	
						[5] 789 (EX)	833	
F–24	C–125			410	640	705 (EN)	823 (EX)	
F–41	C–133	137	357	590	681 (EN)		815 (EX)	
F–45	C–92	110	351		697 (EN)		820 (EX)	
							851	
							884	
F–45	C–94	[6] 138	382		[6] 654 (EN)		817 (EX)	
							866	
F–26	C–93	[6] 155		492	[6] 645		804 (EX)	
					678 (EN)		872	
C. Clinochrysotile plus orthochrysotile								
F–56	C–650	134			689 (EN)	799 (EX)		
F–64	C–728	109	394		687 (EN)		816 (EX)	
							859	
							890	
F–74	C–805	(1)	229			708 (EN)	804 (EX)	
			380					
D. Chrysotile plus lizardite, C > L								
F–57	C–562	89			660	782		
		117			692 (EN)	798 (EX)		
F–51	C–478	88	213	408	671 (EN)	784 (EX)		
		128						
F–73	C–809	(1)	250		690 (EN)		803 (EX)	
F–72	C–803	(1)	224		698 (EN)		805 (EX)	
F–25	C–115		387		615		825 (EX)	916
					698 (EN)			
E. Lizardite plus clinochrysotile, L > C								
F–71	C–804	(1)	286		687 (EN)		811 (EX)	
F–75	C–849	106	308		623	729 (EX)		
					637 (EN)			
					676			
F–76	C–850	133	311		602 (EN)	720		
					627	732 (EX)		
F–3	C–135	139	202		671 (EN)		816 (EX)	

See footnotes at end of table, p. 55.

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TABLE 13.—*Observations of the differential-thermal-analysis curves of chrysotiles and lizardites*—Continued

Specimen	Curve	Temperature (°C) of thermal phenomena for indicated range						
		85°–200°C	200°–400°C	400°–600°C	600°–700°C	700°–800°C	800°–900°C	900°–1000°C
F. Lizardite								
F–46	C–104		365		[7] 686	700 (EN)	807 (EX)	
F–47	C–98		[1]		[7] 689	702 (EN)	812 (EX)	
F–63	C–727	115	379			700 (EN)	815 (EX)	
F–63	C–818		250			707 (EN)	824 (EX)	
			(330?)					
F–23	C–117		264			714 (EN)	819 (EX)	
			372					
F–42	C–729	135	303		681 (EN)		800 (EX)	
							813	
F–43	C–105	113			687 (EN)		824 (EX)	
							854	
							883	
Type lizardite [8]		63			[7] 661		818 (EX)	
		107			698 (EN)			

[1] Present but not measured.
[2] Doublet (706° and 721°C).
[3] Sample treated with HCl.
[4] Specimen contains much calcite.
[5] Doublet (789° and 802°C).
[6] Specimen contains much stevensite.
[7] Inflection.
[8] Temperatures estimated from Midgley (1951).

peak temperature at 803°C. Subsequently the curve drops steeply to the baseline and remains essentially straight until the conclusion of the run. This flat portion of the curve following the exothermic peak is offset above the flat portion which precedes the peak. This offset arises from the difference in the specific heat and conductivity of the phase assemblages existing before and after the exothermic reactions.

An examination of the DTA curves of the clinochrysotile samples (figs. 28 and 29) shows the parallel correspondence of the synthetic and natural materials. In most natural clinochrysotiles the endothermic peak is narrower and deeper than that of the synthetic chrysotile, a consequence of the great difference in grain size. It is of interest that the synthetic chrysotile made by Noll (1950) gave a dehydration curve closely parallel to that of a natural chrysotile from Australia.

THE COLLECTION OF CHRYSOTILE AND LIZARDITE CURVES

A collection of 36 DTA curves (figs. 28 to 37) of specimens consisting of chrysotile or lizardite or of mixtures of chrysotile and lizardite were studied. The thermal-analysis data are gathered together in table 13. A detailed analysis of these curves is given for four somewhat arbitrary temperature ranges.

DETAILED ANALYSIS OF THE CURVES IN THE TEMPERATURE RANGE 85° TO 200°C

Twenty-one of 36 DTA curves of chrysotile and lizardite showed a decided shallow trough which extends over a span of temperatures and indicates a generally constant loss of water. Seven of the curves show faint but definite depressions and eight showed no evidence of a break. A study of the chemical analyses of 10 of these samples shows the H_2O- to range from 0.36 to 1.64 percent with an average value of 0.86 percent (table 14). A correlation of the column "Area of the trough" against the product of the weight of the sample used in the experiment and the analytically determined percentage of H_2O- should be linear.

For those samples whose H_2O- was determined by chemical analysis, there does not seem to be any correlation of this value with the various data in the table. This probably is due to the experimental technique. Since the DTA studies on the different samples were not made at the same time, but over a period of about 10 years and in two different laboratories, humidity probably played an important role in changing the H_2O- content of a given sample while it was being prepared for DTA. The analytical values of H_2O- used for comparison are not the true ones at the time of the experiment. A plot of the column "Area of the trough" against the column "Weight of sample" examined (table 14) shows only the expected general trend.

The data for the column "Area of the trough" in table 14 show that the specimens consisting chiefly of lizardite have much lower amounts of adsorbed water. This is probably not a true relationship because the DTA of Midgley's type lizardite (fig. 39) shows a well-developed trough with two minima.

This adsorbed water, which fine-grained materials and fibers tend to pick up rather readily, may compli-

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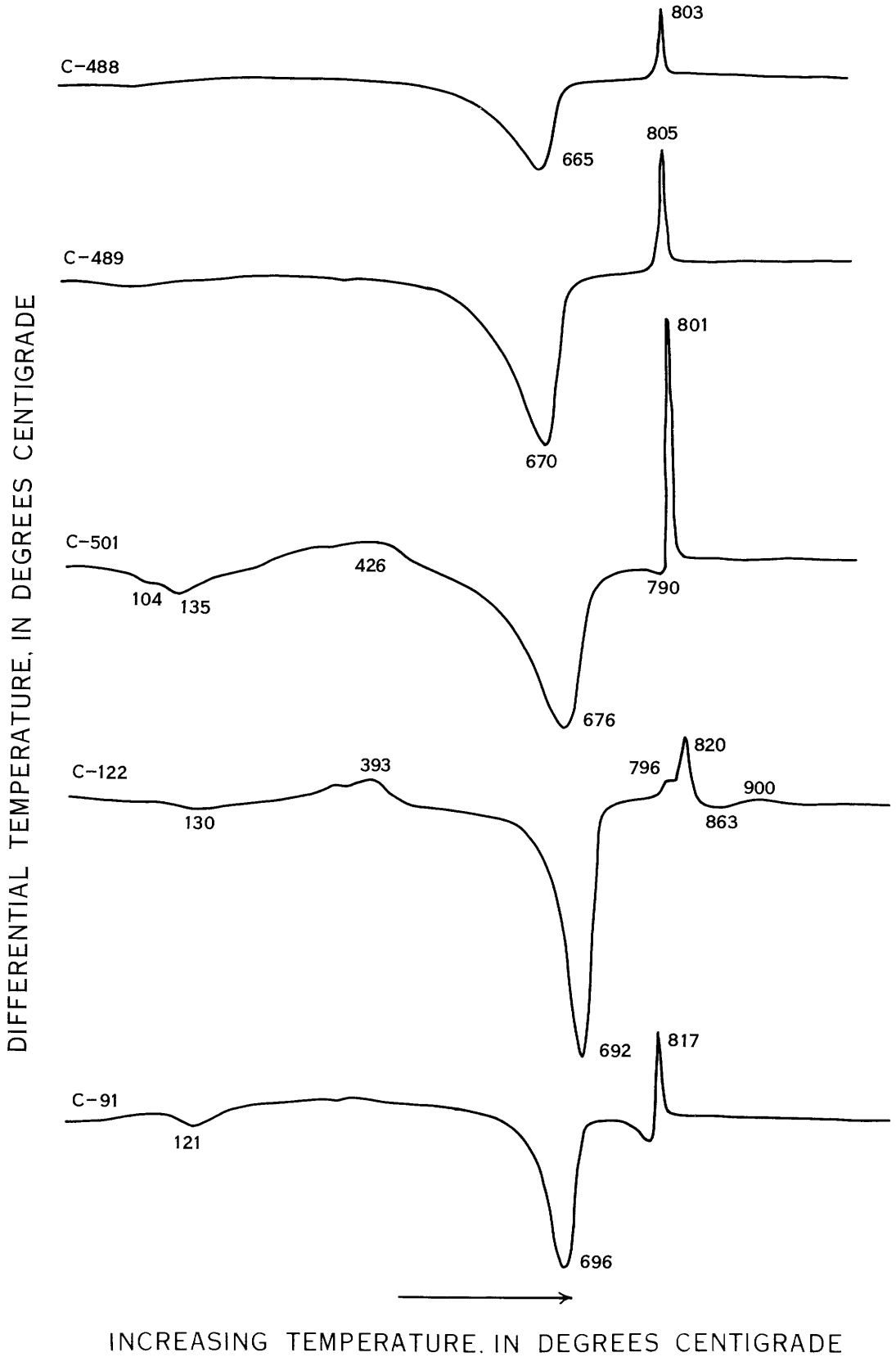


FIGURE 28.—Differential-thermal-analysis curves of clinochrysotile, table 13A. C-488, F-54, synthetic; C-489, F-54, synthetic; C-501. F-52, Sylmar, Chester County, Pa.; C-122, F-22, Montville, Morris County, N.J.; C-91, F-40, Murfreesboro, Pike County, Ark. All curves, except C-489, were obtained with a resistance of 600 ohms in the galvanometer circuit. Curve C-489 was obtained with 999.9 ohms.

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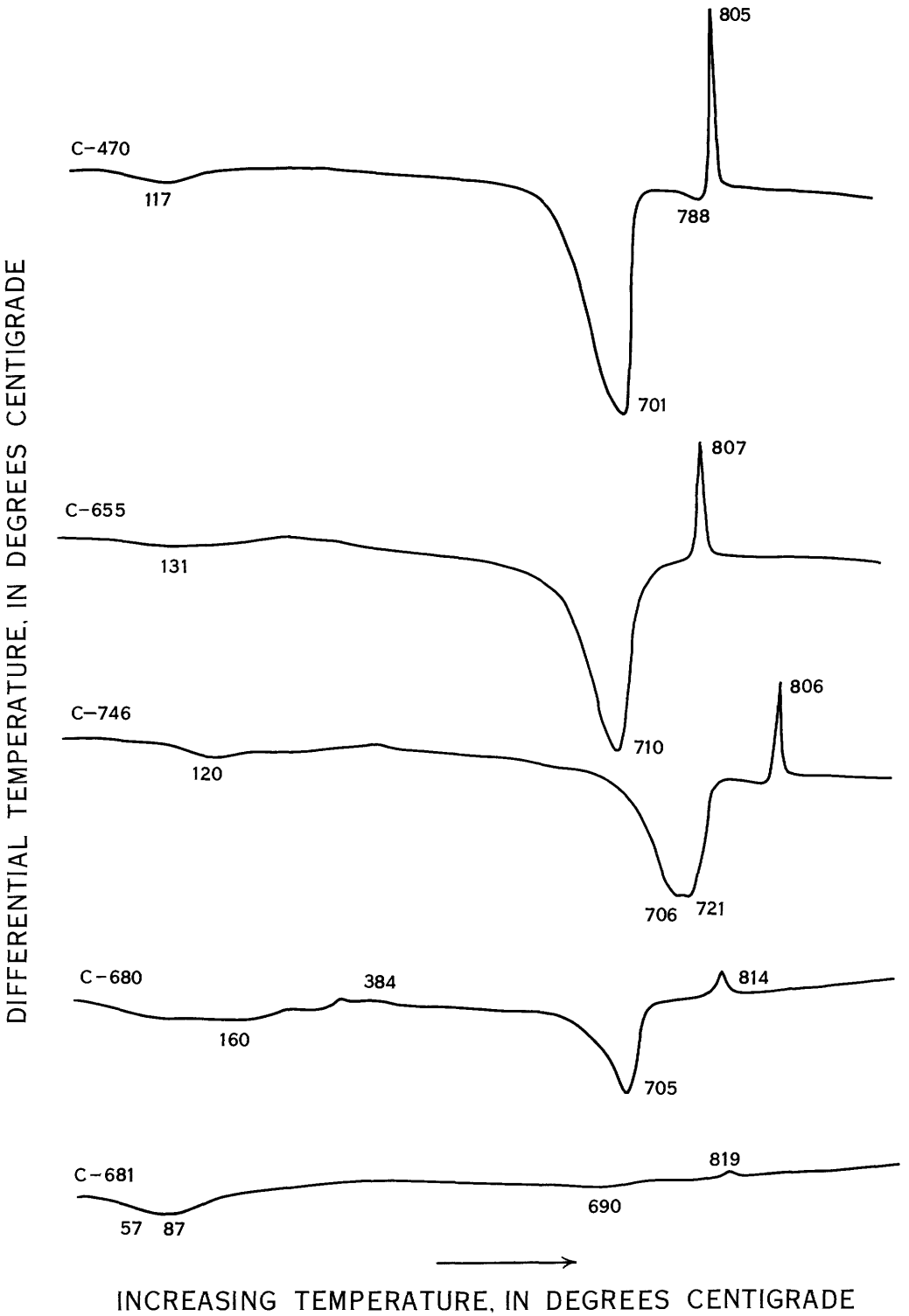


FIGURE 29.—Differential-thermal-analysis curves of clinochrysotile, table 13A. C–470, F–50, near Moa, Oriente Province, Cuba; C–655, F–58, Canyon of Clear Creek, San Benito County, Calif.; C–746, F–70, near Thetford, Megantic County, Quebec; C–680, F–60, near Thetford, Megantic County, Quebec; C–681, F–61, part of the preceding sample F–60, treated with 1 *N* HCl. All curves obtained with a resistance of 600 ohms in the galvanometer circuit.

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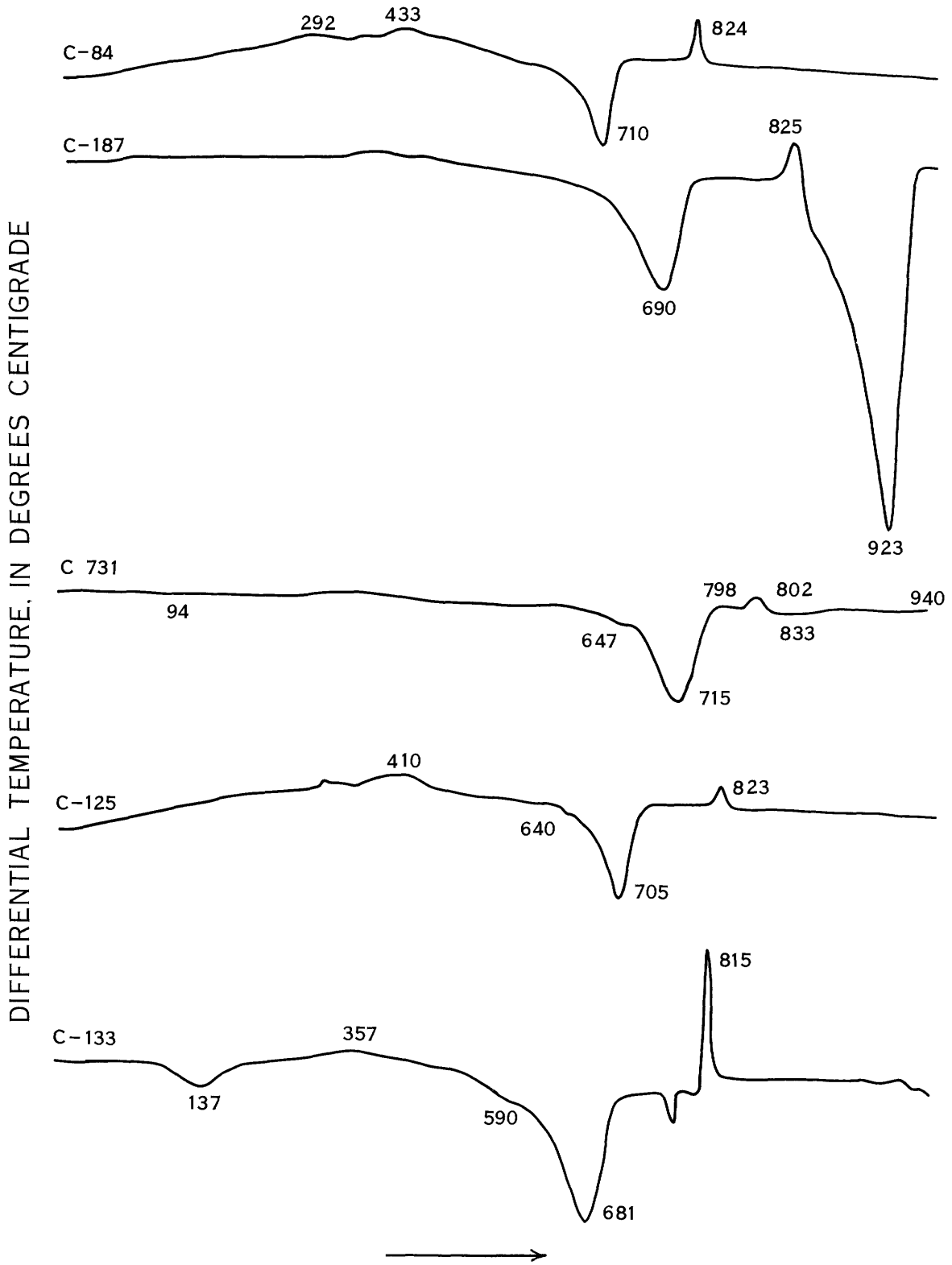


FIGURE 30.—Differential-thermal-analysis curves of clinochrysotile (Globe-type), table 13B. C-84, F-20, Gila County, Ariz.; C-817, F-20A, Gila County, Ariz., contains much calcite; C-731, F-53, Grand Canyon, Ariz.; C-125, F-24, Montville, Morris County, N.J.; C-133, F-41, Currant Creek, Nev. All curves obtained with a resistance of 600 ohms in the galvanometer circuit.

