CONSTITUTION AND CLASSIFICATION OF THE NATURAL SILICATES

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CONTENTS

I. GENERAL INTRODUCTION AND THEORY

INTRODUCTION

The silicic acid theory of the constitution of the silicates and the classification based on that theory is almost as old as the science of Mineralogy (Doelter 1914). Except for the important modifications by Tschermak, of which more will be said in the next section, the theory is essentially today as it was in 1811, and the classification now used in most textbooks is the same as that found in texts more than fifty years old. One may assume, then, that no adequate substitute for this firmly established classification has as yet been presented. Within the past ten years, however, a re-examination of the constitution of the silicates has become possible through x-ray structural studies due mainly to the Braggs.

As a result of this new method of attack a new conception of silicate structure has been evolved and a classification which logically follows from that conception has been proposed by Bragg (1930), Machatschki (1928), and others. Most of the suggestions for a new classification have remained only suggestions. Many papers have appeared in the past ten years in which the new silicate theories have been used to study particular minerals or mineral groups. Winchell has classified the silicates which have thus far been studied structurally. No one, within the writer's knowledge, has made a systematic investigation of all the well-defined

silicates, in order to ascertain the extent to which the newer theories are valid, and how well a classification based on these theories meets the requirements of descriptive mineralogy. It is the purpose of this paper to present the evidence for the validity of the newer concepts and to give a more complete classification based on them.

The writer wishes to acknowledge the interest and encouragement shown by Professors Palache and Larsen of the Department of Mineralogy at Harvard University, as well as their advice in the preparation of this paper. To Professor B. E. Warren of the Massachusetts Institute of Technology the writer expresses his thanks for having introduced him to the interesting x-ray data available on this subject. Professor W. E. Ford of Yale University and Professor A. L. Parsons of the University of Toronto have read the manuscript and have offered valuable criticism. Dr. M. A. Peacock has suggested improvements in the form of the manuscript.

OLDER CONCEPTS CONCERNING THE CONSTITUTION OF THE SILICATES

Doelter (1914) gives a comprehensive summary of the various theories on the constitution of the silicates. For this reason a full discussion need not be given here. It is worthy of note, however, that Tschermak made his first contribution to the study of the chemistry of the feldspars in 1864, and that his paper gave for the first time a real picture of isomorphism in the silicates. It is well also to remember that Tschermak (1864) anticipated the requirement of similar atomic constitution in isomorphous compounds. He wrote the formulae for the plagioclases (p. 37):

Anorthite	$Ca_2Al_2Al_2Si_4O_{16}$
Albite	$Na_2Al_2Si_2Si_4O_{16}$

and today, with our more precise knowledge of the structure of the feldspars, we find that his formulae stand as written. So also he showed the true nature of the chemical relationships in the scapolites and the chlorites, to name a few of the important groups examined by him. Tschermak examined the facts closely and with great skill. He interpreted his findings in a way that is unacceptable in the light of the newer theories derived from x-ray studies; but to him must go the honor of being the greatest worker in the field of mineral chemistry.

Clarke (1914) brought to a culmination the studies of a century in this field. He listed (p. 14) the silicic acids necessary to explain the constitution of the silicates. To these he attributed acid, basic and normal salts forming silicate compounds. He wrote elaborate structural formu-

lae, extreme examples of which appear on pages 68 and 69 of his book.

The real difficulties in the older interpretations arose from the fact that no direct evidence was available upon which to construct an adequate theory. Most of the earlier workers, including Tschermak, attempted first of all to synthesize the various hypothetical silicic acids which they postulated as the basis of the silicate compounds found in nature. Failing in this, they attempted to identify the acids in solutions of the minerals themselves; but this method likewise brought no success. Clarke, searching for some other method of attack, studied the alteration products of the silicates, and thus deduced a relation between their formulae, as he expressed them. The writer believes that this method was no more successful than the others, and for the same reasons.

There have been attempts to study the silicates by analogy with organic compounds (Asch 1914). These have not proved fruitful and are rightly discarded. Short-lived theories which fell of their own weight, so to speak, have been proposed from time to time; an account of these may be found in Doelter (1914).

The problem of the constitution of the silicates is a problem in crystal chemistry, because the silicates are with but few exceptions solid crystalline compounds as we know them in nature. To bring a silicate into solution necessarily destroys the arrangement we are trying to study. To alter the substance by solution, or in any other way, likewise destroys its former constitution. These methods are not adequate for the problem at hand and they fail, therefore, to yield the true answer.

The x-ray method, by which the substance is studied as it is, as a crystal, can hope to solve the problem of its constitution; and this method has already proved fruitful. The recognition of the peculiar ability of this new tool to solve problems in crystal chemistry has led to an enormous amount of experimental work in the new field. The silicates have been particularly studied by Bragg (1930) and his students. Thus far the crystal structures of some forty silicates have been definitely established. Among these are some of the commonest minerals. The structures of many more silicates are incompletely known. Those silicates for which structures have been determined amount to perhaps ten or fifteen per cent of all the species listed in Dana's textbook (1932).

Since the underlying principles of the structures in silicates were soon recognized by workers in this field, the structures already determined represent the main types. It is because of this that a general examination as proposed in this paper can be undertaken with some hope of success, despite the comparatively small number of specific structures determined.

RESULTS OF THE *X*-RAY ANALYSES OF SILICATE STRUCTURES

The material of this section is taken largely from the summary of the knowledge of silicate structures, by Bragg (1930). Here only the data immediately useful to our purpose are given.

In order of importance the general features revealed by the *x*-ray studies, are given below.
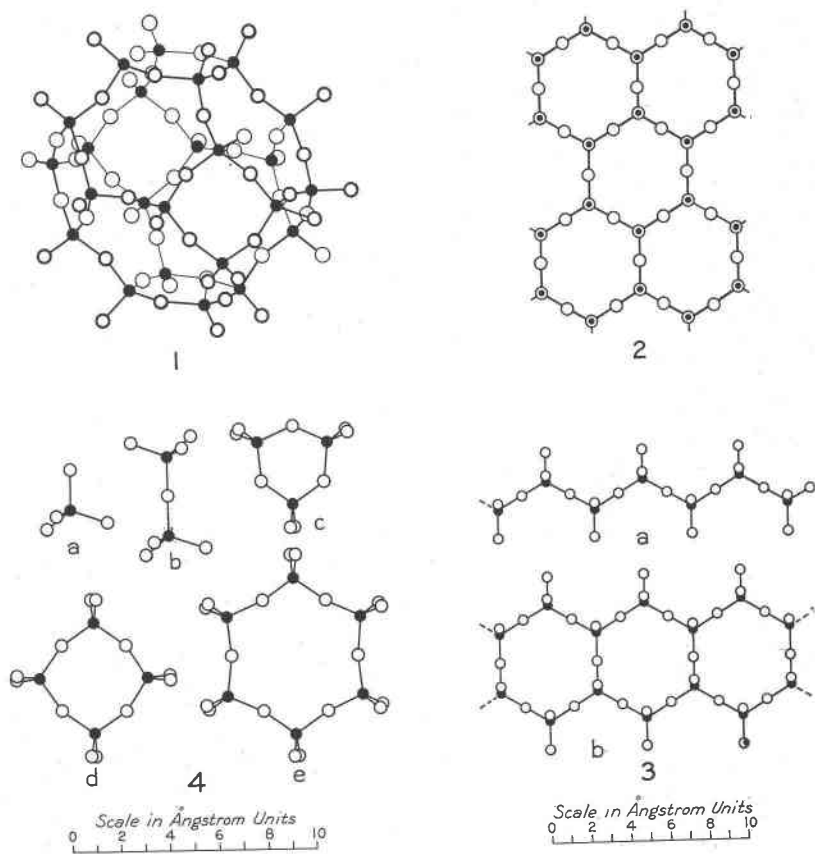
Linkages of silicon-oxygen tetrahedra. Black, silicon, with or without aluminum; white, oxygen. After Bragg (1930).