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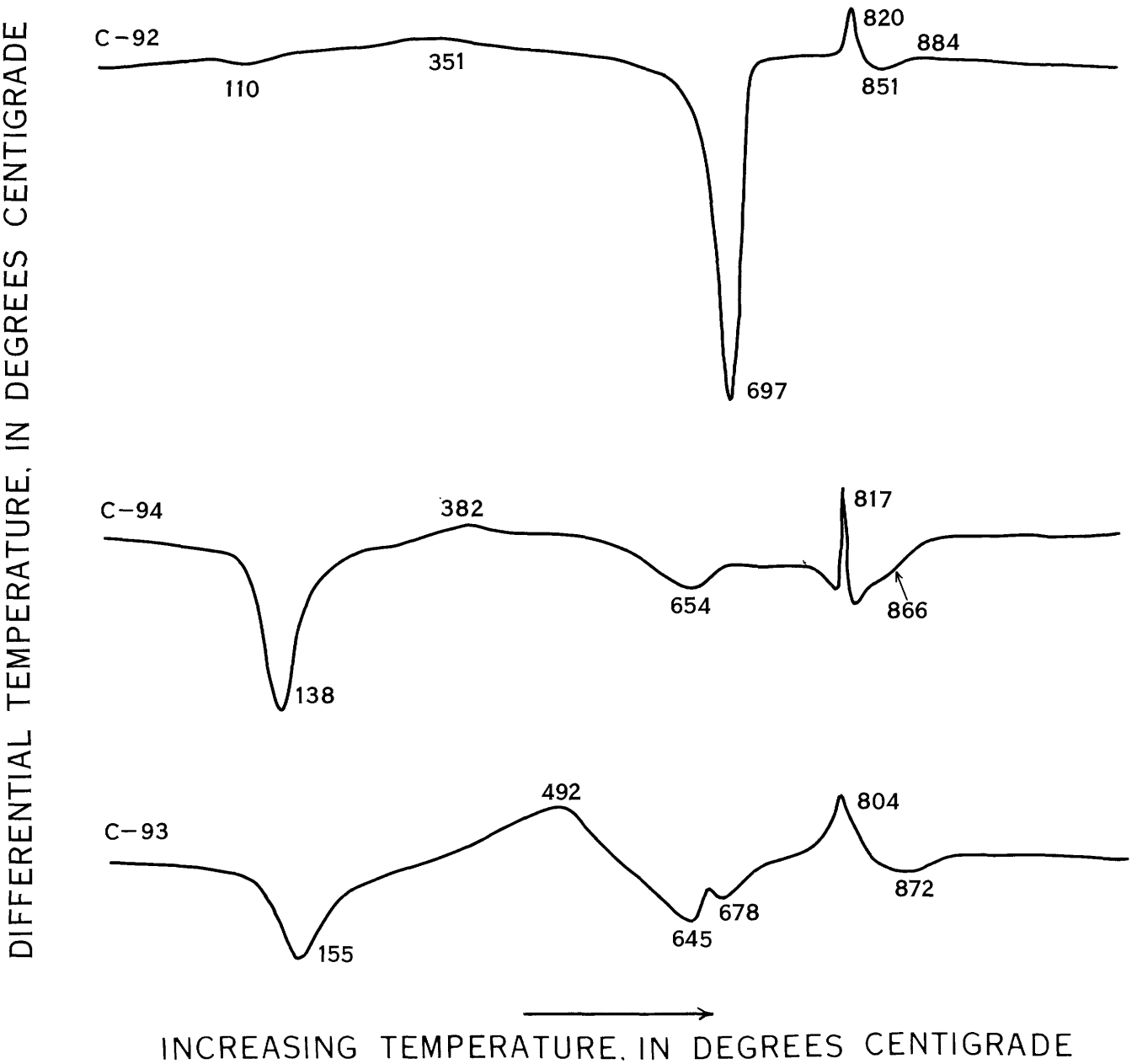


FIGURE 31.—Differential-thermal-analysis curves of clinochrysotile table 13B (Globe-type). C-92, F-45, Wood's chrome mine, Lancaster County, Pa.; C-94, F-45, Wood's chrome mine, Lancaster County, Pa., contains much stevensite; C-93, F-26, Texas, Lancaster County, Pa., contains much stevensite. All curves obtained with a resistance of 600 ohms in the galvanometer circuit.

cate the "low-temperature" portion of the DTA curve. As mentioned previously under the static method of thermal-analysis, Nutting (1943) has shown that water adsorbed on serpentine minerals will affect the "low-temperature" portion of a dehydration curve. The DTA curves (figs. 28–31) show in a similar manner how this adsorbed water modifies the chrysotile curve. If a sample of the related mineral kaolinite is washed and partially dried it will show correspondingly an additional low-temperature endothermic trough.

The low-temperature endotherm of the curves for the serpentine-group minerals may be further complicated by the presence of stevensite in the sample. Stevensite (Faust and Murata, 1953) loses much of its water in the same temperature range (curves C–93 and C–94, fig. 31).

DETAILED ANALYSIS OF THE CURVES IN THE TEMPERATURE RANGE 200° TO 600°C

Almost all the 36 DTA curves show a definite, long range, upward bowing of the curve in the temperature range of 200° to about 550°C. On many of the DTA curves the accidental recording of the polymorphic transformation in the nickel block at 354°C, as recog-

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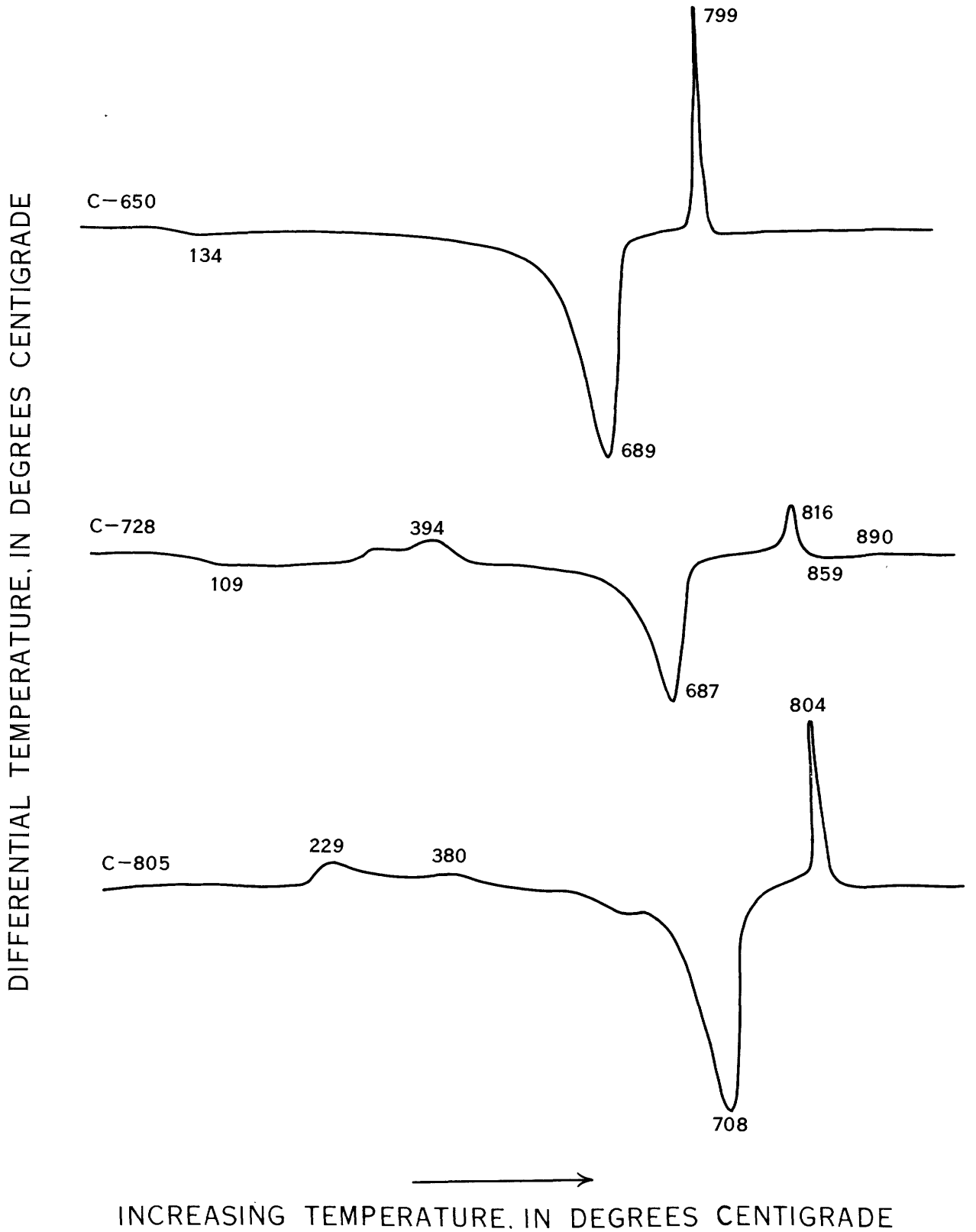


FIGURE 32.—Differential-thermal-analysis curves of clinochrysotile plus orthochrysotile, table 13C. C–650, F–56, Balmat, St. Lawrence County, N.Y.; C–728, F–64, Montville, Morris County, N.J.; C–805, F–74, New Almaden mine, Santa Clara County, Calif. All curves obtained with a resistance of 600 ohms in the galvanometer circuit.

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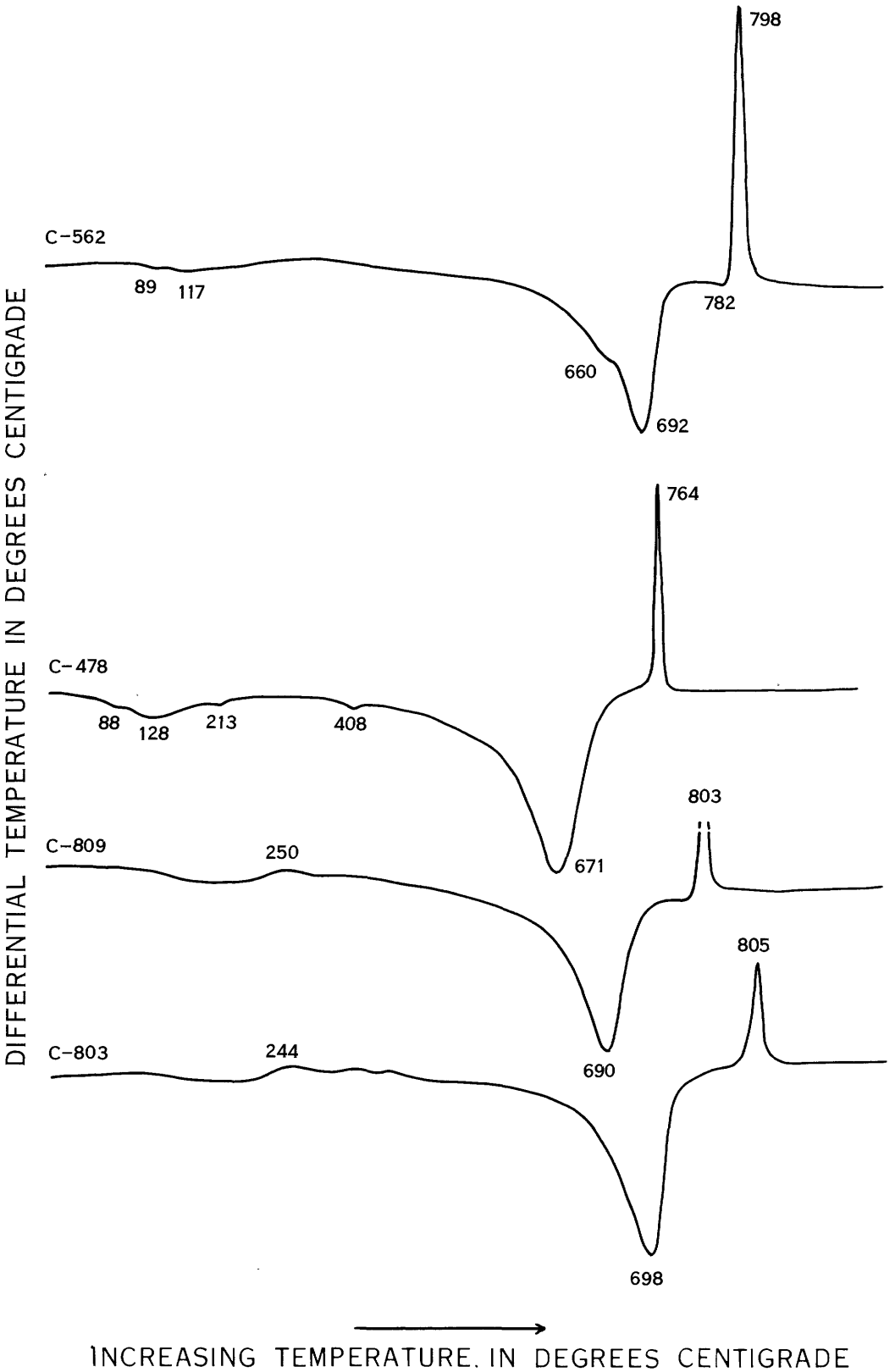


FIGURE 33.—Differential-thermal-analysis curves of chrysotile plus lizardite, C>L, table 13D. C-562, F-57, Talcville, St. Lawrence County, N.Y.; C-478, F-51, Nicaro, Oriente Province, Cuba; C-809, F-73, New Almaden mine, Santa Clara, County, Calif; C-803, F-72, New Almaden mine, Santa Clara County, Calif. All curves obtained with a resistance of 600 ohms in the galvanometer circuit.

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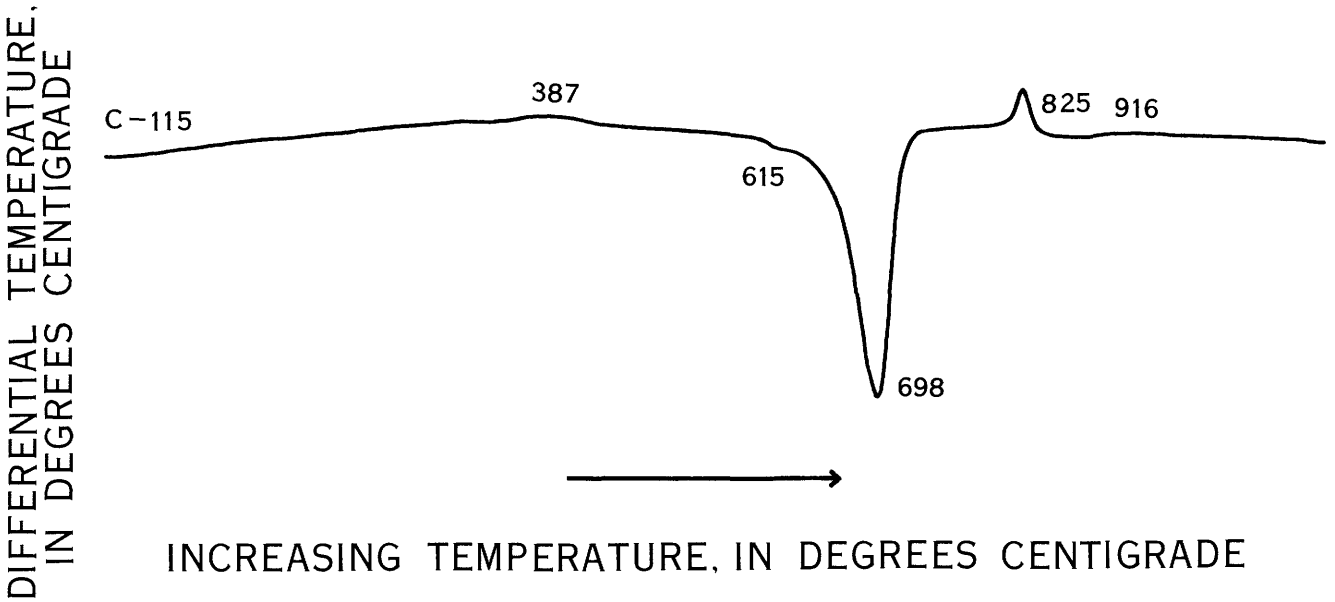


FIGURE 34.—Differential-thermal-analysis curve of chrysotile plus lizardite, C>L, table 13D. C-115, F-25, Montville, Morris County, N.J. Curve obtained with a resistance of 600 ohms in the galvanometer circuit.

nized by Faust (1948), may complicate the phenomena. The magnitude of this extraneous bow or peak may be assessed by comparing the DTA curve of these minerals with that of the curves for quartz or other substances which have no exothermic reactions between 200° and 500°C and which were analyzed at about the same time and under the same experimental conditions. After taking this into consideration, it is observed that a genuine upward bow in the curve is present, and it is concluded that this arises from the occurrence of some phenomena taking place in chrysotile and lizardite in this temperature span. On records C–650, C–731, C–478, C–488, and C–489 (figs. 28, 30, 32, and 33), the upward bowing of the curve is very gentle. On records C–562, C–104, C–746, C–98, C–655, C–115, C–680, and C–117 (figs. 29, 33, 34, 36, and 37), the bow in the curve becomes increasingly larger and the development of a gently rounded peak becomes clear. On records C–727, C–84, C–125, C–728, and C–122 (figs. 28, 30, 32, and 36), there is a distinct peak which is sharp enough so that a maximum can be assigned for measurement.

TABLE 14.—*Relation between* H_2O- *in chrysotiles and lizardites and their behavior in differential thermal analysis*

Sample	H_2O- by chemical analysis (percent)	Temperature of endothermic trough (°C)	Area of the trough (square millimeters)	Weight of sample (grams)
A. Clinochrysotiles				
F-54	[1] 1.2	[2]	10.1	0.2349
F-22	.70	130	17.0	.6231
F-58		131	5.1	.4391
F-70	.54	120	16.0	.2931
F-60		160		.1519
B. Clinochrysotiles (Globe-type)				
F-20	1.64	[3] Not observed		0.2342
F-53	1.18	94	5.4	.2813
F-24	.99	[3] Not observed		.2610
C. Clinochrysotile plus orthochrysotile				
F-56	0.41	134	7.1	0.4650
F-64		109		.5180
D. Chrysotile plus lizardite, C > L				
F-57	1.04	89	31.8	0.5260
		117		
F-25	.50	[2]	20.3	.6383
F. Lizardite				
F-46	n.d.	[2]	3.0	0.2078
F-47	n.d.	Not observed	1.0	.3157
F-63		115		.3605
F-23	0.36	[2]	3.0	.4353

[1] Determined by Dr. Norman L. Bowen.
[2] Temperature not measured.
[3] Although not observed the endotherm may be masked, see curves C-84 and C-125 in figure 30.

The occurrence of a gentle bowing in the curve or the more well developed peaks cannot be ascribed to the burning of organic matter, which may produce a similar phenomenon. Nor can it be traced to the oxidation of ferrous iron to ferric iron, as an examination of the values for these constituents or their ratio in table 15 shows.

Kouřimský and Šatava (1954) used a ceramic block as the reaction cell and used only platinum:platinum-rhodium thermocouples for thermometry. Nine of their 18 curves show a pronounced peak in the temperature range of 278° to 366°C, with an average of 340°C. The specimens showing this phenomenon appear to be

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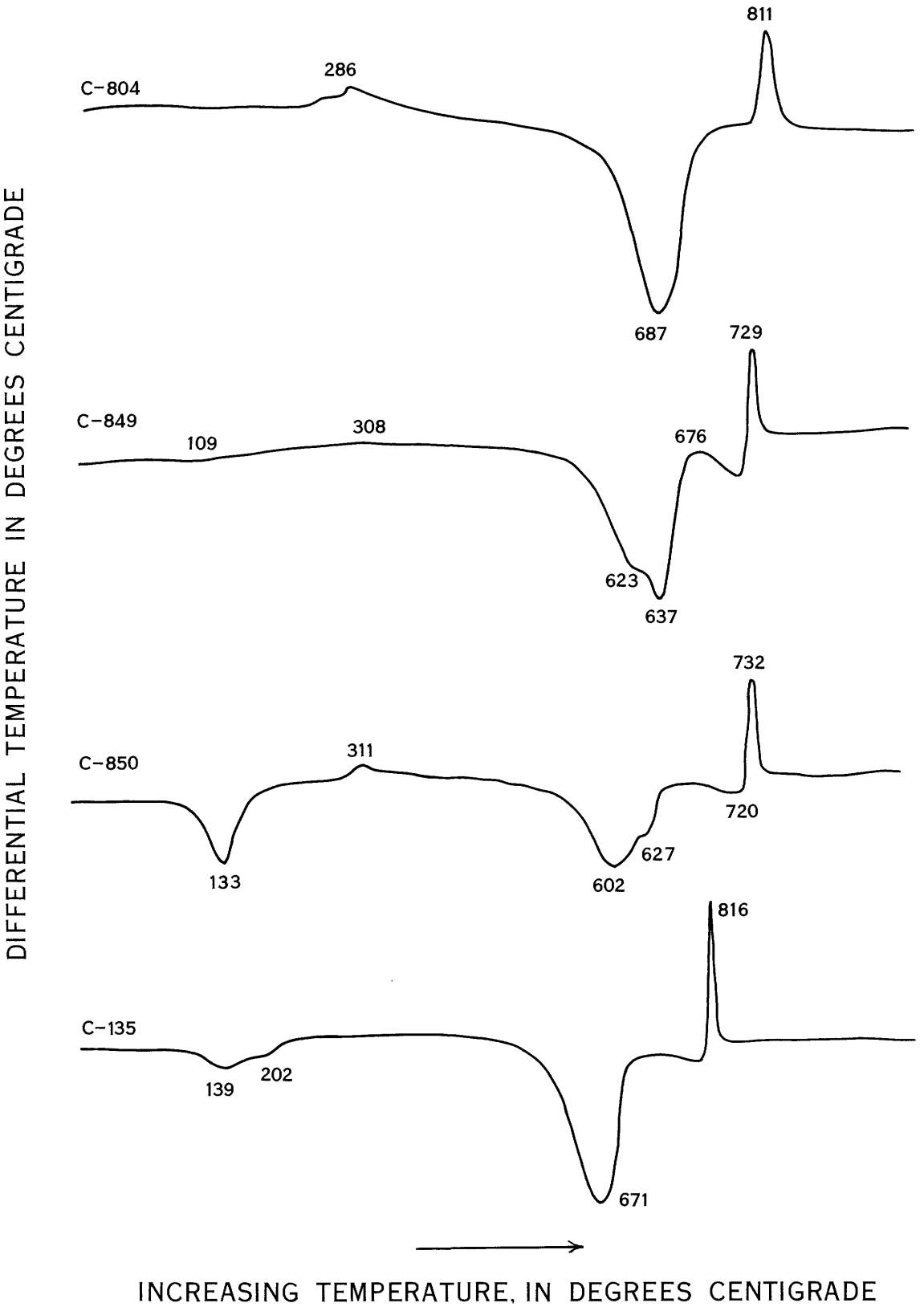


FIGURE 35.—Differential-thermal-analysis curves of lizardite plus clinochrysotile, L>C, table 13E. C–804, F–71, Snarum, Norway; C–849, F–75, Hoboken, Hudson County, N.J.; C–850, F–76, part of the preceding sample, F–75, treated with cold dilute HCl (1:1); C–135, F–3, near Forest Hill, Harford County, Md. All curves obtained with a resistance of 600 ohms in the galvanometer circuit.

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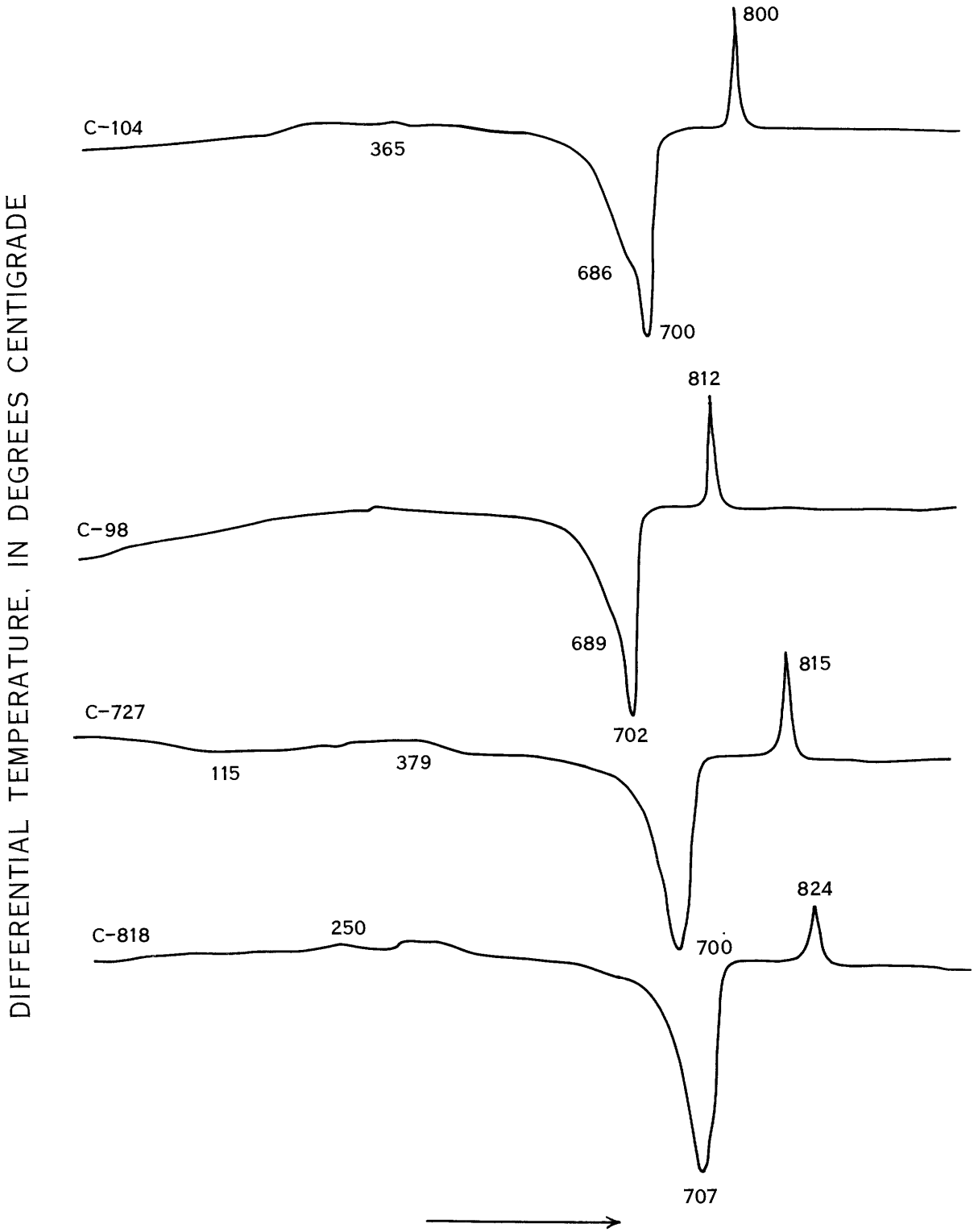


FIGURE 36.—Differential-thermal-analysis curves of lizardite, table 13F. C-104, F-46, near Bellows Falls, Windham County, Vt.; C-98, F-47, Tyrol, Austria; C-727 and C-818, F-63, Staten Island, Richmond County, N.Y. All curves obtained with a resistance of 600 ohms in the galvanometer circuit.

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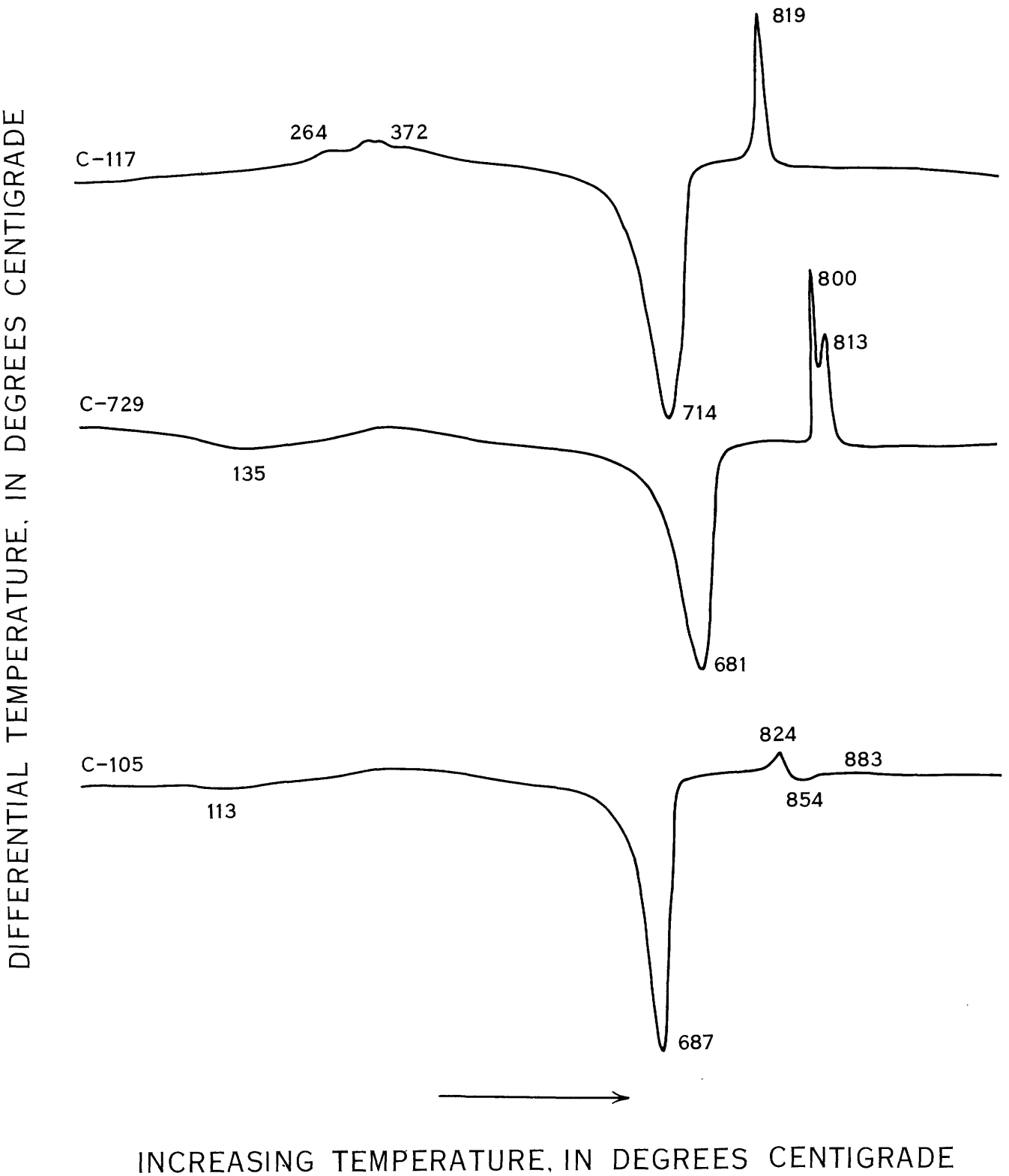


FIGURE 37.—Differential-thermal-analysis curves of lizardite, table 13F. C-117, F-23, Dognacska, Severin Province, Hungary; C-729, F-42, near Norris, Union County, Tenn.; C-105, F-43, Crump's quarry, Mineral Hill, Delaware County, Pa. All curves obtained with a resistance of 600 ohms in the galvanometer circuit.

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TABLE 15.—*Comparison of* FeO *and* Fe_2O_3 *in chrysotiles and lizardites with their thermal behavior in differential-thermal-analysis, and with their paragenesis and mineralogy*

Specimen	Curve	Intensity of thermal effect in temperature range 200° to 600° C	FeO (percent)	Fe_2O_3 (percent)	$\frac{Fe_2O_3}{FeO}$	Paragenetic class	Serpentine-group mineral
F–56	C–650	Gentle bow in curve	0. 16	0. 87	5. 44	B	Clinochrysotile plus orthochrysotile.
F–53	C–731	do	None	. 51	(All Fe_2O_3)	B	Clinochrysotile (Globe-type).
F–51	C–478	do	2. 96	3. 81	1. 29	A	Chrysotile plus lizardite, C>L.
F–54 [1]	C–488	do	None	None			Clinochrysotile.
F–57	C–562	do	. 06	. 26	4. 33	B	Chrysotile plus lizardite, C>L.
F–46	C–104	Definite peak	Tr.	5. 68	(All Fe_2O_3)	A	Lizardite.
F–47	C–98	do	Tr.	5. 55	(All Fe_2O_3)	A	Do.
F–25	C–115	do	. 03	. 19	6. 33	B	Chrysotile plus lizardite, C>L.
F–23	C–117	do	. 18	1. 96	10. 89	B	Lizardite.
F–20	C–84	do	. 11	. 19	1. 72	B	Clinochrysotile (Globe-type).
F–24	C–125	do	None	. 34	(All Fe_2O_3)	B	Do.
F–22	C–122	do	. 09	. 26	2. 89	B	Clinochrysotile.

[1] Synthetic material.

chrysotile, lizardite, or mixtures of chrysotile and lizardite.

No other relation between the intensity of this thermal effect and chemical composition was noted. The possibility that this peak could be associated with the oxidation of magnetite to maghemite (Gheith, 1952), which takes place in this temperature range was also considered. The optical, chemical, and X-ray data do not show magnetite to be present in these samples. If it is assumed that all the iron oxides are present as magnetite, there is still no correlation between the amount of "assumed magnetite" and the intensity of the thermal effect. Nor, as can be seen from table 15, is there any relation to paragenesis or mineralogic composition. Accordingly, it becomes necessary to look for some other factor.

In blowpipe analysis, reference is made to the phenomen of "glowing" or becoming incandescent when heated before the blowpipe. This is an exothermic reaction. A number of minerals such as calcite and brucite possess this property. Scheerer (1840) coined the word "pyrognomic" for this behavior of substances, and it is also called thermoluminescence. Pabst (1952) gives an excellent summary of some previous work on this phenomenon.

Incandescence or "glowing" of some specimens of serpentine minerals has been noted by mineralogists in blowpipe examinations. Simonne Caillère (1934b), who has correlated her DTA studies with the phenomenon of incandescence in serpentine, believes that this phenonenon is related to the exothermic peak at 720°C. Caillère (1935) further points out that the luminescence can be observed at dull-red heat.

In our studies we have noted this "glowing" effect for a few of the chrysotile specimens. The flesh-pink massive form of chrysotile, F–20A, associated with the fibrous form F–20 from Arizona, is particularly pyrognomic and glows at temperatures considerably below a dull-red heat. It is admixed with calcite and the effect may be totally unrelated to the clinochrysotile (see DTA curve C–817, fig. 30).

We plan to investigate the pyrognomic behavior of the serpentines to see if there is any relationship to the exothermic phenomena in the range of 200° to 400°C of these chrysotiles and lizardites. The maximum peak temperature ranges from 264° to 394°C.

DETAILED ANALYSIS OF THE CURVES IN THE TEMPERATURE RANGE 600° TO 750°C

The major thermal effect in the DTA study of chrysotile and lizardite takes place in the temperature range 600° to 750°C and is expressed as an endothermic trough. At the temperature of the beginning of the trough, the phase present is chrysotile or lizardite. As soon as the chrysotile or lizardite starts to decompose and lose water, a mixture of the dissociated material and chrysotile or lizardite is present and the amounts of chrysotile or lizardite decreases as the temperature rises until the temperature of the end of the trough is reached when no more chrysotile or lizardite remains.

The endothermic trough is thus the record of the heat effect accompanying the destruction of the crystal structure and its area is proportional to the weight of the chrysotile or lizardite which is dissociated.

The values of the temperature for the minimum of this trough for each sample are given in table 18. As these minima represent temperatures of an irreversible reaction, no significance can be placed on the absolute values. It is desirable, however, to determine whether or not a correlation of those factors, such as grain size, or habit, which normally influence the temperature of

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irreversible reactions can be made. The data were divided into three groups: (a) the fine-grained specimens which include the translucent varieties called retinalite, schweizerite, and deweylite; (b) the characteristic fibers of chrysotile as "chrysotile" was originally used by von Kobell (1834); and (c) the more coarsely fibrous variety, sometimes called picrolite. The DTA curves for 23 fine-grained specimens have temperatures for the minimum in the range 637° to 714°C, with an average value of 688°C, the curves for 4 samples of fibrous chrysotile in the range 705° to 712°C, with an average value of 708°C, and the curves for 3 so-called "picrolites" in the range 700° to 715°C, with an average value of 708°C. These data suggest that the particles of finer grain size tend to dissociate at somewhat lower temperatures than the coarser material. The synthetic clinochrysotile, having an exceedingly fine grain size bears out this suggestion, for the temperature of its minimum is at 670°C.

There is no apparent correlation between the mineralogic composition and temperature of the minimum of the trough in the DTA curves for these samples. The values for the range in the temperature of the minimum for the subgroups is as follows: (A) clinochrysotile, 670° to 715°C; (B) clinochrysotile (Globe-type), 679° to 712°C; (C) clinochrysotile plus orthochrysotile, 687° to 708°C; (D) chrysotile plus lizardite, C>L, 671° to 698°C; (E) lizardite plus clinochrysotile, L>C, 637° to 687°C; and (F) lizardite, 681° to 714°C.

Angular relationships of the high-temperature endothermic trough of the DTA curves of related minerals of the kaolin group—kaolinite, endellite, and halloysite—were studied by Dean (1947) and more extensively by Bramão, Cady, Hendricks, and Swerdlow (1952). The angles α and β are defined according to the procedure of Dean as shown in figure 38, where the two sides of the angles determined by the DTA curve are formed by the extension of the straight portions of the trough. For most of the DTA curves the whole angle γ was measured. The data are given in table 16.

The whole angle γ of the various subgroups ranges as follows: (A) clinochrysotile 10.5° to 33.5°; (B) clinochrysotile (Globe type) 7.5° to 40°; (C) clinochrysotile plus orthochrysotile 17° to 24°; (D) chrysotile plus lizardite, C>L, 13° to 31°; (E) lizardite plus clinochrysotile, L>C, 21° to 58°; (F) lizardite, 9° to 13°. Midgley's (1951) type lizardite has an estimated angle γ of 21°. Admittedly, all these mineralogical subgroups have values of γ which overlap, so that a measure of γ itself is not diagnostic of its subgroup mineralogic composition. The appearance of an inflection on the DTA curves of some samples containing lizardite is noteworthy. The shoulder appears on the DTA curves of specimen F–57 of subgroup D, specimen

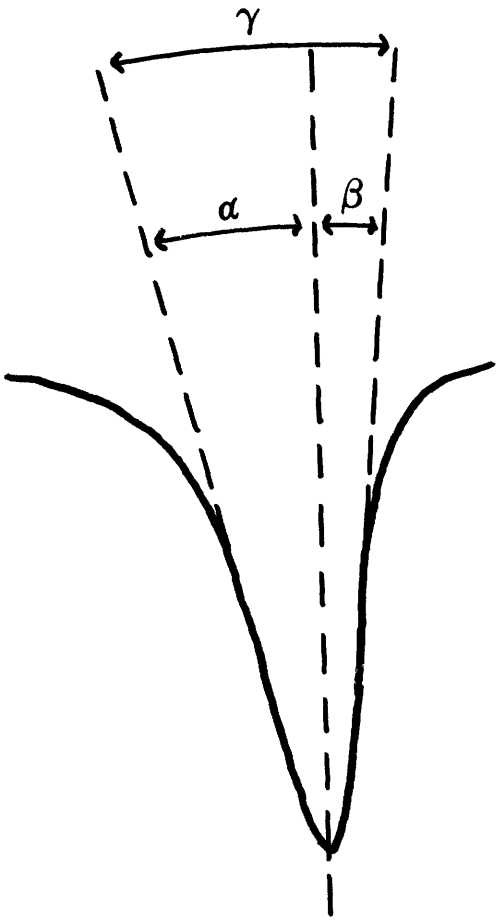


FIGURE 38.—Schematic diagram showing the method of designating the angular relationships in an endothermic trough. Modified from Dean (1952).