FIG. 1. Silica type, SiO_2; three-dimensional linkage.

FIG. 2. Disilicate type, Si_2O_5; two-dimensional linkage.

FIG. 3. Metasilicate type; a. SiO_3, single-chain linkage; b. Si_4O_{11}, double-chain linkage.

FIG. 4. a. Orthosilicate type, SiO_4; independent tetrahedra. b. Pyrosilicate type, Si_2O_7; paired tetrahedra. c. Ring-linkage, Si_3O_9. d. Ring-linkage, Si_4O_{12}. e. Ring-linkage, Si_6O_{18}.

1. In all silicates examined the silicon-oxygen relation is found to be the same; a silicon atom always occurs in the center of four oxygen atoms arranged as a tetrahedron about it. This tetrahedron is the fundamental and apparently invariable unit in the silicate structure (Fig. 4a).

2. The different silicate types arise from the various ways in which the silicon-oxygen tetrahedra in a given structure are related to each other. The rule that tetrahedra can share corners only, and not sides or edges, has been found to be universally true; consequently two tetrahedra can have only one oxygen in common between them. However, every oxygen of every tetrahedron may be shared with another tetrahedron.

3. There are characteristic ways in which tetrahedra have been found to combine in the silicates examined, and these ways of linkage are comparatively few in number. If the tetrahedra are not combined with each other, the composition of the silicate is of the SiO_4 type; if all the corners are shared with other tetrahedra, the composition is that of the different forms of silica, SiO_2. Other relations yield intermediate types. The list is given below.

A. Three dimensional networks (Silica type): All the tetrahedra share their corners with other tetrahedra giving a three dimensional network. Silica, in any of its modifications, is the type substance of this linkage, which results in the composition SiO_2 (Fig. 1).

B. The sheet structure (Disilicate type): This structure is obtained when tetrahedra are placed all in one plane with each tetrahedron being joined to other tetrahedra by three atoms lying in the common plane. An indefinite extension of this linkage produces a hexagonal network in the plane. The type silicate of this structure is mica, with the composition Si_2O_5 (Fig. 2).

C (1). Chain structures (Metasilicate type): Tetrahedra joined together, to produce chains of indefinite extent. There are several modifications of this structure yielding somewhat different compositions: (a) A single chain; one long linkage of tetrahedra of indefinite extent producing a composition SiO_3, as in the pyroxenes (Fig. 3a). (b) A double chain, giving a composition Si_4O_{11}, as in the amphiboles (Fig. 3b). (c) A sort of triple chain, with some modifications (Ito 1933), yielding Si_3O_8 compositions. Other methods of linking tetrahedra in chains to form Si_3O_8 compositions have not yet been thoroughly investigated.

(2) Ring structures (Metasilicate type): Two of the tetrahedral corners shared, as in the chains, but instead of extending indefinitely in one direction the chains make closed units of a ring-like structure. Benitoite with the Si_3O_9 ring (Fig. 4c), and beryl with the Si_6O_{18} ring (Fig. 4e) are type examples.

D. Double tetrahedra structures (Pyrosilicate type): These structures arise from two tetrahedra with a common oxygen between them. The resulting composition is Si_2O_7 (Fig. 4b), and the type mineral is thortvietite.

E. Independent tetrahedral groups (Orthosilicate type): In this type none of the tetrahedra shares corners with another. The resultant composition is SiO_4 (Fig. 4a) and the type mineral is olivine.
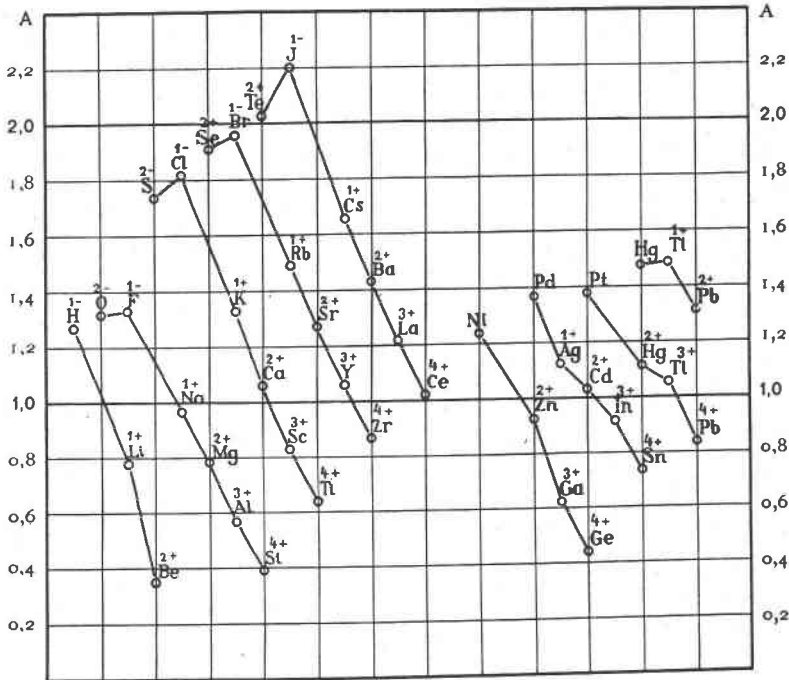

Fig. 5. Ionic radii of some elements including those commonly found in the silicates. After Goldschmidt (1926).

4. Since the oxygen atoms are usually the largest in the structure as found by measurement of ionic radii (Goldschmidt 1926), these atoms are chiefly responsible for the size of the unit cell. From this it follows that the number of oxygen atoms in the formula of a silicate is highly significant.

5. Silicates which are members of an ismorphous series (see later section) have formulae with the same number of oxygens (Berman 1929).

6. It is inferred from x-ray studies that the general type of substitution in isomorphous silicates is atom for atom, regardless of valence, and

that the chief factor governing such substitution is similarity of the volumes of the atoms concerned (Zambonini 1922, Wherry 1923, Goldschmidt 1926). This leads to the conclusion that the total number of atoms in isomorphous minerals is the same. There are some exceptions to this rule, which will be noted as they occur in the classification (Warren 1930 A; Berman and Larsen 1931).

7. X-ray studies have definitely led to the concept of the substitution of Al for Si in a large number of silicates, where the Al occurs in tetrahedra similar to the tetrahedra about the Si (Warren 1930).