F–75 of subgroup E, and on the DTA curves of specimens F–46 and F–47 of subgroup F. It also appears on the DTA curve of the type lizardite (fig. 39) given by Midgley (1951). The whole angle γ is always greater for the inflection than for the "normal" part of the endotherm. Data for curve C–850 are not included, because the results were obtained on an acid-treated specimen. Likewise, the data for curve C–488 are omitted because this curve was obtained with a greater amount of resistance in the galvanometer cicuit and is therefore not comparable with the other curves. It does, however, serve to emphasize the necessity for comparing curves obtained under similar experimental conditions.

The use of a relationship involving the angles α and β has also been advocated and a study was therefore made on a number of the specimens in this collection. From the measured angles α and β the ratio of the tangents of α and β was computed. The data in table 16 show that in curves for subgroup A, clinochrysotile, the value of this ratio ranges from 1.63 to 5.47; in a single curve in subgroup B, clinochrysotile (Globe-type) it

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TABLE 16.—*Angular relationships of the high temperature endothermic trough of the chrysotiles and lizardite*

Specimen	Curve	Angle γ (degrees)	$\frac{\tan \alpha}{\tan \beta}$	Specimen	Curve	Angle γ (degrees)	$\frac{\tan \alpha}{\tan \beta}$
A. Clinochrysotile							
F-54	C-488	[1] 49.5	2.86	F-50	C-470	16	5.47
F-54	C-489	[2] 30	3.46	F-58	C-655	23	2.11
F-52	C-501	32	2.68	F-70	C-746	33	2.81
F-22	C-122	10.5	1.63	F-60	C-680	32.5	1.99
F-40	C-91	17	1.85				
B. Clinochrysotile (Globe-type)							
F-20	C-84	28	----	F-41	C-133	29	----
F-20A	C-817	36	2.40	F-45	C-92	7.5	----
F-53	C-731	40	----	F-45	C-94	[3] 78	----
F-24	C-125	30	----	F-26	C-93	[3] 28	----
C. Clinochrysotile plus orthochrysotile							
F-56	C-650	18	----	F-74	C-805	17	2.43
F-64	C-728	24	----				
D. Chrysotile plus lizardite, C>L							
F-57	C-562	[4] 45	4.59	F-72	C-803	25	2.65
		27	2.40	F-25	C-115	13	----
F-51	C-478	31	----				
F-73	C-809	29.5	2.18				
E. Lizardite plus clinochrysotile, L>C							
F-71	C-804	22	1.32	F-76	C-850	58	1.00
F-75	C-849	[4] 29	3.29			[4] 44	2.07
		28	2.37	F-3	C-135	21	----
F. Lizardite							
F-46	C-104	[4] 23	----	F-23	C-117	13	----
		13	----	F-42	C-729	14	----
F-47	C-98	[4] 25	----	F-43	C-105	9	----
		10.5	----	Type lizardite	Estimated from Midgley	[4] 25	5.49
F-63	C-727	16.5	2.33			21	4.37
F-63	C-818	13	2.27				

[1] Resistance in galvanometer circuit was 999.9 ohms.
[2] Resistance in galvanometer circuit was 600 ohms.
[3] Measured on a curve containing clinochrysotile and stevensite.
[4] Inflection on endotherm.

was 2.40; similarly, a sample of subgroup C, clinochrysotile plus orthochrysotile yielded the value of 2.43; three curves of subgroup D, chrysotile plus lizardite with C>L, ranged from 2.18 to 2.65 with the value for the inflection on curve F–57 of 4.59; subgroup E, curves for lizardite plus clinochrysotile, L>C, yielded values of the ratio ranging from 1.00 to 2.37, with the value for the inflection on curve C–489 of 3.29; curves for subgroup F, lizardite, show ratios obtained on two different samples from the same specimen with values of the ratio of 2.27 and 2.33. Data derived from Midgley's (1951) DTA record give the ratio of 4.37 and the value for the inflection of 5.49.

The ratio $\tan \alpha/\tan \beta$ is an expression of the symmetry of the DTA endotherm. For the case $\alpha=\beta$, (curve C–850, fig. 35), the ratio is unity and the curve is symmetrical. As the angle α becomes progressively larger than the angle β, the ratio increases and the endotherm becomes asymmetrical, with respect to the normal to the baseline. Physically, this means that most of the chyrsotile or lizardite has dissociated before the temperature of the minimum has been reached.

The angular relationships of the endothermic trough are a function of a number of variables including mineralogic composition, particle shape, particle size, and experimental conditions. The data in table 16 do not yield any unambiguous correlation between the various angular relationships and mineralogic composition or estimated particle size. The consistently smaller value of the angle γ for the lizardites is suggestive, but there are overlaps with some of the chrysotiles.

DETAILED ANALYSIS OF THE CHRYSOTILE AND LIZARDITE CURVES IN THE TEMPERATURE RANGE 750° TO 1,000°C

After the chrysotile or lizardite has been dissociated, the trace of the DTA returns to the base line and continues monotonously as a straight line until an exothermic peak is observed. The exothermic peak corresponds to the heat effect accompanying the recrystallization of some of the dehydrated chrysotile (or lizardite) into a new phase assemblage. The area of this peak and its height do not seem to bear any simple relationship to the weight of the sample used in the experiment. Such discordant areal relationships are to be expected in rate processes such as a recrystallization into more stable phases.

Some of the curves also show additional minor peaks which may be sharp or gently rounded and which occur at lower or higher temperatures than that of the principal exothermic peak. The exothermic peaks are probably to be associated with the recrystallization of the dissociated materials. The gently rounded endothermic troughs may represent high-temperature phase transitions.

Chemical, microscope, X-ray and other studies of the products formed by the dissociation and recrystallization of serpentine were made by a number of workers. Haraldsen (1928) fired the serpentine from Snarum, probably dominant lizardite with some clinochrysotile, as judged by his X-ray data, for (*a*) a period of 24 hours at 500°C; (*b*) 24 hours at 700°C; (*c*) 24 hours at 800°C; (*d*) 24 hours at 1,000°C; (*e*) 5 hours at 1,200°C, and 5 hours at 1,300°C and studied the products. At 500°C the X-ray pattern is identical with that of the original serpentine, the lines are a bit more diffuse, and some of the weakest lines are not recognizable. At 600°C a single line, apparently belonging to the olivine pattern, is present with those of serpentine. At 700°C the pattern is clearly that of olivine; the lines are not as intense as those of natural olivine, but this probably is due to the small size and low concentration of olivine. The pattern at 800°C is still stronger and the number of lines has increased representing a growth in the amount of olivine.

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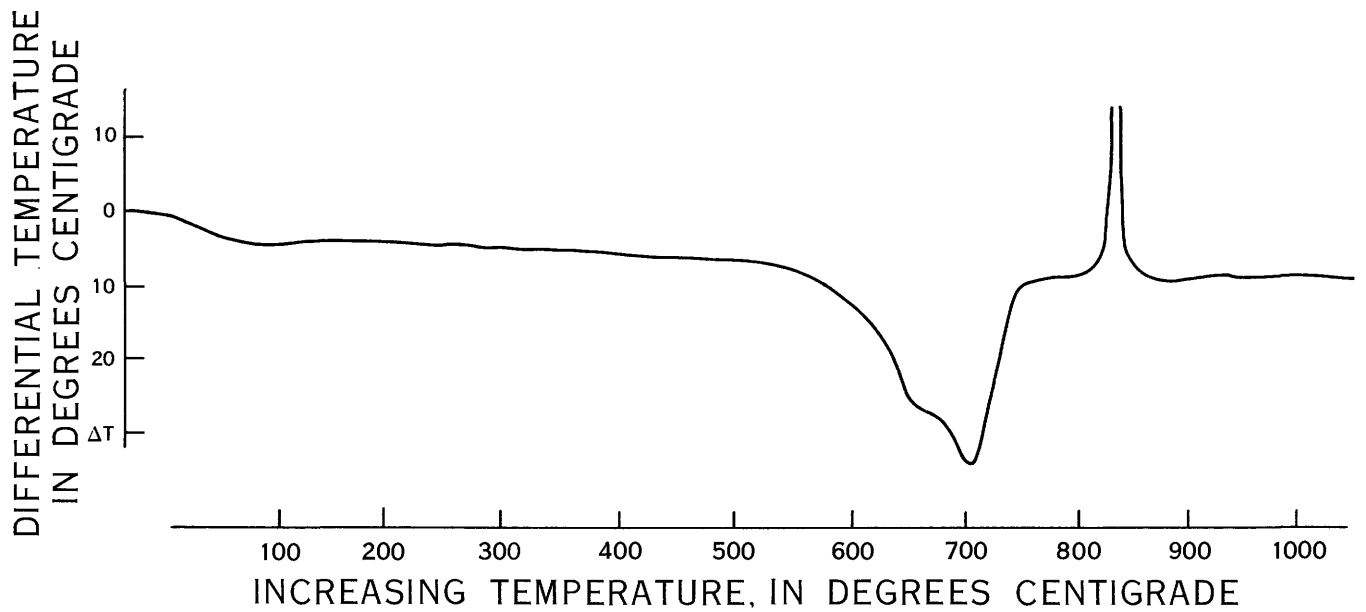


FIGURE 39.—Differential-thermal-analysis curve of the type lizardite from Cornwall, England. Enlarged by pantograph from the original drawing of Midgley (1951).

At 1,000°C the X-ray pattern shows from the sharpness, intensity, and abundance of lines, that the olivine crystals have grown, and in addition a line appears which is due to the presence of "enstatite." At 1,200°C the "enstatite" crystals, as judged from the X-ray pattern are still small in size and present in limited amounts. At 1,300°C the amount of "enstatite" has increased.

Treatment of the material, heated at 800°C and 1,200°C with sodium hydroxide solution, shows the presence of silica; treatment with hydrochloric acid removes the olivine and leaves the "enstatite."

Haraldsen concludes from his studies that the amount of amorphous silica decreases as the temperature is increased, because it is consumed in a reaction of olivine and silica to form "enstatite." The phase "enstatite" is placed in quotation marks here because an examination of Haraldsen's data in terms of the X-ray powder diffraction data for protoenstatite, clinoenstatite, and enstatite of Clark (1946) does not lead to a simple coincidence with enstatite, but suggests the presence of protoenstatite.

Hargreaves and Taylor (1946) found that a sample of chrysotile from Canada heated in excess of 750° ". . . showed an extreamly faint wide band in a position corresponding to the strongest line of the enstatite pattern. . . ." They did not find any evidence of low-temperature formation of enstatite.

Brindley and Zussman (1957) made a very detailed X-ray structural study of the transformation, upon heating, of serpentine into forsterite. They observed a transitional product which for two-layer serpentine shows a spacing at 14.5 A which is nearly constant; for one-layer serpentine the spacing diminishes from about 14 to 10 A. Six-layer serpentine behaved like two-layer serpentine.

The fired products obtained from the DTA studies had been prepared by heating the charges to a temperature of about 1,000°C in 80 minutes and then allowing the charge to cool in the furnace. The heating schedule used in the DTA studies is not the equivalent of the longer heat treatments used by Haraldsen (1928) and Hargreaves and Taylor (1946) and it is less likely that the reactions observed by Haraldsen will occur.

Thirty-five of the specimens on which DTA studies were made for this research were examined by X-ray powder diffraction methods. In all but specimen F-45 the olivine (forsterite) pattern was clearly developed. The patterns contain an abundance of lines and many of these lines are quite dark and somewhat broadened. Table 17 contains the data for these specimens. A collection of eight other serpentine specimens, not related to this study, on which DTA studies had been made were examined by X-ray powder methods and they also yielded similar patterns of olivine. All but one of the samples showed, in addition to the lines of the olivine pattern, two other lines in their powder pattern corresponding to two of the principal lines of a polymorph of enstatite. These lines appear on the pattern at 3.17± A and 2.87± A. On the basis of the relative intensities of these two lines in which $I_{2.87\pm A} > I_{3.12\pm A}$ it is suggested that this polymorph is clinoenstatite.

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TABLE 17.—*Phases identified by X-ray methods in the chrysotile and lizardite specimens heated to about 1,000°C in the DTA studies*

Specimen	Chief phase	Minor phase [1]	Intensity of two principal lines of enstatite pattern	Remarks
A. Clinochrysotile				
F-54	Olivine	Enstatite	Weak	Curve C-488.
F-54	do	do	do	Curve C-489.
F-52	do	do	Medium	
F-22	do	do	Very weak	
F-40	do	do	Strong	The two enstatite lines are sharp.
F-50	do	do	Medium weak	
F-58	do	do	Weak	Extra lines at 2.70, 2.20, 1.84, and 1.69 A.
F-70	do	do	Medium	
F-60	do	Absent(?)		A very faint line at 2.87± A suggests enstatite.
B. Clinochrysotile (Globe-type)				
F-20	Olivine	Absent(?)		Fiber pattern.
F-53	do	Enstatite	Very very weak	
F-24	do	do	Weak	Do.
F-41	do	do	Medium	Based on C-72. Extra lines at 4.15 A, strong; 2.11 A, medium.
F-45	do	do	Weak	Curve C-92.
F-45	Enstatite	Olivine(?)		Curve C-94.
F-26	Olivine	Enstatite	Medium	
C. Clinochrysotile plus orthochrysotile				
F-56	Olivine	Enstatite	Weak	
F-64	do	do	do	
F-74	do	do	Medium	Weak line at 2.10 A.
D. Chrysotile plus lizardite, C>L				
F-57	Olivine	Enstatite	Medium weak	
F-51	do	do	Very very weak	Enstatite line just visible.
F-73	do	do	Medium	Weak line at 2.70 and 2.10 A.
F-72	do	do	Weak	Do.
F-25	do	do	Very very weak	
E. Lizardite plus clinochrysotile, L>C				
F-71	Olivine	Enstatite	Medium	
F-75	do	do	Weak	
F-76	do	do	Medium weak	
F-3	do	do	do	
F. Lizardite				
F-46	Olivine	Enstatite	Medium	
F-47	do	do	Medium weak	
F-63	do	do	Weak	
F-63	do	do	do	
F-23	do	do	Medium weak	
F-42	do	do	Medium	
F-43	do	do	Very very weak	

[1] Enstatite has been used as the name of the phase having the composition $MgSiO_3$. Reasons for believing that the polymorph of $MgSiO_3$ formed in these fired charges is clinoenstatite are given in the discussion of the results in this table.

The phases olivine and clinoenstatite are those which should appear when serpentine is dissociated and recrystallized. These fired charges do not represent equilibrium conditions and this accounts for the relatively poor development of the clinoenstatite.

Sample F–45 is a mixture of clinochrysotile, stevensite, and a small amount of dolomite, and it appears to be converted into clinoenstatite as the chief phase.

The danger of concluding that enstatite or its polymorphs is not present in the fired products, such as F–20 and F–60, table 17, is clearly indicated by Haraldsen's examination of his sample of serpentine heated to 800°C. X-ray powder photographs, containing an abundance of lines, showed only olivine to be present. The treatment of the material with a solution of sodium hydroxide disclosed the presence of amorphous silica. The further treatment with hydrochloric acid removed the abundant olivine and left an insoluble residue. This residue gave an X-ray pattern which contained seven lines equivalent to "enstatite". A comparison of this partially complete pattern with that which he obtained from the residue heated to 1,200°C confirmed the existence of the "enstatite" phase in the charge heated to 800°C.

The possibility that the different polymorphs of chrysotile and lizardite might show a difference in their thermal behavior after the dissociation was investigated by comparing (1) the temperature of the peak of the exothermic reaction and (2) the difference in temperature $\Delta_{(EX-EN)}$ between the temperature of the exothermic peak and the endothermic trough as given in table 18. The average values of these data and their range are given in table 19. The data for the 31 specimens examined in this study, including Midgley's data on the type lizardite, do not show any systematic correlation of the data with the mineralogic composition.

Further study of the form of the DTA curve in the temperature range from the termination of the endothermic trough, at the close of the dissociation process, to the end of the DTA experiment was made, as had been suggested, to see if any correlation of form and mineralogy could be found. The following observations were made: (a) the offset of the base line before and after the high-temperature exotherm, and (b) the approximate distance from the termination of the endothermic trough to the onset of the exothermic peak. In making such observations it is necessary to bear in mind that (1) the phenomena being observed are nonequilibium in nature and (2) that possible instrumental errors may interfere with the recording. In general, the clinochrysotile curves show an offset of the baseline after the high-temperature exotherm of about 0.3 cm. The lizardites on the other hand appear to have no, or exceedingly small, offset. The observations on the various mixtures are, however, very inconsistent.

The approximate distance from the termination of the endothermic trough to the onset of the exothermic peak ranges from about 0.5 to about 2.5 centimeters in the curves for the clinochrysotiles, and from about 1.5 to about 2.7 centimeters in the curves for the lizardites. The range in the curves for the mixtures is again inconsistent. Although no clear-cut difference exists between

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TABLE 18.—*Summary and relations of the thermal data in the temperature range of 600° to 1,050°C of chrysotile and lizardite*

Specimen	Curve	Temperature of the minimum (EN° C)	Temperature of the maximum (EX° C)	Δ(EX-EN) (° C)	Remarks
A. Clinochrysotile					
F-54	C-489	670	805	135	
F-52	C-501	676	801	125	Minor (EN) at 790°.
F-22	C-122	692	820	128	Minor (EX) at 696°. Minor (EX) at 863°.
F-40	C-91	696	817	121	Minor (EN) precedes major (EX).
F-50	C-470	701	805	104	Minor (EN) precedes major (EX) at 788°.
F-58	C-655	710	807	97	
F-70	C-746	715	806	91	Doublet on (EN) at 706° and 721°. Minor (EN) precedes major (EX).
F-60	C-680	705	814	109	
B. Clinochrysotile (Globe-type)					
F-20	C-84	710	824	114	
F-53	C-731	712	795	83	Doublet on (EX) at 789° and 802°.
F-24	C-125	705	823	118	
F-41	C-133	681	815	134	
F-45	C-92	697	820	123	Minor (EN) at 851°.
C. Clinochrysotile plus orthochrysotile					
F-56	C-650	689	799	110	
F-64	C-728	687	816	129	Minor (EN) at 859°.
F-74	C-805	708	804	96	Major (EX) has an inflection above 804°.
D. Chrysotile plus lizardite, C>L					
F-57	C-562	692	798	106	Minor (EN) at 782°.
F-51	C-478	671	784	113	
F-73	C-809	690	803	113	
F-72	C-803	698	805	107	
F-25	C-115	698	825	127	Minor (EN) after major (EX).
E. Lizardite plus clinochrysotile, L>C					
F-71	C-804	687	811	124	
F-75	C-849	637	729	92	Minor (EN) at 715°.
F-3	C-135	671	816	145	Minor (EN) precedes major (EX).
F. Lizardite					
F-46	C-104	700	807	107	
F-47	C-98	702	812	110	
F-63	C-727	700	815	115	
F-63	C-818	707	824	117	
F-23	C-117	714	819	105	
F-42	C-729	681	800	119	Major (EX) is a doublet 800° and 803°.
F-43	C-105	687	824	137	Minor (EN) at 854°.
Type	Midgley (1951)	698	818	120	Estimated.

the form of the curve and the mineralogic composition for this portion of the DTA curve, such suggested differences combined with other observations might prove useful in identification.