8. It has been noted (Bragg 1930) that the elements found in the silicates, as well as in many other compounds, usually have a characteristic arrangement of oxygen about them, regardless of the compound. The number of oxygens characteristically associated with an atom is known as its *co-ordination number*. Some atoms have two or three co-ordination numbers. Below is a list of the elements commonly found in the silicates and their co-ordination numbers, as observed in determined structures.

TABLE 1. CO-ORDINATION NUMBERS
(BRAGG 1930)

Element	Co-ordination numbers	Element	Co-ordination numbers
Be	4	Ti	6
B	3, 4	Mn''	4, 6, 8
Na	6, 8	Fe''	4, 6, 8
Mg	4, 6, 8	Fe'''	4?, 6
Al	4, 5, 6	Zn	4
Si	4	Zr	8
Ca	6, 7, 8	Ba	6, 12
Sc	6		

A THEORY OF THE CONSTITUTION OF THE SILICATES, DERIVED FROM X-RAY STRUCTURAL STUDIES; AND SOME RELEVANT DEFINITIONS

If we accept the accumulated evidence of the structural studies of the silicates, we must conclude that the old silicic acid theory is untenable. In its place we must postulate that the chief variations in the constitution of silicates are due to the various ways, already mentioned, in which the fundamental motif, namely the silicon-oxygen tetrahedron, combines with its neighboring tetrahedra to form more or less complex groups extending indefinitely throughout the crystal. This concept, and the various types of silicates arising from it, is not just another way of indicating a new group of silicic acids, because the silicates cannot be regarded, in this new theory, as acid radicals with the metallic elements. We must

think of the silicates as frameworks of silicon-oxygen tetrahedra indefinitely extended in the crystal. Typical acid compounds are made up of discrete radicals not joined together like the silicate tetrahedra.

Corresponding to different linkages of the tetrahedra we have different compositions, habits and physical properties in the several types of silicates. The sheet structure, for instance, produces the platy form of the micas, the chlorites, the kaolins and other minerals, as discussed later. The chain structures produce prismatic or fibrous crystals as exemplified in the pyroxenes and amphiboles. The three-dimensional network structures usually produce equidimensional crystals. There are characteristic density ranges and refractive index limits in the different types corresponding to differences of structure. These and other properties easily recognized serve to distinguish one type from another, so that one can often infer the structural type from the external properties.

The term isomorphism, as here used, describes the relationship between two silicates which are structurally alike and are members of a series in which there is continuous change in the physical and chemical properties from one member to another. The term as first used (Mitscherlich 1820) had essentially this meaning. It has been modified (Tutton 1922), and used to mean simply, "having the same form," by x-ray crystallographers. Thus olivine and chrysoberyl have been called isomorphous. The definition given in this paper corresponds to that commonly used by mineralogists. Minerals with similar form and structure, which do not form series, may be described as isostructural (Tutton 1922).

Since two isomorphous compounds must have the same structure, they necessarily have the same number of oxygen atoms in their formulae. Likewise they must in general have the same total number of atoms, since their unit cell dimensions are usually almost alike. The atomic, or ionic, radii of most of the elements entering into the silicates do not permit of several atoms of one kind substituting for one of another without considerably changing the volume of the unit cell; substitution is, therefore, atom for atom in isomorphous compounds.

Another rule, of somewhat less importance, is that substituting atoms must be of approximately the same volume, since the structure is not much distorted in isomorphism. It is to be noted that the theory of isomorphism does not require that the substituting atoms have the same valence or chemical nature as the substituted atoms. But it is necessary that the total valence, or electrostatic charges, in the two isomorphous compounds must be the same, since they have the same number of oxygen atoms. If a divalent atom substitutes for a monvalent

atom, there must be a concomitant substitution somewhere else in the structure in order that the resultant valences be the same in the two compounds. This sort of substitution is found in the plagioclase series as well as in many other silicate series.

Mixed crystals are intermediate members of an isomorphous series. The term is unsatisfactory, but no other is available, and it is generally used as defined here. Olivine $(Mg, Fe)_2SiO_4$ is a mixed crystal, the atoms of Mg and Fe being structurally equivalent. It is perhaps well to point out here that the formulae of mixed crystals are not written as if they consisted of two components, as is often done in mineralogical literature. The form $m\ Mg_2SiO_4 + n\ Fe_2SiO_4$, with m and n as percentages, to indicate an olivine is avoided for several reasons. In the first place, the indications from structural studies (Vegard and Schjelderup 1917) point to the conclusion that Mg and Fe are statistically distributed throughout the olivine structure and there are no discrete blocks of Mg_2SiO_4 alongside of Fe_2SiO_4. Second, the adopted style of formula does not postulate the actual existence of the two end components. The ratio Mg/Fe fully expresses the part of the series to which a particular olivine belongs. To appreciate the hazards of the method of expressing the composition of mixed crystals in terms of their probable components, we can use another example from the olivine group, namely the forsterite-monticellite series. The mixed crystals have the composition $(Mg, Ca)_2SiO_4$. But Ca_2SiO_4 is not an end component of the series because it does not have the same structure, and no mixed crystals are found having a composition with Ca/Mg > 1. The mistake of using probable components to express intermediate composition has led to the common practice of proposing so-called "end members" which have often no existence and thereby confuse the study of the constitution of the silicates.

When mixed crystals are known to exist from one pure component to the other, as in the forsterite-fayalite series, the series is said to be one of complete miscibility. If, however, the series is not complete and the evidence indicates that a complete miscibility is unlikely, the series is said to be one of limited miscibility. The forsterite-monticellite series is an example of limited miscibility. The conditions of limited miscibility in a series may be caused by several structural factors, according to the theory of the constitution of the silicates here given.

(1) If the substituting atoms in the series are of a volume approaching the limit of difference tolerated by the structure, only a small amount of substitution can take place, since the stability of the structure will be disturbed by the necessary distortion. This is exemplified by the universal presence of only small amounts of K in the Na silicate miner-

als. There are probably no silicates forming a complete K, Na series. The temperature at which minerals form has much to do with the degree of miscibility. In general, at a higher temperature miscibility is probably more easily accomplished because of a distended lattice. When the crystal cools, it may or may not retain its ability to carry certain elements. The phenomenon of exsolution is an expression of limited miscibility in this sense.

(2) Limited miscibility may be due to the fact that chemically like atoms, as the Mg of forsterite, are sometimes structurally in non-equivalent positions (Bragg 1930, p. 243) and it is possible for the substitution to be made in only one set of non-equivalent atoms. This is the case in the forsterite-monticellite series, where one Mg of the forsterite structure can be replaced by Ca, the other cannot without destroying the olivine type of structure, since Ca is considerably larger than Mg in ionic radius (fig. 5).

A CLASSIFICATION BASED ON THE THEORY

The classification here proposed is based on the various types of linkage of the silicon-oxygen tetrahedra found to be the fundamental motif of the silicate structures. This is essentially a chemical classification since the composition of each type is characteristic. Within the type, structural differences introduce crystallographic variations leading to a division into families and groups. This is more or less in conformity with the older classifications now in use. In addition, certain other physical characteristics, as noted under the types, are also of value in making the broad divisions of the classification.

The major divisions here designated as structural types are perhaps not the only types possible. However, a rather careful survey of all the reliable silicate descriptions has failed to show any important group of minerals which cannot reasonably be placed in one of the types listed below.

Silica type	$Z:O=1:2$
Disilicate type	$Z:O=2:5$
Metasilicate type	
Chains	$Z:O=3:8$
	$Z:O=4:11$
	$Z:O=1:3$
Rings	$Z:O=n:3n$
Pyrosilicates	$Z:O=2:7$
Orthosilicates	$Z:O=1:4$

Z indicates the silicon-like atoms which include also Al in part, and

sometimes Be in part. O refers to oxygen or oxygen-like elements such as (OH) and F, which may in rare cases replace the oxygen.

The type names here used are essentially those of the older classifications. However, according to the newer theories these names do not imply that the minerals of the types are salts of hypothetical acids. The sense in which the old names are used in this paper has already been indicated.

Within each type the broadest division is into families, wherever such division can profitably be made. Thus in the disilicates the aluminum silicates constitute a family, the divalent metal aluminum silicates constitute another, and the alkali aluminum silicates still another.

The families are further divided into groups, the members of which are more restricted in variation and more nearly alike in structure and composition and consequently in crystallographic and physical properties. The term group is used here approximately as in the standard textbooks. Groups are further divided into isomorphous series where such are evident.

The members of a series are species. These are the representatives of the series most commonly found in nature, or some convenient compositional range which includes the commonly occurring members of the series. The term species is also applied to minerals that, so far as known, have fixed compositions; such species are nearly all rare silicates that have been found but once and therefore we have no evidence of their variability. Surprisingly few silicates have no important variation in composition. Species are then either members of a series, or of fixed composition. In either case, they are the smallest important unit of our classification. In the silicates it is generally true that species are members of a series; and it is for this reason that the writer regards the series as the most important unit of the classification. In the sense that species are arbitrary segments of a series they are not the natural units in the silicates. When one has completely described a series, one has at the same time described all of the species of that series. Undue emphasis in the past on the minute variations of a series and the too profuse naming of these variants have encumbered the literature of the silicates with many insignificant names. If many of these are not found in our classification, it is not because they have not been considered; but because, according to the writer's views, they would only obscure the pertinent data.

Corresponding to the divisions of the classification the formulae are progressively less generalized, beginning with the type formula, where it is feasible to write one, and ending with that of the series or the species.

Each formula of a more general nature embraces all of the succeeding formulae. In many of the types a general formula defining the type must be so generalized that little profit is gained by giving it. On the other hand, a type formula of the silica type gives a clear picture of all the members. Accordingly, a completely consistent procedure cannot well be followed. Where clarity is gained, all the formulae will be given.

As an example of the method of treatment in the study of a silicate to determine its constitution, the amphiboles will be used, for several reasons. (1) They are perhaps the most complex chemical compounds among the silicates. (2) They afford a good example of groups containing many series which show various types of chemical complexity.

The amphiboles are a well-studied group chemically. Literally hundreds of analyses exist. The first step in the study consisted of determining the ratios of the various atoms (and possible groups of atoms) to each other, assuming that a constant number of oxygen atoms are in the formulae of all amphiboles. From the structural study (Warren 1929) a clear picture of the relation between the atoms is obtained. Tremolite, which was studied in detail by Warren, has 44 oxygens and 4 hydroxyls in the unit cell. Assuming that the same holds for all the amphiboles, their analyses were computed on that basis. The analyses as given in the literature are in the oxide form. It is necessary, however, to express the analysis in terms of metals and oxygen, because in our studies atomic relations are important, and the oxide form frequently masks the true relations. The method of treating the analysis is as follows. Taking as an example riebeckite from Pike's Peak, Colorado, as analysed by Kunitz (1930), we have a division into six columns as given.

TABLE 2. DISCUSSION OF A HORNBLENDE ANALYSIS

	1	2	3	4	5	6
SiO_2	49.46	0.820	1.640	0.820	7.9	8.0
Al_2O_3	1.05	0.010	0.030	0.020	0.2 ⎫	2.1
Fe_2O_3	15.78	0.099	0.297	0.198	1.9 ⎭	
FeO	21.03	0.292	0.292	0.292	2.8 ⎫	3.1
MgO	0.62	0.015	0.015	0.015	0.1 ⎭	
MnO	1.23	0.017	0.017	0.017	0.2	
Na_2O	8.19	0.132	0.132	0.264	2.6 ⎫	2.9
K_2O	1.72	0.018	0.018	0.036	0.3 ⎭	
H_2O	1.15	0.064	0.064	0.128	1.2	1.2
	100.23		2.506			
			f = 9.58			

1. The percentage composition expressed in terms of the oxide.
2. The molecular ratio.
3. The oxygen atoms of the ratio given in 2; each ratio in column 2 is multiplied by the number of oxygen atoms in the corresponding oxide.
4. The positive atoms in the ratio in column 2, each multiplied by the number of positive atoms in the corresponding oxide. If by x-ray analysis the dimensions and molecular weight of the unit cell have been determined, the atomic contents of the cell may be directly computed from column 4 by multiplying each term by the molecular weight of the unit cell.
5. The total of the oxygen atoms in column 3 is multiplied by a factor f, in order to bring that total to the required oxygen number, in this case 24. This same factor f is used to multiply each ratio of column 4 to obtain the values in column 5.
6. Structurally equivalent, or isomorphous groups of atoms are combined to yield the formula; in this case $(Na, K)_3(Fe'', Mg, Mn)_3(Fe''', Al)_2(Al, Si)_8O_{23}(OH)$.

The formula here given is half the content of the unit cell. It is often possible to discuss the constitution of a series by using a small fraction of the true unit and thereby simplify the formula. However, there is often a necessity to use the full cell contents, no matter how large, in order to grasp the full significance of the variations in a complex series. Precisely the same procedure is followed for all the analyses which in the author's opinion are complete and made on fairly pure material. The study yields a general formula for the amphibole group, as follows:

$$(WXY)_{7-8}(Z_4O_{11})_2(O, OH, F)_2$$
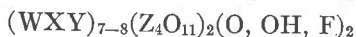
with $W = Ca$; Na, K in minor amount, and sometimes Li.

   $X = Mg$, Fe'', Mn'', Al in part.

   $Y = Al$, Fe''', Ti, principally.

   $Z = Si$ principally and Al in part.

The symbols W, X, Y, Z are used throughout the classification to indicate atoms of the same kind, namely atoms having given ionic radii and co-ordination numbers. The W atoms are mainly the alkalies and Ca, Ba, Sr; the X atoms are divalent atoms for the most part, having intermediate radii and large co-ordination numbers; the Y atoms are trivalent or tetravalent with generally smaller ionic radii. The Z atoms are predominantly Si, with some Al in certain silicates, such as the amphiboles. The Z atoms are of small radius and have the co-ordination number 4.

A further study of the amphiboles showed that there are probably four major series comprising the group. These series are:

The anthophyllite series—$X_7(Z_4O_{11})_2(OH)_2$; with $X = Mg$, Fe and Mg/Fe large; Ca subordinate; $Z = Si$ almost entirely; Al sometimes in small amounts.