The occurrence of minor endothermic troughs just before, or following, the high-temperature exotherm has been mentioned. The following were observed: The curves for three of the clinochrysotiles, group A, had small endothermic troughs preceding the major exotherm; those for three of the clinochrysotiles (Globe-type), group B, had endothermic troughs following the major exotherm; those for the mixtures of clinochrysotile and orthochrysotile, group C, contained only one curve with a small endothermic trough following the major exotherm; the curve for the chrysotiles plus lizardite, where C>L, group D, contained two DTA curves with endothermic troughs before the major exotherm, and one curve showed it following the major exotherm; the DTA curves of lizardite plus chrysotile, where L>C, group E, contained three curves which showed small endothermic troughs before the major exotherm; only one curve of the lizardite specimens, group F, showed a small endothermic effect and this followed the major exotherm. Some of the DTA curves showed a gentle slope upward from the base line and merging with the major exotherm. This was observed on one curve in group A, two in group C, two in group D, and three in group F. No real criterion for the differentiation of chrysotiles from lizardite is apparent in these observations, and this is in agreement with the common behavior of substances in nonequilibrium systems.

A TYPICAL ANTIGORITE CURVE

A typical antigorite is the green translucent gem material williamsite from the famous mineral locality at the State Line Pits, specimen F–1. This specimen is noteworthy because of its low content of ferrous and ferric iron oxides (table 2). The DTA curve is given in figure 40, as curve C–124. The curve is relatively simple. Over the temperature range 25° to 700°C the curve is essentially monotonic save for a slight bowing which has a maximum at 344°C. Owing to the low intensity of this bow it appears as a broad trough. Its closeness to the temperature at which nickel undergoes its magnetic transition at 353°C strongly suggests that this bow represents a subdued manifestation of the nickel transition. At approximately 675°C the antigorite begins to dissociate and the curve descends into a well-formed endothermic trough with the temperature of the minimum at 796°C. The curve then returns to the base line at about 830°C. Subsequently a minor endothermic trough appears with a minimum at 874°C. The significance of this trough is not known. Such

TABLE 19.—*Comparison of the high-temperature thermal data of the chrysotiles and lizardites*

Serpentine-group minerals	Temperature (°C) of the maximum (EX)		ΔEX-EN (°C)	
	Average	Range	Average	Range
A. Clinochrysotile	809	801–820	114	91–135
B. Clinochrysotile (Globe-type)	815	795–824	114	83–134
C. Clinochrysotile plus orthochrysotile	806	799–816	112	96–129
D. Chrysotile plus lizardite, C>L	803	784–825	113	106–127
E. Lizardite plus clinochrysotile, L>C	785	729–816	120	92–145
F. Lizardite	815	800–824	116	105–137

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high-temperature troughs are generally suggestive of a phase transformation of some type. After this minor endotherm the curve becomes straight.

THE COLLECTION OF ANTIGORITE CURVES

A collection of six chemically analyzed specimens of antigorite, or of samples made up chiefly of antigorite, were studied by DTA methods. In addition, a number of DTA curves of unanalyzed specimens of antigorite were examined to check the consistency of the data. The thermal-analysis data for the analyzed specimens of antigorite are given in table 20, and their DTA curves are shown in figure 40.

DETAILED ANALYSIS OF THE ANTIGORITE CURVES IN THE TEMPERATURE RANGE 25° TO 700°C

Four of the six curves of antigorite show a very slight downward bowing in the range of 85° to about 125°C. This bow arises from the loss of the absorbed water. Two of the DTA curves, C–121 (F–13) and C–116 (F–19), exhibited sufficient area under the curve, associated with the loss of adsorbed water, to be measured. Sample F–13 contains 0.93 percent H_2O-, and 0.4025 grams of this mineral yielded an area under the curve of 12.7 square millimeters. Sample F–19 contains 0.55 percent H_2O-, and 0.2285 grams of this sample yielded an area under the curve of 1.7 square millimeters. The reduction of the data, that is, the weight of the sample used in the DTA experiment and the analytically determined percentage of H_2O-, to an equivalent basis for specimens F–13 and F–19 shows that the area under curve for specimen F–13 should be about three times greater than that for specimen F–19. The considerable discrepancy, cited above, is to be attributed to the drying out of sample F–19 in the balance case previous to the DTA study.

The gentle upward bow which appeared in the DTA curves of chrysotile and lizardite in the temperature range of 300° to 400°C apparently does not occur in antigorite. One record of antigorite, C–124, specimen F–1, does in fact show a slight bow, but as has been pointed out previously this bow is probably to be attributed to the magnetic transition in nickel. The curve for specimen F–13, likewise shows an upward bow, and it is more pronounced than that shown by specimen F–1. As sample F–13 contains chrysotile the upward bow in the curve C–121 may be due in part to the nickel transition and in part arises from the chrysotile in the sample.

In the temperature range 25° to 700°C antigorite gives a DTA pattern which is nearly a straight line.

DETAILED ANALYSIS OF THE ANTIGORITE CURVES IN THE TEMPERATURE RANGE 700° TO 800°C

All the antigorites undergo the major decomposition in this temperature range. The shape of the endotherm varies from the simple trough in the curves for specimens F–1 (C–124) and F–14 (C–120) to the slightly inflected form of the curve for specimen F–8 (C–126), to the more highly inflected forms shown by the curves for specimens F–15 (C–64) and F–13 (C–121). The inflections on the low-temperature side of the endotherm may arise from (1) the presence of some chrysotile in the sample, (2) heterogeneity within the specimen itself, such as the presence of some iron-rich portions of serpentine within the specimen, or (3) nonequilibrium factors.

Actual resolution of this inflection to form two separate troughs is shown by the specimen F–19, curve C–116 (fig. 40). This specimen is the variety baltimorite and consists of both antigorite and chrysotile. Nagy and Faust (1956) reported the sample to contain about 50 percent of antigorite and 50 percent chrysotile on the basis of the Nagy and Bates (1952) solution test.

A study of the angular relationships of the principal endotherm was made to aid in the detection of possible admixtures with chrysotile (table 21). The conven-

TABLE 20.—*Observations of the differential-thermal-analysis curves of antigorite and samples composed chiefly of antigorite*

[These curves were all obtained with a resistance of 600 ohms in the galvanometer circuit. Principal endotherms marked (EN), principal exotherms marked (EX)]

Specimen	Curve	Temperature of thermal phenomena for indicated range						
		85°–200°C	200°–400°C	400°–700°C	700°–800°C	800°–900°C	900°–1000°C	1000°–1100°C
F–15	C–64				[1] 762	802 (EN)		1023
						872		
F–1	C–124		344		796 (EN)	874		
F–8	C–126	(2)			([1] [2])	828 (EX)		
					790 (EN)			
F–14	C–120	(2)			760 (EN)	829 (EX)		
F–13	C–121	(2)	(2)		739 (EN)	811 (EX)		1039 (EX)
F–19	C–116	(2)			733 (EN)	815 (EX)	939	
					763 (EN)			

[1] Inflection
[2] Present but not measured.

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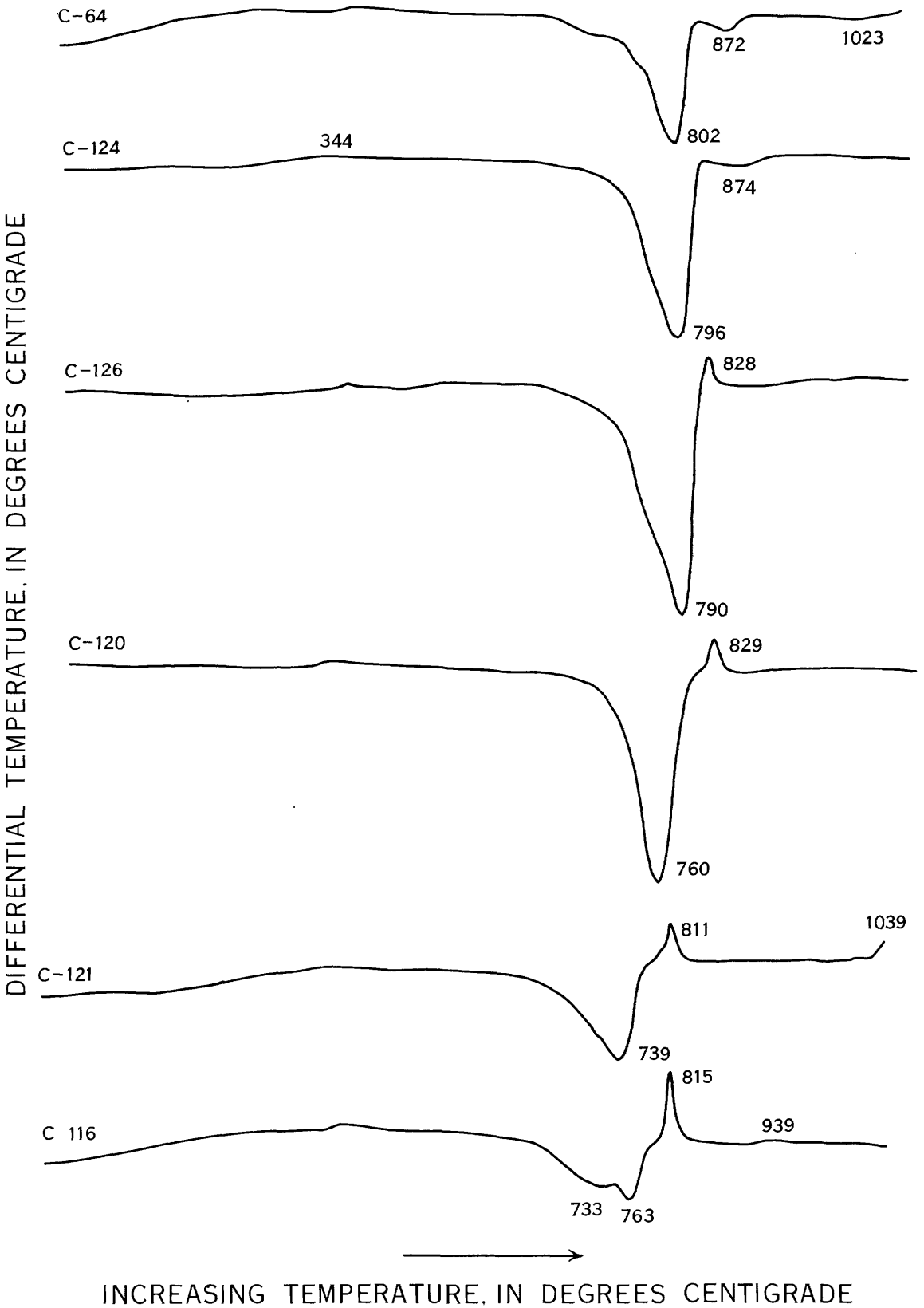


FIGURE 40.—Differential-thermal-analysis curves of antigorites. C-64, F-15, Val Antigorio, Italy; C-124, F-1, State Line Pits, Lancaster County Pa.; C-126, F-8, Smithfield, Providence County, R.I.; C-120, F-14, "Yu-Yen Stone," Manchuria; C-121, F-13, Tilly Foster iron mine, near Brewster Station, N.Y.; C-116, F-19, Bare Hills, Baltimore County, Md. All curves obtained with a resistance of 600 ohms in the galvanometer circuit.

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tions for measurement are the same as those used in describing the chrysotiles. The only observation that may be made is that concerning the low-temperature inflection on the principal endotherm, which has a larger angle γ and a higher value for the ratio of tan α/tan β. In curve C–116, for specimen F–19, where the inflection is resolved as two seperate troughs only the angle α could be measured for the endotherm at 733°C, but from this it is obvious that the angle γ will be larger for it than the angle γ for the endotherm at 763°C.

Curves for samples which are pure or practically pure specimens of antigorite—specimens F–15, F–1, and F–8 (table 20)—have a temperature for the minimum of the trough of 790° to 802°C; whereas those for specimens known to contain another phase, chrysotile, have lower temperatures for the minimum of 739° to 760°C. The curve for a mixture of approximately 50 percent antigorite and 50 percent chrysotile has minima at 733° and 763°C. These data suggest that curves for an admixture of chrysotile and antigorite may show a lower temperature for the minimum of the endothermic trough than that of a pure specimen of antigorite.

DETAILED ANALYSIS OF THE ANTIGORITE CURVES IN THE TEMPERATURE RANGE 800° TO 1,100°C

After the end of the dissociation there appears in the curves for some of the antigorites a small, rather round to bow-shaped endotherm of minor proportions. It is best developed in curve C–64. It is much smaller in curve C–124 and practically negligible in curves C–126, C–120, and C–116. Curve C–121 does not exhibit any trace of an endotherm following the main endotherm. Very commonly the area "under the curve" for these endotherms is small so that the identity of the phase or mechanism responsible for them may be difficult to determine.

The existence of such endotherms has generally been attributed to a possible phase transformation. They may also be due to the presence of compositional zoning or to the presence of a few larger particles amongst a fine matrix. More recently, studies of diffusion in heated phases undergoing dissociation in a nonequilibrium process have suggested that some swapping of sites by atoms or groups of atoms to form slightly more stable configurations or metastable phases might occur. Just what this mechanism may be has not been determined. The following suggest themselves: (1) The dissociation of a disordered (or defect) structure followed by annealing with the production of domains of less ordered (or defective) configuration. Diffusion of water vapor through this may permit the formation of the more stable form of the original phase. This will decompose at somewhat higher temperatures than the original phase. (2) The production of a new, less hydrous phase. Hedvall (1938) has indicated the ease of synthesizing phase in such assemblages, and Stubican (1959) has investigated relationships of this kind with ordered and disordered kaolinites and halloysites.

The DTA curve for the pure or nearly pure antigorites after the principal endotherm, save for the presence of a minor endotherm, is essentially a straight line.

The crystalline phases present in the specimens of antigorite after they have been heated to about 1,000°C in the DTA studies were indentified by X-ray diffraction techniques and the data are given in table 22. The chief phase is olivine and its powder pattern dominates the X-ray film. Minor amounts of enstatite constitute the second crystalline phase. Enstatite is most abundant in the pseudocubic serpentine from Brewster Station, N.Y. (F–13) and the baltimorite from Bare Hills, Md. (F–19).

EFFECT OF SOME ADMIXED MINERALS ON THE DTA PATTERNS OF SERPENTINE

In the general application of the DTA method to the study of serpentine-group minerals, it is necessary to consider the probable effects of any mineral with which they are admixed. Such mixtures may consist of the minerals they replaced, were replaced by, or which were introduced at a later stage in the paragenesis. Ad-

TABLE 21.—*Angular relationships of the principal endotherm of antigorite*

Specimen	Curve	Angle γ (degrees)	Angle α (degrees)	Angle β (degrees)	tan α / tan β
F–1	C–124	22	15½	6½	2.43
F–15	C–64	26	16½	9½	1.77
F–8 (Inflection)	C–126	19½	14	5½	2.59
		21½	16	5½	2.98
F–14	C–120	17½	10	7½	1.34
F–13 (Inflection)	C–121	44½	30½	14	2.36
		47	33	14	2.60
F–19 EN at 763°C	C–116	46	26½	19½	1.41
F–19 EN at 733°C			61		

TABLE 22.—*Phases identified by X-ray diffraction methods in specimens of antigorite heated to about 1,000°C in DTA studies.*

Specimen	Chief phase	Minor phase [1]	Intensity of two principal lines of enstatite pattern	Remarks
Antigorite				
F–15	Olivine	Enstatite	Medium	
F–1	do	do	Very very weak	
F–8	do	do	weak	
Antigorite plus chrysotile				
F–14	Olivine	absent (?)		
F–13	do	Enstatite	Strong	This specimen is richest in enstatite.
F–19	do	do	do	X-ray pattern almost the same as F–13, above.

[1] The presence of enstatite in all these samples is based on the presence of the two principal lines of enstatite with spacings at d=3.15 A and d=2.85 A. The intensity of the two lines is nearly the same but the line at d=2.85 A seems to be somewhat the stronger of the two.

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mixture of minerals which yield thermal effects in the range where the serpentine minerals are thermally active may modify the DTA patterns of serpentines to a notable extent. Some of the common associates of serpentine minerals which are capable of modifying the DTA curves are magnetite, chromite, talc, chlorite, pholgopite, stevensite, calcite, dolomite, magnesite, brucite, hydrous magnesium carbonates such as artinite and hydromagnesite, and the silica minerals opal and quartz.

Talc generally does not complicate the DTA record of serpentine group minerals because it usually shows an endothermic trough at 950° to about 1,050°C. Confusion may result, however, if serpentine specimens which exhibit a minor high-temperature endotherm are contaminated with talc. A DTA curve of a sample of what at one time was considered to be a hydrous talc (Foshag and Wherry, 1922) is shown in figure 41 as curve C–540. This specimen from the Atwater serpentine quarry of the Westfield Marble Company, Russell Mass., is seen to consist of talc, "chrysotile," and probably a very small amount of calcite. Fahey found about 0.1 percent of CO_2 in Foshag's tube sample indicating the presence of approximately 0.25 percent calcite.

The chlorites, when present as a major constituent with serpentine minerals in a DTA sample, can modify the curve to such an extent as to make it difficult to interpret. In fact DTA curves of some chlorites are remarkably similar to those of serpentine-group minerals. Fortunately, the chlorites associated with serpentines are easily detected by other means and they can be accounted for when they are present as admixtures in samples studied by DTA.

The magnesium-rich micas, phlogopite, and magnesian biotite are sometimes found with serpentines. A DTA pattern of a mixture of phlogopite with some serpentine, probably chrysotile, is shown in figure 41 as curve C–730. This specimen, F–68, is from the Verdolite quarry, Easton, Pa.

Stevensite, the magnesium end-member of the montmorillonite-group (Faust and Murata, 1953), is also an associate of the serpentine-group of minerals. Samples of serpentine minerals containing stevensite as an admixed impurity are given in figure 31 as curves C–94 and C–93. The rather large size of the low-temperature endotherm and the more complicated character of the curve in the range of the exothermic peak are caused by the presence of stevensite in the samples. The absence of stevensite in the DTA curve C–92 (fig. 31), prepared from part of the same specimen from which the material for curve C–94 was obtained, is apparent.

All the carbonates associated with serpentine produce large endothermic troughs, when they dissociate in thermal-analysis studies, that make their presence apparent. The hydrous carbonates have even more complicated patterns arising from the loss of water as well as carbon dioxide. Calcite when present as a major constituent produces a considerable endothermic trough; it appears in the normal temperature range at which calcite decomposes, between 850° to about 975°C, so that abundant calcite does not confuse the interpretation of the pattern. Such an admixture is represented by specimen F–20A, and is shown as curve C–817 in figure 30. Small amounts of calcite, less than 25 percent, may complicate the DTA records as is shown in the curve for N–6 (C–75, fig. 41). This specimen consists of a clinochrysotile (Globe-type) with some calcite. The calcite in this admixture has a temperature for the minimum of 809°C. This endothermic reaction is followed by an exothermic reaction. The DTA curve indicates that there is an overlapping of the two reactions and that these curves represent in part an algebraic addition of the two opposing reactions. Dolomite likewise, in large amounts, is usually easy to recognize and account for in the DTA curve of a mixture with serpentine. It does however complicate the DTA curve because the average temperatures of the minima of its two endotherms are about 790° and 948°C for pure material. Curve C–143 (fig. 41) illustrates the behavior of such a mixture. This curve was prepared from a specimen from the Ala-Mar deposit, Nye County, Nev. In smaller amounts dolomite may prove troublesome. A clinochrysotile (Globe-type), specimen F–41, from the Windous deposit, White Pine County, Nev., contains a small amount of dolomite (as observed under the microscope and verified by X-rays) and its DTA pattern (curve C–133, fig. 30) reveals a small trough at about 777°C and an inflection on the principal endotherm at 590°C.