The cummingtonite series—$X_7(Z_4O_{11})_2(OH)_2$; $X = Mg$, Fe''. Mn and Zn subordinate; Al in minor amounts; $Z = Si$ predominant, Al sometimes in small amounts.

Tremolite-actinolite series—$W_2X_5(Z_4O_{11})_2(OH)_2$; $W = Ca$ predominantly, Na in minor amount; $X = Mg$, Fe″, with some Al; $Z = Si$ predominantly, Al in minor amount.

Hornblende series—$W_3(X, Y)_5(Z_4O_{11})_2(OH, F)_2$

X	Y	Z = Si:Al	Species
5	0	7:1	Hornblende-edenite
4	1	6:2	Hastingsite
3	2	8:0	Glaucophane
4	1	8:0	Arfvedsonite

$W = Ca$, Na with Ca never greater than 2 in formula; Li rare (in holmquistite); K in subordinate amounts. $X = Mg$, Fe″, Mn″; $Y = Al$, Fe‴, Ti; $Z = Si$, Al, in ratios given above.

It is to be noted that the general group formula is such that the formulae of the series may be derived from it. The series formulae give the general variations within a specified range and show the character of that variation. In the regular classification a list of the species, with specific formulae, corresponding to some part of the series, is given. This is the method of presenting the data.

II. A TABULATED ARRANGEMENT OF THE SILICATES ACCORDING TO THE NEW CLASSIFICATION

Silica Type $W(Z_rO_{2r}) \cdot N$

$W = Ca$, Na, K; Li, Cs rare; Mn, Fe, Zn very rare; $Z = Si$, Al; Be rare; $N = S$, Cl, CO_3, SO_4, and in the zeolites H_2O.

Silica group:	SiO_2
Petalite group:	WZ_5O_{10}
Petalite	$(Li, Na)AlSi_4O_{10}$
Milarite	$(Ca, K)(Al, Be, Si)_5O_{10}$
Leifite	$Na_4Al_2Si_9O_{22}F_2$
Feldspar group:	WZ_4O_8
Monoclinic members:	
Orthoclase	$KAlSi_3O_8$
Soda-orthoclase	$(K, Na)AlSi_3O_8$
Hyalophane	$(K, Na, Ba)Al(Al, Si)Si_2O_8$
Celsian	$BaAl_2Si_2O_8$
Triclinic members:	
Microcline series:	$(K, Na)AlSi_3O_8$
Microcline	$KAlSi_3O_8$
Soda-microcline	$(K, Na)AlSi_3O_8$
Anorthoclase	$(Na, K)AlSi_3O_8$
Plagioclase series:	$(Na, Ca)Al(Al, Si)Si_2O_8$
Albite	$NaAlSi_3O_8$

Labradorite	$(Na, Ca)Al(Al, Si)Si_2O_8$
Anorthite	$CaAl_2Si_2O_8$
Anemousite	$(Na, Ca, Na_2)Al(Al, Si)Si_2O_8$

Pollucite	$W_4Z_{13}O_{26} \cdot H_2O$
Leucite	WZ_3O_6

Nephelite group: WZ_2O_4

Nephelite	$(Na, K)(Al, Si)_2O_4$
Kaliophilite	$(K, Na)(Al, Si)_2O_4$
Eucryptite	$Li(Al, Si)_2O_4$

Cancrinite group: $W_{6-8}Z_{12}O_{24}N_{1-2} \cdot 2\text{--}3H_2O$

Cancrinite	$(Na, K)_{6-8}Al_6Si_6O_{24} \cdot (CO_3)_{1-2} \cdot 2\text{--}3H_2O$
Microsommite ⎰	
Davyne ⎱	$(Na, Ca, K)_8Al_6Si_6O_{24} \cdot (Cl, SO_4)_3$

Sodalite group: $W_{8\pm}Z_{12}O_{24} \cdot N_{1-2}$

Sodalite	$Na_8Al_6Si_6O_{24} \cdot Cl_2$
Hackmanite	$Na_8Al_6Si_6O_{24} \cdot (Cl, S)_2$
Noselite	$Na_8Al_6Si_6O_{24} \cdot SO_4$
Hauyne	$(Na, Ca)_{6-8}Al_6Si_6O_{24} \cdot (SO_4)_{1-2}$
Lazurite	$Na_{8-10}Al_6Si_6O_{24} \cdot S_{2\pm}$
Helvite	$(Mn, Fe)_8Be_6Si_6O_{24} \cdot S_2$
Danalite	$(Mn, Fe, Zn)_8Be_6Si_6O_{24} \cdot S_2$

Scapolite series: $W_4Z_{12}O_{24} \cdot N$

Marialite	$(Na, Ca)_4Al_3(Al, Si)_3Si_6O_{24}(Cl, CO_3, SO_4)$
Meionite	$(Ca, Na)_4Al_3(Al, Si)_3Si_6O_{24}(Cl, CO_3, SO_4)$

ZEOLITE FAMILY $W_mZ_rO_{2r} \cdot sH_2O$

Mordenite series:	$(Ca, Na, K)_{5-7}Al_7(Al, Si)Si_{32}O_{80} \cdot 22H_2O$
Heulandite group:	
Clinoptilolite	$Ca_2Na_3Al_7Si_{33}O_{80} \cdot 23H_2O$
Heulandite	$(Ca, Na, K)_6Al_{10}(Al, Si)Si_{29}O_{80} \cdot 25H_2O$
Epistilbite	$Ca_5NaAl_{11}Si_{29}O_{80} \cdot 25H_2O$
Brewsterite	$(Ca, Ba, Sr)_5NaAl_{11}Si_{29}O_{80} \cdot 25H_2O$

Stilbite group:

Stilbite	$(Ca, Na, K)_6Al_{10}(Al, Si)_2Si_{28}O_{80} \cdot 30H_2O$
Epidesmine	$(Ca, Na)_6Al_{10}(Al, Si)_2Si_{28}O_{80} \cdot 30H_2O$
Harmotome	$Ba_5(Na, K)Al_{11}Si_{29}O_{80} \cdot 25H_2O$
Phillipsite	$(Ca, Ba, K, Na)_{12}Al_{16}(Al, Si)_4Si_{20}O_{80} \cdot 30\text{--}40H_2O$
Wellsite	$(Ca, Ba, Sr, K, Na)_{12}Al_{16}(Al, Si)_4Si_{20}O_{80} \cdot 30\text{--}40H_2O$

Gismondite	$(Ca, K)_{10}Al_{17}(Al, Si)_2Si_{21}O_{80} \cdot 36\text{--}40H_2O$
Erionite	$Ca(Na, K)Al_4Si_{12}O_{32} \cdot 12H_2O$
Stellerite	$CaAl_2Si_7O_{18} \cdot 7H_2O$

Chabazite group:

Chabazite	$(Ca, Na, K)_7Al_{12}(Al, Si)_2Si_{26}O_{80} \cdot 40H_2O$
Gmelinite	$(Na, Ca)_{12}Al_{12}(Al, Si)_2Si_{26}O_{80} \cdot 40H_2O$

Levynite	$Ca_8Al_{16}Si_{24}O_{80} \cdot 40H_2O$

Thomsonite group:

Thomsonite	$(Ca, Na)_{12}Al_{16}(Al, Si)_4Si_{20}O_{80} \cdot 24H_2O$
Gonnardite	$Ca_4Na_8Al_{16}Si_{24}O_{80} \cdot 28H_2O$
Arduinite	$(Ca, Na)_{12}Al_{16}(Al, Si)Si_{23}O_{80} \cdot 29H_2O$
Ashcroftine	$(Ca, Mg)_6(K, Na)_8Al_{18}Si_{22}O_{80} \cdot 35H_2O$

Natrolite group:

Natrolite	$Na_2Al_2Si_3O_{10} \cdot 2H_2O$
Mesolite	$Ca_2Na_2Al_6Si_9O_{30} \cdot 8H_2O$
Scolecite	$CaAl_2Si_3O_{10} \cdot 3H_2O$
Edingtonite	$BaAl_2Si_3O_{10} \cdot 4H_2O$

Miscellaneous zeolites:

Faujasite	$CaNa_2Al_4Si_{10}O_{28} \cdot 20H_2O$
Analcite	$NaAlSi_2O_6 \cdot H_2O$
Laumontite	$(Ca, Na)_7Al_{12}(Al, Si)_2Si_{26}O_{80} \cdot 25H_2O$
Ferrierite	$Mg_2Na_4Al_8Si_{32}O_{80} \cdot 20H_2O?$

Doubtful species:

Laubanite	$Ca_2Al_2Si_5O_{15} \cdot 6H_2O$
Didymolite	$Ca_2Al_6Si_8O_{27}$
Dachiardite	composition doubtful

Cordierite	$(Mg, Fe, Mn)_2(Al, Fe)_4Si_5O_{18} \cdot H_2O$

DISILICATE TYPE

ALUMINUM DISILICATES:	$Y_pSi_4O_{10}(OH)_{3p-4} \cdot sH_2O$

	p	s	
Pyrophyllite	2	0	$Al_2Si_4O_{10}(OH)_2$
Anauxite	$2\frac{2}{3}$	1	$Al_8(Si_4O_{10})_3(OH)_{12} \cdot 3H_2O$
Kaolin group	4	0–2	$Al_4Si_4O_{10}(OH)_8$
Canbyite	4	4	$Fe_4'''Si_4O_{10}(OH)_8 \cdot 4H_2O$
Batchelorite	4	s^*	$Al_4Si_4O_{10}(OH)_8 \cdot sH_2O$
Beidellite	$2\frac{2}{3}$	4	$Al_8(Si_4O_{10})_3(OH)_{12} \cdot 12H_2O$

NON-ALUMINUM DISILICATES:

Talc group:

Talc	$Mg_3Si_4O_{10}(OH)_2$
Antigorite series:	$X_6Si_4O_{10}(OH)_8$
Antigorite	$Mg_6Si_4O_{10}(OH)_8$
Nepouite	$(Mg, Ni)_6Si_4O_{10}(OH)_8$

Connarite	$(Ni, Mg)_8(Si_4O_{10})_3(OH)_4 \cdot 6H_2O$

Freidelite group:	$X_nSi_6O_{15}(OH, F, Cl)_{2(n-3)}sH_2O$
Zeophyllite	$Ca_3Si_6O_{10}(OH, F)_{10}$
Friedelite	$Mn_8Si_6O_{15}(OH, Cl)_{10}$
Pyrosmalite	$(Mn, Fe)_8Si_6O_{15}(OH, Cl)_{10}$
Schallerite	$Mn_8(Si, As)_6O_{15}(OH, Cl)_{10-}$

Ferroschallerite	$(Fe, Mn)_8(Si, As)_6O_{16}(OH, Cl)_{10-}$
Centrallassite	$Ca_4Si_6O_{16}(OH)_2 \cdot 5H_2O$
Truscottite	$(Ca, Mg)_4Si_6O_{15}(OH)_2 \cdot 5H_2O$
Gyrolite	$(Ca_4Si_6O_{15}(OH)_2 \cdot 3H_2O$

Miscellaneous non-aluminum disilicates:

Bementite	$Mn_5Si_4O_{10}(OH)_6$
Errite	$Mn_4Si_4O_{10}(OH)_4 \cdot 3H_2O$
Apophyllite	$Ca_4K(Si_4O_{10})F_2 \cdot 8H_2O$
Okenite	$Ca_2(Si_4O_{10}) \cdot 4H_2O$

ANHYDROUS NON-ALUMINUM DISILICATES:

$$X_n(Si_4O_{10})$$

Gillespite	$BaFeSi_4O_{10}$
Sanbornite	$Ba_2Si_4O_{10}$

CHLORITE FAMILY: $X_nZ_4O_{10}(OH)_{2(n-2)} \cdot sH_2O$

Chlorite group: $(Mg, Fe)_{6-p}(Al, Fe''')_{2p}Si_{4-p}O_{10}(OH)_8$

Leptochlorite group: $(Mg, Fe)_{n-p}(Al, Fe''')_{2p}Si_{4-p}O_{10}(OH)_{2(n-2)} \cdot sH_2O;$
$5.5 > n > 4; 2 > p > 0.7$

Vermiculite group: $(Mg, Fe'')_{n-p}(Al, Fe''')_{2p}Si_{4-p}O_{10}(OH)_{2(n-2)} \cdot sH_2O$
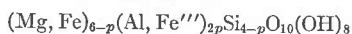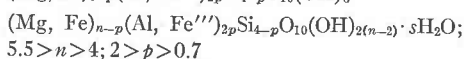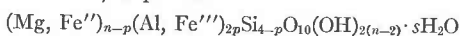
	n	p	s
Vermiculite	4	0.80	4
Saponite	3.64	0.36	4
Griffithite	3.5	0.67	3.5
Roseite	3	1.33	4

BRITTLE MICA FAMILY: $(Mg, Ca, Fe'', Mn)_{n-p}(Al, Fe''')_{2p}Si_{4-p}O_{10}(OH)_{2(n-2)} \cdot sH_2O$
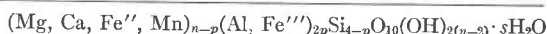
	n	p
Chalcodite	3	4/10
Epichlorite	$3\frac{1}{4}$	$\frac{3}{4}$
Stilpnomelane	2	1
Ottrellite	$2-2\frac{1}{2}$	$1\frac{1}{2}-1$
Margarite	3	2
Ephesite	4	2
Prehnite	3	1
Chloritoid	4	2

Clintonite $X_4Z_4O_{10}(OH)_2$
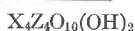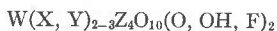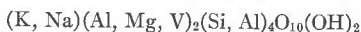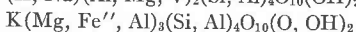
Mica group: $W(X, Y)_{2-3}Z_4O_{10}(O, OH, F)_2$

Muscovite series $(K, Na)(Al, Mg, V)_2(Si, Al)_4O_{10}(OH)_2$
Biotite series $K(Mg, Fe'', Al)_3(Si, Al)_4O_{10}(O, OH)_2$
Lithia mica series $K(Mg, Fe'', Mn, Li, Al, Fe''')_3(Si, Al)_4O_{10}(O, OH, F)_2$

Miscellaneous disilicates:

Glauconite	$K_2(Mg, Fe)_2Al_6(Si_4O_{10})_3(OH)_{12}$
Pholidolite	$KMg_6AlSi_7O_{20}(OH)_4 \cdot 3H_2O$
Cookeite	$(Li, Al)_4(Si, Al)_4O_{10}(OH)_4 \cdot 2H_2O$
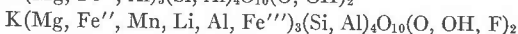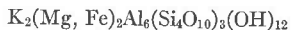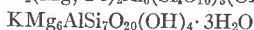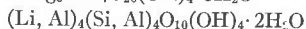
Bityite $\quad$ $Ca_4(Li, Be, Al)_{12}[(Si, Al)_4O_{10}]_3(OH)_{20}$
Ganophyllite $\quad$ $NaMn_6Al_2(Si_4O_{10})_2(OH)_{11}$

METASILICATE TYPE

Chain Structures:

Amphibole group: $\quad$ $(W, X\ Y)_{7-8}(Z_4O_{11})_2(O, OH, F)_2$

Anthophyllite series: $\quad$ $X_7(Z_4O_{11})_2(OH)_2$

Anthophyllite $\quad$ $(Mg, Fe)_7Si_8O_{22}(OH)_2$
Gedrite $\quad$ $(Mg, Fe, Al)_7(Al, Si)_8O_{22}(OH)_2$

Cummingtonite series: $\quad$ $X_7(Z_4O_{11})_2(OH)_2$

Cummingtonite $\quad$ $(Mg, Fe)_7Si_8O_{22}(OH)_2$
Grünerite $\quad$ $(Mg, Fe, Mn)_7Si_8O_{22}(OH)_2$

Tremolite-actinolite series: $\quad$ $W_2X_5(Z_4O_{11})_2(OH)_2$

Tremolite $\quad$ $Ca_2Mg_5Si_8O_{22}(OH)_2$
Actinolite $\quad$ $Ca_2(Mg, Fe)_5Si_8O_{22}(OH)_2$

Hornblende series: $\quad$ $2W_3(X, Y)_5(Z_4O_{11})_2(O, OH, F)_2$

Edenite $\quad$ $Ca_4Na_2Mg_{10}Al_2Si_{14}O_{44}(OH, F)_4$
Pargasite $\quad$ $Ca_4Na_2Mg_9Al_4Si_{13}O_{44}(OH, F)_4$
Hastingsite $\quad$ $Ca_4Na_2Mg_8Al_6Si_{12}O_{44}(OH, F)_4$
Hornblende $\quad$ $Ca_4Na_2(Mg, Fe'')_8(Al, Fe''', Ti)_6Si_{12}O_{44}(O, OH)_4$
Kearsutite $\quad$ $Ca_4Na_1(Mg, Fe'')_7(Al, Fe''')_5Ti_2Si_{12}O_{46}(OH)_2$
Arfvedsonite $\quad$ $Na_6Mg_8Al_2Si_{16}O_{44}(OH, F)_4$
Arfvedsonite $\quad$ $Ca_2Na_4Fe_7''(Al, Fe''')_6Si_{13}O_{44}(OH)_4$
Holmquistite $\quad$ $CaNaLi_2Mg_6Al_5Si_{15}O_{44}(OH)_4$
Glaucophane $\quad$ $Na_4Mg_6Al_4Si_{16}O_{44}(OH, F)_4$
Riebeckite $\quad$ $Na_6Fe_6''Fe_4'''Si_{16}O_{46}(OH)_2$

Narsarsukite $\quad$ $Na_2(Ti, Fe''')Si_4(O, F)_{11}$; Ti:Fe$=3$:1
Chrysotile $\quad$ $(Mg, Fe)_6Si_4O_{11}(OH)_6 \cdot H_2O$

Pyroxene group: $\quad$ $W(X, Y)(Z_2O_6)$

Enstatite series: $\quad$ WXZ_2O_6

Enstatite $\quad$ $Mg_2Si_2O_6$
Hypersthene $\quad$ $(Mg, Fe)_2Si_2O_6$

Pigeonite series: $\quad$ WXZ_2O_6

Clinoenstatite $\quad$ $Mg_2Si_2O_6$
Pigeonite $\quad$ $(Ca, Mg)(Mg, Fe)Si_2O_6$

Diopside series: $\quad$ $W(X, Y)Z_2O_6$

Diopside $\quad$ $CaMgSi_2O_6$
Hedenbergite $\quad$ $CaFeSi_2O_6$
Augite $\quad$ $Ca(Mg, Fe, Al)(Al, Si)_2O_6$
Schefferite $\quad$ $Ca(Mg, Fe, Mn)Si_2O_6$
Zinc schefferite $\quad$ $Ca(Mg, Mn, Zn)Si_2O_6$
Jeffersonite $\quad$ $Ca(Mg, Mn, Fe, Zn)Si_2O_6$

Acmite-jadeite series: $\quad$ WYZ_2O_6

Acmite $\quad$ $NaFe'''Si_2O_6$

Jadeite	$NaAlSi_2O_6$
Aegirite	$(Ca, Na)(Mg, Fe''', Al)Si_2O_6$
Spodumene	$LiAlSi_2O_6$

PYROXENOID FAMILY:

Rhodonite series: WXZ_2O_6

Rhodonite	$(Mn, Ca)MnSi_2O_6$
Fowlerite	$(Mn, Ca)(Mn, Zn)Si_2O_6$
Iron rhodonite	$(Mn, Ca)(Mn, Fe)Si_2O_6$
Pyroxmangite	$Mn(Mn, Fe)Si_2O_6$
Sobralite	$(Mn, Ca)(Mg, Fe)Si_2O_6$

Wollastonite group: $W_3X_3Z_6(O, OH)_{18}$

Wollastonite	$Ca_3Ca_3Si_6O_{18}$
Bustamite	$Ca_3Mn_3Si_6O_{18}$
Pectolite	$Ca_4Na_2Si_6O_{16}(OH)_2$
Schizolite	$(Ca, Mn)_4Na_2Si_6O_{16}(OH)_2$

Alamosite	$Pb_3Pb_3Si_6O_{18}$

Miscellaneous pyroxenoids:

Margarosanite	$(Pb, Ca, Mn)SiO_3$
Babingtonite	$Ca_2Fe''Fe'''Si_5O_{14}(OH)$
Taramellite	$Ba_2Fe_2'''Si_5O_{15}$
Hyalotekite	$(Ba, Ca, Pb)_4BSi_6O_{17}(F, OH)$
Neptunite	$(Na, K)(Fe'', Mn'', Ti)Si_2O_6$

CALCIUM METASILICATE FAMILY:

Xonotlite	$Ca_3Si_3O_8(OH)_2$
Inesite	$(Ca, Mn)_3Si_3O_8(OH)_2$
Hillebrandite	$Ca_2SiO_3(OH)_2$
Riversideite	$Ca_2Si_2O_6 \cdot H_2O$
Jurupaite	$(Ca, Mg)_2Si_2O_6 \cdot H_2O$
Crestmoreite	$CaSiO_3 \cdot 2H_2O$
Radiophyllite	$CaSiO_3 \cdot H_2O$
Afwillite	$Ca_3Si_2O_6(OH)_2 \cdot 2H_2O$