DTA curves for magnesite generally show the minima on its endothermic trough in the temperature range of 650° to about 700°C. This mineral may be present in small amounts in some chrysotile specimens. Its presence is indicated by a separate small endothermic trough at a lower temperature than the principal endotherm of the curve of the chrysotile mineral or as an inflection on the low temperature side of the principal endotherm of the chrysotile curve. Brucite is always apparent in a DTA pattern of a serpentine because it produces an endotherm, usually somewhere near 450°C, that is sharp and well separated from any DTA manifestations of serpentines. Likewise the DTA patterns of hydromagnesite and artinite occur at temperatures well below the principal endotherm in curves of the serpentine minerals. Their DTA patterns are noteworthy for the abundance of endothermic troughs.

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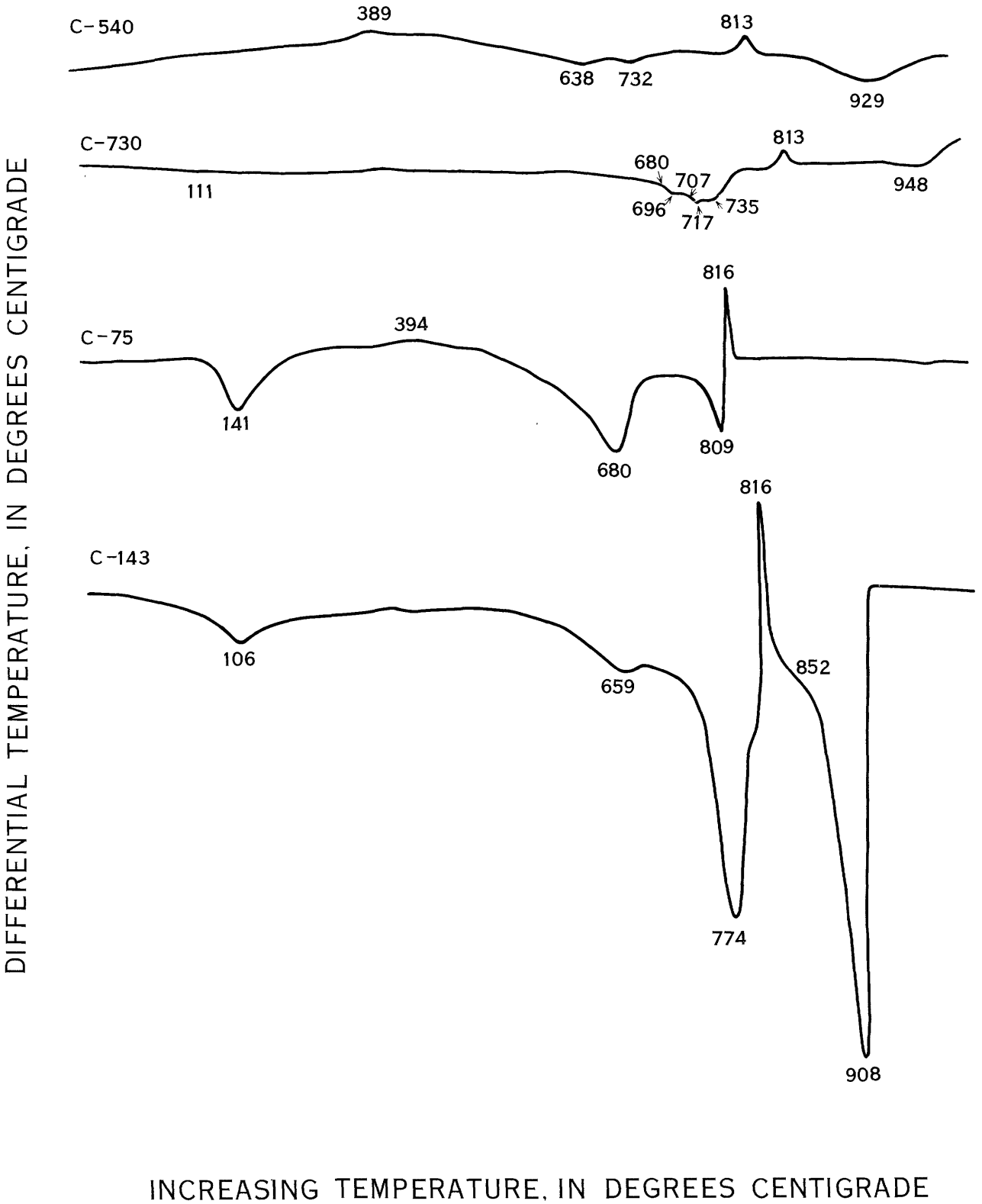


FIGURE 41.—Differential-thermal-analysis curves of serpentine-group minerals admixed with paragenetically associated minerals. C-540, hydrous talc, Atwater serpentine quarry of the Westfield Marble Co., Russell, Mass., a portion of the tube sample used by Foshag; C-730, F-68, serpentinized phlogopite, Verdolite quarry, Easton, Northampton County, Pa.; C-75, N-6, clinochrysotile plus calcite, vein filling, Nevada magnesite deposit, Currant Creek, White Pine County Nev., similar to F-41; C-143, A-1008, dolomite plus clinochrysotile, Ala-Mar deposit, Currant Creek, Nye County, Nev. All curves obtained with a resistance of 600 ohms in the galvanometer circuit.

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Quartz, if present in any quantity at all, is generally recognized by the characteristic trough it produces at 573°C. Opal very commonly does not affect the DTA pattern of serpentine. However, it is always necessary to remember that if the opal contains cristobalite it may produce an effect in the temperature range of 70° to 280°C.

The spinels magnetite and chromite, if they are present as an essential constituent in a sample of serpentine, will produce two broad exothermic peaks with maxima at about 350° and 850°C for magnetite and 450° and 900°C for chromite. The low-temperature exotherm is generally larger than that appearing at higher temperatures.

APPLICATION OF THE DTA STUDIES ON THE SERPENTINE-GROUP MINERALS TO PROBLEMS OF IDENTIFICATION

The DTA studies of the serpentine-group minerals show that it is possible to determine whether a given sample of serpentine consists of antigorite or the undifferentiable pair chrysotile and lizardite. This in itself is very valuable differentiation. A comparison of the curves of the chrysotiles and lizardite with those of antigorite shows that the former dissociate at a much lower temperature than do the antigorites. The curves for chrysotiles and lizardite have a temperature for the minimum of 637° to 715°C with an average temperature for 32 curves of 693°C. The curves for antigorites have a temperature for the minimum on the endotherm in the range of 790° to 802°C. In curves for mixtures of antigorite with other serpentine-group minerals, the temperature of the minimum drops to the range of 733° to 763°C. In addition to the considerable difference in the temperatures of the minimum of the principal endotherm, there is another characteristic of the curves for the chrysotile-lizardite pair which is noteworthy—that is, the appearance of an exothermic peak at 83° to 145°C above the temperature of the minimum. This exothermic peak does not appear, in these studies, on the DTA curves of pure samples of antigorite. It does, however, appear on curves for antigorite which contain some chrysotile or lizardite. On such curves the separation of the minimum of the principal endotherm from the maximum of the exotherm ranges from 38° to 72°C. This value is notably lower than that in curves for the chrysotile-lizardite specimens. The data further indicate that a gentle or pronounced bowing in the temperature range of 200° to 400°C is caused by the presence of chrysotile or lizardite or both in a sample.

The application of DTA methods in a regional mineralogical study of an area containing considerable serpentine-group minerals may reveal that it is even possible to detect or infer the presence of mixtures of chrysotile and lizardite. Such a relationship would have to be established first by other techniques before it could be used.

X-RAY STUDIES

X-RAY CLASSIFICATION OF THE SERPENTINE-GROUP MINERALS

Selfridge (1936) examined a suite of about 100 serpentine-group minerals by the X-ray powder diffraction method and found that he could classify the powder patterns into two groups as follows:

> The first, here considered to belong to the mineral serpentine consists of varieties whose interplanar spacing is similar to that of chrysotile . . . The name chrysotile, however, is reserved for serpentine that occurs in veins and consists of flexible fibers . . . The second, here considered to belong to the mineral antigorite, includes varieties structurally similar to antigorite from the Antigorio valley, Piedmont, Italy.

Gruner (1937) confirmed the work of Selfridge and he attempted to index the lines in his powder patterns. As a result of his study he was lead to suspect that the crystal structure determinations of Warren and Bragg were incorrect, a conclusion later shown to be true.

Whittaker and Zussman (1956) restudied the powder patterns of the serpentine-group minerals using the excellent structural studies of Whittaker (1951, 1952, 1953, 1954, 1955a, b, c) as a basis for indexing. Their work constitutes a valuable contribution to the study of the serpentine-group minerals. They classify the serpentine group of minerals as follows:

Serpentine	Chrysotile	Orthochrysotile
		Clinochrysotile
		Parachrysotile
	Lizardite	
	Antigorite	

X-RAY POWDER DIFFRACTION STUDIES

X-ray powder diffraction patterns were made on our specimens, using rolled spindles. For a few specimens, coated rods were also used. The most satisfactory patterns were obtained with copper radiation and a nickel filter although for a few specimens iron radiation and a manganese filter were more useful.

The results of our study are given in table 23. The criteria used for the identification were those of Whittaker and Zussman (1956).

We have followed the classification, given above, in this paper. Early in our studies we recognized the presence of additional lines in some of our powder patterns and it was concluded that they represented either polymorphism in the serpentine composition or, for some of the lines, an orientation effect due to the fibrous character of the chrysotile specimens. The work of Whittaker and Zussman (1956) has supplied us with the answer.

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TABLE 23.—*Classification of the serpentine specimens studied by X-ray powder diffraction methods*

Specimen	Locality	Remarks
	A. Clinochrysotile	
F-54	Synthetic mineral prepared by Bowen and Tuttle (1949).	Taken as representative pattern $I_{202}>I_{201}$.
F-52	Sylmar, Chester County, Pa.	Deweylite, stevensite(?).
F-22	Turkey Mountain, near Montville, Morris County, N.J.	
F-40	Prairie Creek area of peridotite, south-southeast of Murfreesboro, Pike County, Ark.	Deweylite.
F-50	Chrome mine near Moa, Oriente Province, Cuba.	Deweylite, stevensite(?).
F-58	Canyon of Clear Creek, New Idria quadrangle, San Benito County, Calif.	
F-70	Near Thetford, Megantic County, Quebec, Canada.	
F-60	do	
F-61	do	Partly decomposed by treatment with 1 *N* HCl.
	B. Clinochrysotile (Globe-type)	
F-20	Asbestos deposits, Gila County, Ariz.	
F-20A	do	Contains much calcite.
F-53	do	
F-24	Turkey Mountain, near Montville, Morris County, N.J.	
F-41	Windous deposit, Currant Creek magnesite deposits. White Pine County, Nev.	Deweylite.
F-45	Wood's chrome mine, Lancaster County, Pa.	Deweylite. A study of three X-ray powder patterns shows clinochrysotile plus some stevensite. A fourth pattern shows, in addition, dolomite.
F-26	Texas, Lancaster County, Pa	Deweylite. Contains much stevensite.
	C. Clinochrysotile plus orthochrysotile	
F-56	Fifth level, at the shaft, Gouverneur Talc Co., Balmat Corners, St. Lawrence County, N.Y.	
F-64	Turkey Mountain, near Montville, Morris County, N.J.	
F-74	New Almaden mine, Santa Clara County, Calif.	
	D. Chrysotile plus lizardite, C>L	
F-57	International Talc mine, Talcville, St. Lawrence County, N.Y.	
F-51	Nicaro, Oriente Province, Cuba	
F-73	New Almaden mine, Santa Clara County, Calif.	
F-25	Turkey Mountain, near Montville, Morris County, N.J.	
	E. Lizardite plus clinochrysotile, L>C	
F-71	Snarum, Modum Canton, Parish of Buskerud, Norway.	
F-75	Campus of the Stevens Institute of Technology, Castle Point, Hoboken, Hudson County, N.J.	
F-76	do	
F-3	Near Forest Hill, Harford County, Md.	Deweylite.
	F. Lizardite	
F-46	Near Bellows Falls, Windham County, Vt.	
F-47	Tyrol, Austria	
F-63	Staten Island, Richmond County, N.Y.	
F-23	Dognacska, 10 km west from Reschitza, Severin Province, Hungary.	
F-42	Near Norris, Union County, Tenn.	
F-43	Mineral Hill, Delaware County, Pa.	Deweylite.

TABLE 23.—*Classification of the serpentine specimens studied by X-ray powder diffraction methods*—Continued

Specimen	Locality	Remarks
	G. Antigorite	
F-15	North of Domodossola in Val Antigorio, Novara Province, Piedmont region, Italy.	
F-1	State Line Pits, Lancaster County, Pa.	Williamsite.
F-8	Smithfield, Providence County, R.I.	
F-14	Pei-wa-kou, Hsiu-yen Hsien, Liaoning Province, Manchuria.	
F-13	Tilly Foster iron mine, near Brewster Station, Putnam County, N.Y.	
F-19	Bare Hills, Baltimore County, Md.	Baltimorite.
	H. Stevensite plus chrysotile S>C	
F-48	Mine Creek, Bakersville, Mitchell County, N.C.	Deweylite.

The clinochrysotile patterns are divided into two groups: clinochrysotile and clinochrysotile (Globe-type). These patterns differ slightly but significantly enough to separate them. The chief differences are as follows:

1. In a pattern of clinochrysotile such as that of the synthetic material, F–54, there is a strong line at about 2.456A and a band extending from it to about 2.594A. The band is medium weak in intensity.
2. In a pattern of clinochrysotile (Globe-type) such as F–20, there are two lines of medium intensity at about 2.456A and 2.604A. In between these lines there is a band of medium weak intensity.

A survey of the intensities of the 20*l* reflections other than the 201 at 2.604A and the 202 at 2.456A did not disclose any real differences in these patterns. A line in the "Globe-type" at 2.500A also appears to be absent. From the work of Whittaker and Zussman (1956) it seems that these differences might arise from the presence of a small amount of orthochrysotile in the "Globe-type" specimens.

STATUS OF DEWEYLITE

Ebenezer Emmons (1826) first described deweylite as follows: "Colour white, yellowish and greenish white. Translucent. Lustre vitreous, inclining to resinous, faint . . . Surface rough and sometimes drusy, exhibiting small mammillary concretions."

Thomas Nuttall (1822) had previously described the variety of serpentine occurring at Hoboken, N.J., which he called marmolite. This is a thin foliated variety and the folia are thin and separable. The usage was extended to specimens in which the laminae are not sepa-

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rable. Dana (1850, p. 255) notes that this variety has been misnamed kerolite by some mineralogists.

These two varietal names have been used over the years to include many similar materials until confusion over what is truly deweylite has now arisen. A number of specimens of so-called deweylite which we have seen in various collections and some of which we have studied do not fit the description of Emmons.

Specimens F–3, F–40, F–41, F–26, F–48, and F–43 were labeled deweylite. All these except F–43 fall on the line connecting the calculated formulas for serpentine and stevensite (fig. 19); F–43 falls within the rectangle of the serpentines. Specimen F–45, for which there is no analysis, is also a mixture of serpentine and stevensite. The evidence obtained by the DTA, X-ray, and chemical studies is given in table 24.

The data contained in table 24 show clearly that deweylite is not a mineral species but is actually a fine-grained mixture of a serpentine-group mineral, usually clinochrysotile, but occasionally lizardite, and the mineral stevensite. There is no justification for keeping the name deweylite except as a field term. Two other unanalyzed samples called deweylite give DTA patterns which suggest that they contain stevensite; they are F–52 (curve C–501, fig. 28) and F–50 (curve C–470, fig. 29).

The chemical analyses taken from the literature also support this conclusion. There is a very good distribution of analyses astride and close to the line connecting theoretical serpentine and theoretical stevensite (fig. 21). Not all the analyses falling in this area are necessarily mixtures with stevensite; some are mixtures with other minerals such as the residual cores of the pyroxenes diopside and enstatite, and the amphiboles tremolite and hornblende. Such mixtures will, however, be close to the serpentine rectangle.

It is quite easy to detect stevensite if it is present by the use of DTA and X-ray techniques. Mixtures of stevensite and clinochrysotile are completely decomposed by hydrochloric acid.

GEOCHEMICAL STUDIES

The results of the studies by Faust, Murata, and Fahey (1956) on the minor elements in serpentines of different origins have a distinct bearing on the theory of the origin of ultrabasic rocks. This subject is being briskly controverted again by those who advocate the genesis of ultrabasic rocks from sedimentary rocks. It

TABLE 24.—*Chemical, differential-thermal-analysis, and X-ray data on some minerals called deweylite*

Specimen	Calculated formula based on the chemical analysis	Phases identified by—	
		DTA	X-ray
Theoretical serpentine.	$[Mg_6][Si_4]O_{10}(OH)_8$		
F–43	$[Mg_{5.74}Fe^{2+}_{.01}Fe^{3+}_{.10}Al_{.03}][Si_{4.02}]O_{10}(OH)_7$ $\Sigma=5.88$ oct $\Sigma=4.02$ tet	C–105. "Chrysotile-like" pattern	Lizardite.
F–3	$[Mg_{5.53}Fe^{2+}_{.02}Fe^{3+}_{.07}Al_{.12}Ni_{.01}][Si_{4.09}]O_{10}(OH)_8$ $\Sigma=5.75$ oct $\Sigma=4.09$ tet	C–135. "Chrysotile-like" and probably some stevensite. Note montmorillonite-group-type low-temperature endotherm.	Lizardite and clinochrysotile L>C.
F–40	$[Mg_{5.45}Fe^{2+}_{.05}Fe^{3+}_{.09}Al_{.03}Ti_{.01}][Si_{4.15}]O_{10}(OH)_8$ $\Sigma=5.63$ oct $\Sigma=4.15$ tet	Curve C–91. Chrysotile plus a low-temperature endotherm at 121 suggestive of stevensite.	Clinochrysotile.
F–41 [1]	$[Mg_{5.54}Fe^{3+}_{.01}Al_{.01}][Si_{4.22}]O_{10}(OH)_8$ $\Sigma=5.56$ oct $\Sigma=4.22$ tet	Curve C–133. Chrysotile with probably some stevensite.	Clinochrysotile (Globe-type).
F–26	$[Mg_{5.06}Al_{.02}Mn_{.01}Na_{.01}][Si_{4.45}]O_{10}(OH)_8$ $\Sigma=5.10$ oct $\Sigma=4.45$ tet	Curve C–93. Stevensite and chrysotile.	Clinochrysotile (Globe-type).
F–48	$[Mg_{4.33}Fe^{2+}_{.45}Ca_{.02}][Si_{4.60}]O_{10}(OH)_8$ $\Sigma=4.80$ oct $\Sigma=4.60$ tet	C–546. Stevensite with chrysotile	Stevensite and clinochrysotile.
F–45	No analysis	C–94. Stevensite and chrysotile	Clinochrysotile and stevensite.
		C–92. Chrysotile and small amount of stevensite.	
Stevensite (calculated as serpentine).	$[Mg_{3.82}][Si_{5.09}]O_{10}(OH)_8$		

[1] See also the static dehydration curve (fig. 26) for sample F-41a which was made on very similar material.

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is desirable therefore to (a) review briefly some of the data on the geochemical distribution of the minor elements related to this study, (b) to present our data, (c) to review briefly the theories that have been proposed on the processes that generate ultrabasic rocks from sediments, and (d) to draw some conclusions from our studies.

DISTRIBUTION OF MINOR ELEMENTS IN MAGNESIUM-RICH MINERALS AND ROCKS AND IN SOME CONTRASTED ROCK TYPES

To provide background for our studies it is desirable to review the work of others on the distribution of minor elements in magnesium-rich rocks and minerals. This subject has attracted the attention of geochemists for a long time. Goldschmidt and Peters (1931), using spectrographic methods, noted that scandium is usually present in the olivines and pyroxenes of ultrabasic rocks. Robinson, Edgington, and Byers (1935) studied the infertile soils from the serpentine barrens of the United States, Cuba, and Puerto Rico and found that they contain a comparatively high percentage of chromium and nickel. The Cr_2O_3 content ranges from 0.03 to 5.23 percent, and the NiO content ranges from a trace to 0.45 percent. Only one of the soil samples was tested for cobalt, which was found to be present.

Grimmet (1938–39) showed that ultrabasic rocks were much richer than limestones in cobalt, finding 67 to 115 ppm cobalt in the former and 0.2 to 5.1 ppm cobalt in the latter. Rigg (1942) obtained similar values, namely, 83 ppm cobalt in serpentine rich rocks and 0.2 to 12.5 ppm for limestones. Sedletskii and Ivanov (1941) studied the distribution of copper in the main soil types of Russia and found that an olivine basalt having 0.0092 percent copper weathered to a copper-enriched product having 0.0110 percent copper.

Wells (1943) described the relative abundance of nickel in the earth's crust and stressed its relation to the ultrabasic rocks. Sahama (1945) determined the boron content of ultrabasic rocks from Finland. Pieruccini (1946a, b) measured spectrographically the concentration of nickel and chromium in the ophiolite formations of Italy. He reported for 24 serpentines and amphibolites that the Cr_2O_3 content ranged from 0.0000 to 1.63¼ percent; NiO ranged from 0.00278 to 0.403 percent; and CuO ranged from 0.000024 to 0.00716 percent (one sample gave 0.0141 percent). Pieruccini concluded from his studies that the CuO in the ophiolite was too small to account for the copper deposits in the ophiolites.

Lundegårdh (1945a, b, 1949) studied the occurrence of chromium, cobalt, nickel, and zinc in 253 samples of Swedish minerals, rocks, and soils and noted that in the early differentiates produced by fractional crystallization of a basic magma the sequence is Cr>Ni >Co, and that in the late differentiates the order is Co>Ni>Cr. In the Swedish argillaceous sediments and their metamorphosed phases the order is Zn>Ni >Co>Cr. Fenoglio (1948, 1949–50, 1950, 1952) in a series of papers described his trace-element studies on the peridotites and serpentines of the Alps of Piedmont, Italy, which occur in Mesozoic calcareous schists, and the ophiolites of the region of Monte Rosa-Monte Viso. The peridotites contain from 0.04 to 0.22 percent NiO. The serpentines of San Vittore (Balangero) contain 0.24 percent NiO; the Bec Barmasse (Champorocher) serpentines contain 0.19 percent NiO. Fenoglio notes an enrichment of nickel in the hydrous magnesium silicates. Sundius (1949) likewise noted an enrichment of nickel in the hydrous magnesium silicates and found that a sample consisting chiefly of serpentine contained 0.23 percent NiO and 0.26 percent Cr_2O_3. Minguzzi (1953) studied the inorganic composition of plants grown on the ophiolites of Impruneta, Italy, and concluded that the infertility of the serpentine soil is due to the presence of nickel, chromium, and cobalt. Young, Benfield, and Strachan (1954) found that 10 samples of kimberlites from the Premier diamond mine, Transvaal, contained 0.003 to 0.008 percent cobalt and 0.09 to 0.15 percent nickel.

Du Rietz (1956) studied the occurrence of nickel in Swedish ultrabasic rocks, both in fresh and serpentinized rocks. He found that the weathering of these rocks had been so slight that no secondary enrichment of the nickel was observed at or near the surface. Earley (1958) noted an increase in the chlorine content of serpentinized dunite over that of dunite in the Precambrian dunites from Ontario, Canada, "the amount ranging from a few thousandths of a percent to several tenths of a percent." Hahn-Weinheimer (1959) studied the abundance of the minor elements in the lens-shaped masses of serpentine and eclogite within the Münchberger Gneismasse and in the border zone of this mass. For the elements chromium, nickel, cobalt, manganese, scandium, vanadium, titanium, barium, strontium, and zirconium, she noted that the variation is greater within the serpentinites of the border zone than for the centrally located serpentinites.

All these scientists agree that the rocks of the ultrabasic suite and their hydrothermally altered forms rich in serpentine contain an unusually high concentration of nickel, chromium, cobalt, and scandium. Moreover, some of them have observed that the carbonate-rich rocks, in contrast, contain very small to practically negligible concentrations of these elements.

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Goldschmidt's (1954) statement on this problem is particularly cogent.

> In calcareous marine sediments the amounts of nickel and cobalt are always exceedingly small, a few parts per million or less, and the same is true for dolomite rocks. Special attention has been paid by the author and his colleagues to the problem of whether nickel is associated with magnesium not only in magmatic rocks, but also in the processes leading to the formation of dolomite. The question can in general be answered in the negative. In nearly all dolomites the amount of nickel is of the order of a very few ppm—that is, distinctly less than 0.01 percent of the magnesium. This is also true for nickel in hydrothermal dolomites, and ankerites and siderites from hydrothermal veins. In such veins nickel usually concentrates in the sulphides and arsenides.

MINOR ELEMENTS PRESENT IN THE SERPENTINE MINERALS STUDIED

Faust, Murata, and Fahey (1956) showed the relation of the minor-element content of serpentine minerals to their geological origin. The data for these and additional samples and a graphical plot of the data for eight of the elements are presented here as table 25 and figure 42, respectively. The data on these samples are given in table 26. Fuller details on the description, mineralogic composition and geologic occurrence are to be found in the section on "Description of the minerals" and elsewhere in the text.

Data are given for 20 elements for many of the samples. Consideration of the ionic radii suggests that of these elements the following enter octahedral sites in the serpentine structure: Nickel, chromium, cobalt, scandium, copper, manganese, titanium, zirconium, aluminum (in part), zinc, gallium, and vanadium. Some of the aluminum, the boron, germanium, arsenic, and beryllium may be located in the tetrahedrally co-ordinated sites. The enigmas, the alkali sodium and the alkaline earths calcium and barium, are probably entrapped or absorbed.

A study of the data on the minor elements shows that the serpentine minerals derived from ultrabasic rocks through deuteric or subsequent hydrothermal replacement (class A) are notably richer in minor elements than those derived from various types of metamorphic limestones and dolomites, from contact metamorphic deposits, and from hydrothermal replacements and hydrothermal veins contained in the aforementioned types (class B), and that the serpentines of class A are characterized by a distinctive suite of minor elements (namely, nickel, chromium, cobalt, and scandium) present almost always in geochemically significant amounts.

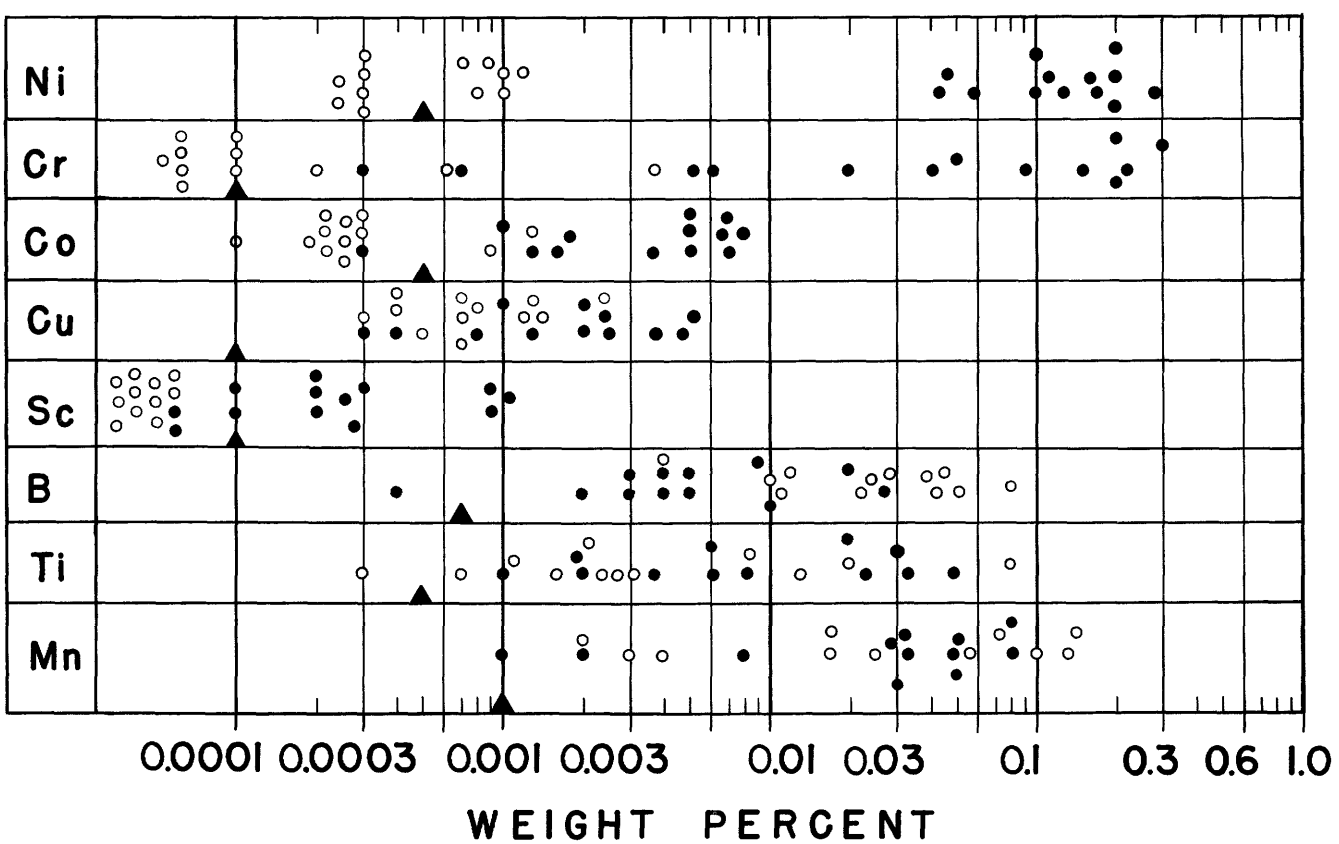


FIGURE 42.—Graphical representation of the concentration of some minor elements in the serpentine-group minerals. Triangular index represents sensitivity limit for the element. Points to the left of the index are samples in which the element was not detected. Dots represent serpentines associated with ultrabasic rocks. Circles represent serpentines from other rock associations.

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TABLE 25.—*Minor elements in serpentines*

[Most of these spectrographic analyses were made by K. J. Murata, and a graph of his data is given in Faust, Murata, and Fahey (1956). Harry Bastron and Harry J. Rose supplied additional spectrographic data. Data are given in weight percent for the elements. 0 = looked for but not found; -- = not looked for. Also looked for but not found: Ag, Cu, Cd, In, Tl, Sn, Pb, Bi, Te, Pt, Mo, W, Nb, Y, Sb, La, Li, and P]

	Ni	Cr	Co	Sc	Cu	B	Mn	Ti	Zr	Al	Ca	Ba	Zn	Ge	Ga	As	V	Na	Be	Hg
Class A																				
[Geological occurrence: formed in ultrabasic rocks]																				
F-40	0.043	0.020	0	0	0.0024	0.003	0.049	0.049	0.006	0.40	0.03	0.007	0	0	0	0	0.014	0	0	0.00005
F-74	.1	.2	.005	.0001	.001	.009	.03	.006	------	------	------	<.0009	------	------	------	------	------	------	------	------
F-51	.2	.05	.008	.0003	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------
F-72	.2	.2	.005	.0014	.002	.01	.08	.03	------	------	------	<.0009	------	------	------	------	------	------	------	------
F-73	.2	.3	.006	.0017	.002	.02	.05	.02	------	------	------	<.0009	------	------	------	------	.004	------	------	------
F-3	.046	.0052	.0018	0	.0003	.004	.008	.0082	0	.76	.02	0	0	0	0	0	0		0	------
F-42	.10	.15	.0037	.0002	.0038	.027	.033	.033	0	.65	.08	.001	0	0	.001	0	.004	0	0	.00005
F-43	.059	.0062	.0016	.0001	.0004	.002	.002	.0018	0	.027	.03	0	0	0	0	0	0	0	.0002	------
F-46	.16	.0007	.0067	.0009	.0025	.005	.030	.0019	0	.29	.01	.007	0	0	0	0	0	.05	0	.0001
F-47	.17	.0003	.0070	.0009	.0008	.005	.032	.0011	0	.17	.01	.001	0	0	0	0	0	.06	0	------
F-1	.28	.041	.0013	.0002	.0013	.003	.001	.0037	0	.59	.01	.001	0	0	0	0	0	------	0	.0001
F-15	.13	.22	.0051	.0010	.0052	0	.081	.023	0	1.9	.12	0	.02	0	0	0	.006	0	0	------
F-19	.12	.092	.0068	.0002	.0047	.004	.051	.0061	0	.58	.07	0	0	0	0	0	0	.05	0	------
Class B																				
[Geological occurrence: formed in various types of metamorphic rocks and in hydrothermal veins]																				
F-22	0	0.0001	0	0	0.0004	0.042	0.056	0.0085	0	0.25	0.05	0	0	0	0	0	0	0	0.0002	0.0001
F-20	0	0	.0013	0	.0004	.024	.10	.0020	0	.31	.01	0	.02	0	0	0	.003	0	.0001	------
F-24	0	0	0	0	.0007	.051	.025	.0011	0	.15	.01	0	0	0	0	0	0	.05	0	------
F-41	.0009	0	0	0	.0013	.012	.003	.0016	.006	.12	1.6	.002	0	0	0	0	.003	0	0	.0001
F-53	.0012	.0002	.0009	0	.0005	.039	.13	.0007	0	.043	.03	0	0	0	0	0	0	.10	0	------
F-56	.0008	.0037	0	0	.0003	.045	.14	.0031	0	.13	.33	0	0	0	0	0	0	0	0	0
F-25	0	.0001	0	0	.0014	022	.017	.020	0	.21	.02	0	0	0	0	0	0	0	0	------
F-57	.0007	0	.0001	------	.0007	.08	1.0	.08	.003	------	------	.002	.02	------	------	------	------	.01	------	------
F-23	0	0	0	0	.0007	.028	.017	.013	0	.33	.09	0	.03	.004	.001	.04	0	0	0	.00009
F-8	.0010	.0006	0	0	.0012	.011	.002	0	0	.06	.11	0	0	0	0	0	0	0	0	------
F-13	.0010	0	0	0	.0008	.010	.073	.0023	0	.37	.35	0	0	0	0	0	0	0	.0001	------
F-14	0	.0001	0	0	.0024	.004	.004	.0027	0	.35	.01	0	0	0	0	0	0	0	0	------

The characteristic suite nickel, chromium, cobalt, and scandium are just those elements which Goldschmidt (1954) and Goldschmidt and Peters (1931) have shown to be overwhelmingly concentrated in the early crystal fractions, rich in magnesium, which accumulate during the differentiation of the magma and which under suitable chemical and geological conditions may give rise to ultrabasic rocks. The minor elements of the serpentines of class A thus inherit their distinctive suite of elements from their parent ultrabasic rocks.

Goldschmidt (1954) and his colleagues have shown that the parent rocks of the class B serpentines, the magnesian limestones and dolomite, are unusually low in nickel and cobalt. Scandium is likewise generally present in negligible amounts in carbonate sediments (Rankama and Sahama, 1950) and the same is true for chromium.

The concordance between the content of the minor elements nickel, cobalt, chromium, and scandium of the parent rocks of class A and class B, as determined by other scientists and of the values obtained in this study from serpentines derived from similar rocks, is clear.

A comparison of the average data for the nickel content in ultrabasic rocks as determined by other scientists and such data as are available for the parent rocks of some of the serpentines studied here with the data presented in this study for serpentines derived from ultrabasic rocks (class A) strongly indicates that there is no loss of nickel during serpentinization. The process of serpentinization is defined here as the formation of serpentine group minerals from preexisting magnesian or ferromagnesian minerals by hydrothermal solutions. The hydrous magnesium silicates stevensite, talc, saponite, and chlorite are commonly part of the same paragenetic sequence and they too may contain notable quantities of nickel, becoming in some environments nickeloan stevensite, genthite, and pimelite, but the total amount of these minerals is generally small compared to that of the serpentine-group minerals.

The geochemistry of boron in these serpentine minerals is more complex than that of the other elements. Sahama (1945) investigated the boron content of dunites and of their serpentinized equivalents and concluded that boron was introduced during serpentinization. The boron content of the serpentine minerals reported here ranges from 0.0002 to 0.05 percent and there seems to be a tendency for the serpentine minerals of class B to be richer in this element. It is a well-known geologic observation that pegmatites of a later age than the serpentinized ultrabasic rocks are commonly present in close proximity to them, or they may actually intrude them. The late-stage hydrothermal solutions associated with these pegmatites, if they serpentinize the ultrabasic rocks could easily introduce boron into the serpentine thus formed. This field relationship between ultrabasic rocks and associated pegmatites places the interpretation of the boron

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TABLE 26.—*Basic data on the serpentine group minerals studied geochemically*

Sample	Locality	Mineralogy	Geological occurrence
	Class A		
	[Geological origin: formed in ultrabasic rocks]		
F–40	Prairie Creek area of peridotite in T. 8 S., R. 25 W., 2½ miles south-southeast of Murfreesboro, Pike County, Ark.	Clinochrysotile	Hydrothermal veins formed through the alteration of ultrabasic rocks. Alnoite-kimberlite-mica peridotite suite.
F–74	New Almaden Mine, Santa Clara County, Calif.	Clinochrysotile plus orthochrysotile.	Highly sheared serpentine derived from lherzolite. Ultramafic suite.
F–51	Nicaro, Oriente Province, Cuba	do	Hydrothermal alteration of ultrabasic rocks. Ultramafic suite.
F–72	Near Almaden Mine, Santa Clara County, Calif.	Chrysotile plus lizardite, C > L.	Completely serpentinized lherzolite. Ultramafic suite.
F–73	do	do	Do.
F–3	New Forest Hill, Harford County, Md	Lizardite plus clinochrysotile, L > C.	Hydrothermal alteration of ultrabasic rocks. Ultramafic suite.
F–42	Near Norris, Tenn	Lizardite	Hydrothermal alteration of a mica-peridotite.
F–43	Crump's Quarry, Mineral Hill, one-fourth mile north of state road, about one mile west of Media, Delaware County, Pa.	do	Hydrothermal alteration of ultrabasic rocks. Ultramafic suite.
F–46	Near Bellows Falls, Windham County, Vt	do	Do.
F–47	Tyrol, Austria	do	Do.
F–1	State Line Pits, Low's Mine, approximately 1.2 miles west-northwest of Rock Springs, Cecil County, Md.	Antigorite	Do.
F–15	North of Domodossola in Val Antigorio, Novara Province, Piedmont region, Italy.	do	Hydrothermal alteration of ultrabasic rock (augite-olivine rock). Ultramafic suite.
F–19	Bare Hills, Baltimore County, Md	Antigorite plus chrysotile.	Hydrothermal alteration of ultrabasic rocks. Ultramafic suite.
	Class B		
	[Geological origin: formed in various types of metamorphic rocks and in hydrothermal veins]		
F–22	Turkey Mountain, near Montville, Morris County, N.J	Clinochrysotile	Hydrothermal alteration of diopside in metamorphosed limestones.
F–20	Asbestos deposits, Gila County, Ariz	Clinochrysotile (Globe-type).	Hydrothermal vein deposits in limestone.
F–24	Montville, Morris County, N.J	do	Hydrothermal vein deposit in metamorphosed limestone.
F–41	Windous deposit, Currant creek magnesite deposits, White Pine County, Nev.	do	Hydrothermal replacement of calcareous tuffs by magnesium-rich solutions.
F–53	Asbestos deposits, Grand Canyon, Ariz	do	Hydrothermal vein deposits in limestone.
F–56	Fifth level, at the shaft, Gouverneur Talc Co., Balmat, N.Y.	Clinochrysotile plus orthochrysotile	Replacement of diopside in a diopsidic, calcitic marble.
F–25	Montville, Morris County, N.J	Chrysotile plus lizardite, C > L.	Hydrothermal alteration of diopside in metamorphosed limestone.
F–57	Talcville, St. Lawrence County, N.Y	do	Replacement of diopside in a diopsidic calcitic marble.
F–23	Dognacska, 10 kilometers west from Reschitza, Hungary.	Lizardite	Hydrothermal alteration of ferromagnesian minerals in a contact-metamorphosed limestone.
F–8	Smithfield, Providence County, R.I	Antigorite	Hydrothermal alteration of ferromagnesian minerals in metamorphosed limestone beds.
F–13	Tilly Foster iron mine, near Brewster station, Putnam County, N.Y.	Chiefly antigorite	Hydrothermal alteration of ferromagnesian minerals in a contact-metamorphic deposit.
F–14	Pei-wa-kou (and Lao-yeh-ling), Hsiu-yen Hsien, Liaoning Province, Manchuria.	do	Hydrothermal replacement of ferromagnesian minerals in metamorphosed dolomite of Precambrian age.

content of these serpentine minerals in doubt. In order to answer this problem at a given locality, further study will be necessary on specimens of known spatial relationship with respect to the ultrabasic rocks, the pegmatites, and the hydrothermal rocks, which entered into this geologic environment.

SOME THEORIES ON THE ORIGIN OF SERPENTINE AND SERPENTINE-RICH ROCKS

The field observation that ultrabasic rocks, especially the ultramafic suite, alter into serpentine has been known for a long time. In those occurrences where the olivine could not be easily recognized, the origin of the

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mineral serpentine and of serpentine-bearing rocks was a subject of considerable debate, sometimes quite heated. The pseudomorphism of serpentine after olivine, and the chemistry of the process involved, at the famous locality in the "Waldes des Hofes Uhlen" in Snarum, Modum Canton, Parish of Buskerud, Norway, was the subject of vigorous disputation. Here the ultrabasic rocks are enclosed as elliptically shaped masses in an area of gneisses, granites, mica schists, and hornblende schists. Quenstedt (1835, 1836), Böbert (1838), Haidinger (1850), Scheerer (1846), and Gustav Rose (1851) all participated in the controversy. The observations of Quenstedt (1835) and Gustav Rose (1851) on the morphology of the serpentine pseudomorphs and Rose's interpretation of Scheerer's chemical analysis of this material as a mixture of serpentine and olivine dispelled all doubt regarding the preexistence of olivine and the derivation of serpentine from ultrabasic rocks. Helland (1873) further strengthened the proof.

A summary of many observations on the origin and paragenesis of serpentine is given as chapter 40 in the classic reference work on chemical geology by Gustav Bischof (1855). Bischof's comment on one statement is particularly pertinent to this discussion (p. 422–423):

> V. Buch states that in the dolomite, which occurs as a bed in crystalline schistose rocks, near Rothzechau, in Silesia, there are veins of serpentine, at the utmost, an inch and a half thick. G. Rose is of opinion that in this later instance, the serpentine is a product of the alteration of dolomite. *Assuming that the dolomite contained the silicates of which the serpentine consists, no objection can be offered to this veiw.* [Italics by authors.]

Bischof's remark shows clearly that he recognized the importance of the presence of ferromagnesian silicates in the dolomite rock for the formation of serpentine by hydrothermal solutions.

T. Sterry Hunt (1859) proposed a new theory of origin of serpentine-rich rocks as follows:

> In like manner the interstratified serpentines of these regions are undoubtedly indigenous rocks resulting from the alteration of silico-magnesian sediments, although the attitude of the serpentine in many countries has caused them to be ranked with granites and traps, as intrusive rocks.

In his book Hunt (1875, p. 317) states his theory more fully, and for the large deposits of serpentine commonly associated with hornblende, talc, and chlorite he writes that they were formed from: ". . . the molecular rearrangement of *diagenesis* of aqueous magnesian sediments, and not from the chemical alteration or *epigenesis* of erupted plutonic masses." Delesse (1861), apparently unaware of the paper by Hunt, likewise advanced the theory that the magnesian rocks were formed by the recrystallization of sepiolites or "magnesian clays" in the sedimentary rocks into serpentine, talc, and chlorite. If the magnesian clay is rich in silica, talc will form; if it is poor in silica, serpentine will form, and if alumina and iron oxides are sufficiently abundant in the magnesian clay, chlorite will form. Some of Hunt's views were sharply contested by James D. Dana (1872).

For nearly a hundred years, these theories of T. Sterry Hunt, Delesse, and others have lain essentially dormant. The occurrence of serpentine in ultrabasic rocks and as replacement or vein deposits in carbonate rocks has been well established by both field and laboratory studies. Save for the paper on the serpentines of the Pyrenees by Michel Longchambon (1912), who proposed that "basic" and ultrabasic rocks in the Pyrenees were formed according to the following equation by the process of assimilation,

$$\text{granitic magma} + \text{dolomite} \longrightarrow CO_2 + \text{basic magnesium silicates} + \text{pegmatites ("fumeroles")},$$

almost all have agreed to a magmatic origin for ultrabasic rocks. With the development of another school of thought in petrology based on the principal that solid diffusion is probably a dominant mechanism in petrology, the old theories of T. Sterry Hunt and Delesse have been rejuvenated with an injection of a "dry elixir." A recent summary of the work of those scientists maintaining these views is given by Henri and Geneviève Termier (1956) in their book "L'évolution de la lithosphère, v. 1, Petrogénèse," p. 398:

> The formation by metasomatism of basic and ultrabasic rocks starting with dolomitic limestones, as one can infer from the preceding considerations seems proved in several ways—Kabylie de Collo (Roubault), Sud de l'Espagne (Van Bemmelen), Pyrenees (Longchambon), Groenland (Sørensen), monzonites (Ogilvie Gordon).

Ramberg (1952) attempts to explain the occurrence of dunitic (or ultrabasic) masses in gneisses by the process of "basification"; he writes—

> Within the zones of metamorphism where quartzo-feldspathization takes place, basification appears to be a rather local and small-scale phenomenon, in agreement with the reasonable conclusion that calco-ferromagnesian elements are less mobile in ordinary rocks than are granitic elements. Along growing pegmatites, calco-ferromagnesian minerals may concentrate (fig. 120), and inclusions or remnants in metasomatic granites may be basified. The Mg-Al metasomatism creating cordierite-anthophyllite rocks may also represent a facies of basification (Bugge, 1943). Several authors have reported field observations indicating that dunitic bodies have grown by Mg metasomatism of dolomites or limestones. Relationships between small dunitic bodies and amphibolites in gneisses from West Greenland are interpreted as if the ultrabasites formed by extraction of Ca, Al, Na, and Si from common amphibolites (unpublished observations by the writer). The latter are but small-scale processes.

That olivines do form in small clots in metamorphosed dolomites and impure marbles is, of course, a matter of petrologic observation, but the extension of this theory to explain a body of olivine the size of a dunitic mass is a totally unjustified extrapolation. Moreover, the

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geologic setting is not that characteristic of the alpine type. Hess (1955, p. 401–402) has emphasized the observation that

> The serpentines are most abundant along the margins of the alpine systems where the deformation has not been intense. They form extensive concordant sills in low-dipping sedimentary rock-shales, graywackes, sandstones and phyllites.

As observed today, these are the ultrabasic masses, sometimes completely altered to serpentine, as at Snarum, Norway, occurring within granitic gneisses and schists. The serpentines of such rocks are characterized by the suite of minor elements, nickel, cobalt, chromium, and scandium, whereas the serpentines derived from the forsterites of metamorphosed dolomites, will be totally lacking in these elements, or contain some of them in negligible amounts.

MINOR ELEMENTS IN SERPENTINE MINERALS AS PETROLOGICAL INDICATORS

Our studies of the minor elements in the serpentine minerals differentiate between serpentine derived from the alteration of ultrabasic rocks and serpentine formed in the metamorphosed dolomites and limestones. The ability to do this may be of much help in unraveling the history of rocks which have passed through one or more facies change or have been altered by hydrothermal solutions.

Ultrabasic rocks are very commonly the source rocks of serpentines and their serpentinization commonly takes place in more than one stage. The sequence of serpentinization given by Du Rietz (1935) for the Caledonian ultrabasic rocks of Sweden is typical of many other areas in the world. In Sweden the ultrabasic rocks occur as lens-shaped bodies, a little less than a kilometer in length, enclosed conformably within folded sedimentary rocks. The simplest sequence of serpentinization is (1) during intrusion, (2) during folding, and (3) during regional metamorphism when the ultrabasic rocks are invaded by granites and pegmatites. Stage (1) may range from a very minor effect to a major process. Rost (1949) describes the serpentine-gabbro occurrence of Wurlitz, Germany. On the basis of petrographic and chemical studies, he concludes that the original rocks were an ultramafic suite consisting of peridotite, wehrlite, gabbro, and plagioclasite. Metamorphism took place in several stages. The olivine was serpentinized; the plagioclase saussuritized. Subsequently tremolite and chlorite were formed. The last stage is represented by the action of granite intrusions which caused the formation of garnet and idocrase. Rost gives spectrographic data on nickel, cobalt, manganese, chromium, scandium, vanadium, and titanium. It will be observed that his minor-element data are in accord with our observations that such serpentines as were formed have been derived from ultrabasic rocks. The studies by Hahn-Weinheimer (1959, 1961) on the serpentines of the Münchberger gneismasse likewise support the conclusions that their minor-element content indicates their derivation from ultrabasic rocks. Lundegårdh (1949) concluded from spectrographic studies that the trace elements nickel, cobalt, chromium, and zinc are immobile during palingenesis.

Serpentines formed in metamorphosed limestones and dolomites and contact-metamorphic deposits and as hydrothermal veins may also have been formed in more than one stage. Where replacement of ferromagnesian minerals has taken place, it is not uncommon to find—in addition to the pseudomorphs—lenses, pods, and small veins of serpentine, which have derived their constituents from the preexisting minerals and which probably formed as a result of the increase in bulk volume during serpentinization. Merrill (1888) has described such a replacement of diopside in massive dolomite at Turkey Mountain, Montville, N.J., with the formation of nodules of serpentine and, to a lesser extent, of small seams and veins of serpentine. Our minor-element studies of this serpentine show either absence of or a very low concentration of nickel, cobalt, chromium, and scandium.

Solutions rich in magnesium may be derived by the dedolomitization of dolomites, brucite marbles, predazzite and pencatite (Faust, 1949). Serpentine deposited from such solutions will contain a suite of minor elements that is typical of serpentine of class B. Faust and Callaghan (1948) described serpentine occurring with magnesite in deposits which were formed in the replacement of calcareous tuffs by hydrothermal solutions rich in magnesium and carbon dioxide. The suite of minor elements in a sample of the serpentine mineral, F–41, shows that it is not related to the serpentine from ultrabasic rocks but belongs to our class B serpentine. Our studies on the minor elements in class B serpentine lend no support to the views of T. Sterry Hunt and Delesse of the early school, or to those of Roubault and others of the later school, that ultrabasic rocks are produced by metamorphism from magnesian limestones, dolomites, or other magnesian sedimentary rocks.

Since the publication of the paper by Faust, Murata, and Fahey (1956) a study of the serpentine derived from the peridotite of di Germagnano in the Val di Lanzo, Italy, by Rigault (1958) has been made. Nickel and chromium were determined to be present by quantitative chemical analysis. Spectrographic examination revealed the presence of scandium and cobalt. Hill (1958) used the minor-element data for the nickel, chromium, and cobalt content of the schistose serpentinite at Minas Carlota, Cuba, in judging its igneous origin. He concluded on the basis of the various data

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that the schistose serpentine was derived from gabbro and microgabbro.

The chemical analyses of the serpentine minerals of class A (table 2) and class B (table 3) show a greater concentration of FeO, Fe_2O_3, and Al_2O_3 in those of class A. The values are as follows: Class A, average of 11 selected analyses, FeO = 1.40 percent, Fe_2O_3 = 2.56 percent, Al_2O_3 = 1.18 percent; class B, average of 10 selected analyses, FeO = 0.34 percent, Fe_2O_3 = 0.49 percent, and Al_2O_3 = 0.44 percent. As a result of the greater concentration of the iron oxides (and alumina) in class A serpentine minerals, their color is generally darker than those of class B. Low-iron serpentine minerals are likely to be found among those of class B which are derived from the alteration of low-iron olivines and pyroxenes. Class B serpentine forming in hydrothermal deposits with sulfides would likely be low-iron serpentine because the distribution coefficient of iron between silicates and sulfides would appear to favor the sulfides over the silicates. The color of most of the analyzed specimens is given in the section on the "Description of the minerals." The few exceptions to the generalization on color in class A are minerals labelled deweylite, and they probably represent later generation of serpentine-group minerals than the darker colored varieties.

TABLE 27.—*Geographic finding list for description of specimens used in this study*

Locality	*Specimen*
Austria:	
Tyrol	F-47
Canada:	
Quebec Province: Thetford	F-60, F-61, F-70
Cuba:	
Oriente Province:	
Moa	F-50
Nicaro	F-51
Dutch New Guinea:	
Hollandia: Cyclops Mountains	F-66
Hungary: Dognacska, now Dognecea, Rumania	F-23
Italy:	
Novara Province: Val Antigorio	F-15, F-67
Manchuria	F-14
Norway: Snarum	F-71
United States:	
Arizona:	
Coconino County: Grand Canyon	F-53
Gila County	F-20, F-20A
Arkansas:	
Pike County: Murfreesboro	F-40
California:	
San Benito County: Canyon of Clear Creek	F-58
Santa Clara County: New Almaden mine	F-72, F-73, F-74
Maryland:	
Baltimore County: Bare Hills	F-19
Harford County: Forest Hill	F-3
Nevada:	
White Pine County: Currant Creek	F-41
New Jersey:	
Hudson County: Hoboken	F-75, F-76
Morris County: Montville	F-22, F-24, F-25, F-64
New Mexico:	
Organ Mountains	F-65
New York:	
Putnam County: Brewster Station	F-13
Richmond County: Staten Island	F-63
St. Lawrence County:	
Balmat	F-56
Talcville	F-57
North Carolina:	
Jackson County: Webster	F-69
Mitchell County: Bakersville	F-48
Pennsylvania:	
Chester County: Sylmar	F-52
Delaware County: Mineral Hill	F-43
Lancaster County:	
Low's mine	F-1
Texas	F-26
Wood's chrome mine	F-45, F-49
Northampton County: Easton	F-68
Rhode Island:	
Providence County: Smithfield	F-8
Tennessee:	
Union County: Norris	F-42
Vermont:	
Windham County: Bellows Falls	F-46

TABLE 28.—*Geographic finding list for chemical analyses taken from the literature*

Locality	*Analysis No.*
Afghanistan	150
Australia	54
Austria:	
Tyrol	11
Other	44
Canada:	
British Columbia	80
Quebec	42, 53, 87, 97, 101, 192, 200, 202, 203, 206, 212, 217, 222, 225, 228
Thetford	89, 94, 115, 134, 196, 229
China	126
Cuba	214
Cyprus	76
Czechoslovakia	40, 83, 124, 131, 154, 185
Finland	100, 113, 128, 226
France	6, 17, 148, 204
Germany:	
Hesse-Nassau	138, 172, 182
Saxony	187
Waldheim	2, 13
Other	197, 255, 256, 257
Great Britain:	
Lizard	32, 60, 77, 82, 146
Shetland Island	33, 72, 112
Italy:	
Tyrol	10, 137
Val Antigorio	15, 20, 25, 30, 78
Val d'Aosta	43, 190, 191
Villa Rosa	29
Other	205, 244, 245

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TABLE 28.—*Geographic finding list for chemical analyses taken from the literature*—Continued

Locality	*Analysis No.*
Kashmir	218
Madagascar	5, 149, 178
New Caledonia	165, 171, 176
New Zealand	49, 163
Norway: Snarum	47, 62, 90, 114, 116, 221, 227, 243
U.S.S.R.:	
Caucasus	3, 175
Urals	79
Uzbek	238, 239
Silesia	1, 61, 71, 152
Southern Rhodesia	14, 28, 35, 37, 67, 84, 111, 129, 210
Sweden	127, 136, 162, 237
Switzerland	12, 50, 63, 96, 132, 133, 199, 207
Union of South Africa:	
Transvaal	16, 18, 19, 21, 45, 66, 75, 86, 121, 164, 180
United States:	
Arizona:	
Gila County	250, 251
Globe	246, 247, 248, 249
California:	
New Idria	41
Sulphur Bank	38, 92
Connecticut	161
Maryland:	
Bare Hills	31, 159
Massachusetts	98, 139, 259
Montana	145
New Jersey:	
Franklin	147, 215, 240, 241, 242
Hoboken	125, 220
Montville	27, 48, 52, 64, 68, 70, 194, 258, 260
New York:	
Aboutville	88, 91
Brewster Station	39, 73, 81, 93, 102, 213
Orange County	235, 236
Port Henry	36
North Carolina	130, 261
Pennsylvania:	
Berks County	170, 181, 193, 198, 219
Chester County	95, 110, 157, 177, 179
Delaware County	65, 69, 140, 151, 155, 166
Lancaster County:	
Low's mine	158, 183, 201
Texas	34, 85, 156, 173, 174
Wood's chrome mine	153
Lebanon County: Cornwall	135
Montgomery County	186
Northampton County:	
Easton	4, 26, 46, 99, 122, 123, 160, 195, 216
Rhode Island	208, 209, 211
Venezuela	51, 120

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