COPPER METASILICATE FAMILY: $CuSiO_3 \cdot sH_2O$

Chrysocolla	$CuSiO_3 \cdot 2H_2O$
Bisbeeite	$CuSiO_3 \cdot H_2O$
Shattuckite	$2(CuSiO_3) \cdot H_2O$
Plancheite	$3(CuSiO_3) \cdot H_2O$

Miscellaneous metasilicates:

Carpholite	$MnAl_2(SiO_3)_2(OH)_4$
Stokesite	$CaSn(SiO_3)_3 \cdot 2H_2O$
Searlesite	$NaB(SiO_3)_2 \cdot H_2O$
Bavenite	$Ca_4BeAl_2Si_9O_{25}(OH)_2$
Cenosite	$Ca_2(Ce, Y)_2(SiO_3)_4 \cdot CO_3 \cdot H_2O$

Eudidymite	$H_2Na_2Be_2(Si_3O_8)_2$

Epididymite	$H_2Na_2Be_2(Si_3O_8)_2$
Elpidite	$H_2Na_2Zr(Si_3O_8)_2 \cdot H_2O$
Leucosphenite	$BaNa_2(Ti, Zr)(Si_3O_8)_2$
Ussingite	$Na_2Al(Si_3O_8)(OH)$

Ring Structures:

Benitoite	$BaTiSi_3O_9$

Catapleiite series:

Catapleiite	$(Na_2, Ca)ZrSi_3O_9 \cdot 2H_2O$
Natron-catapleiite	$Na_2ZrSi_3O_9 \cdot 2H_2O$
Eudialyte (eucolite)	$(Ca, Na)_2(Zr, Ce, Fe'', Mn)Si_3O_8(OH, Cl)$
Steenstrupine	$(Ca, Na)_4Mn(Ce, La, Al, Fe''')_6(Si, Ti)_9O_{27}(OH)_7 \cdot 3H_2O$

Tourmaline series: $WX_3Y_6(Z_3O_9)_3(O, OH, F)_4$

Dravite	$NaMg_3B_3Al_3(Al_3Si_6O_{27})(OH)_4$
Ca-tourmaline	$CaMg_3B_3Al_3(Al_3Si_6O_{27})(O, OH)_4$
Indicolite	$Na(Al, Fe'', Li, Mg)_3B_3Al_3(Al_3Si_6O_{27})(O, OH, F)_4$
Tourmaline	$(Na, Ca)(Mg, Fe'', Fe''')_3B_3Al_3(Al_3Si_6O_{27})(O, OH)_4$
"Schorl"	$NaFe_3B_3Al_3(Al_3Si_6O_{27})(OH)_4$

Beryl	$Al_2Be_3Si_6O_{18}$

PYROSILICATE TYPE

Thalenite group:

Thalenite	$Y_2Si_2O_7$
Thortvietite	$(Sc, Y)_2Si_2O_7$
Cerite	$(Ce, Y, Pr, Nd)_2Si_2O_7 \cdot H_2O$
Rowlandite	$(Y, Ce, La)_4Fe''(Si_2O_7)_2 \cdot F_2$

Melilite group:

Melitite series: $W_2(X, Y)Z_2O_7$

Åkermanite	$Ca_2MgSi_2O_7$
Gehlenite	$Ca_2Al(AlSiO_7)$
Soda-melilite	$CaNaAlSi_2O_7$
Hardystonite	$Ca_2ZnSi_2O_7$
Leucophanite	$CaNaBeSi_2O_6F$
Meliphanite	$(Ca, Na)_2Be(Al, Si)_2O_6F$

Barysilite group:

Barysilite	$Pb_3Si_2O_7$
Ganomalite	$(Ca, Pb)_{10}(Si_2O_7)_3(OH)_2$
Nasonite	$(Ca, Pb)_{10}(Si_2O_7)Cl_2$

HEMIMORPHITE FAMILY:

Hemimorphite	$Zn_4Si_2O_7(OH)_2 \cdot H_2O$
Clinohedrite	$Ca_2Zn_2Si_2O_7(OH)_2 \cdot H_2O$
Bertrandite	$Be_4Si_2O_7(OH)_2$
Cuspidine	$Ca_4Si_2O_7F_2$
Molybdophyllite	$Pb_2Mg_2Si_2O_7(OH)_2$
Murmanite	$Na_2Ti_2Si_2O_7(OH)_4$

Miscellaneous pyrosilicates:

Barylite	$BaBe_2Si_2O_7$
Lawsonite	$CaAl_2Si_2O_7(OH)_2 \cdot H_2O$
Harstigite	$(Ca, Mn, Mg)_8Al_2(Si_2O_7)_3(OH)_4$
Danburite	$CaB_2(Si_2O_7)O$
Astrophyllite	$(Na, Ca)_5(Fe'', Al, Ti)_{15}(Si_2O_7)_6(F, OH)_8$
Aenigmatite	$(Na, Ca)_4(Fe'', Mn, Fe''', Ti, Al)_{13}(Si_2O_7)_6$

ORTHOSILICATES

Normal Orthosilicates:

Chrysolite group:	X_2SiO_4
Olivine series:	$(Ca, Mn, Mg, Fe, Pb)(Mg, Fe, Mn, Zn)SiO_4$
Forsterite	Mg_2SiO_4
Olivine	$(Mg, Fe)_2SiO_4$
Hortonolite	$(Mg, Fe, Mn)_2SiO_4$
Knebelite	$(Fe, Mn)_2SiO_4$
Fayalite	Fe_2SiO_4
Tephroite	$(Mn, Zn, Mg)_2SiO_4$
Roepperite	$(Fe, Mn, Zn)_2SiO_4$
Glaucochroite	$CaMnSiO_4$
Monticellite	$CaMgSiO_4$
Larsenite	$PbZnSiO_4$
Calcium larsenite	$(Pb, Ca)ZnSiO_4$
Larnite	Ca_2SiO_4
Merwinite	$Ca_3Mg(SiO_4)_2$
Phenakite group:	X_2SiO_4
Phenacite	Be_2SiO_4
Willemite	Zn_2SiO_4
Troostite	$(Zn, Mn)_2SiO_4$
Trimerite	$(Mn, Ca)BeSiO_4$
Dioptase	H_2CuSiO_4
Humite group:	$X_{2r+1}(SiO_4)_r(OH, F)_2$
Norbergite	$Mg_3(SiO_4)_1(OH, F)_2$
Chondrodite	$Mg_5(SiO_4)_2(OH, F)_2$
Humite	$Mg_7(SiO_4)_3(OH, F)_2$
Clinohumite	$Mg_9(SiO_4)_4(OH, F)_2$
Hodgkinsonite group:	$X_{2r+1}(SiO_4)_r(OH, F)_2$
Hodgkinsonite	$(Zn_2Mn)(SiO_4)(OH)_2$
Alleghanyite	$Mn_5(SiO_4)_2(OH, F)_2$
Leucophoenicite	$Mn_7(SiO_4)_3(OH)_2$
Gageite	$(Mn, Mg, Zn)_{16}(SiO_4)_6(OH)_8 \cdot 3H_2O$

Garnet group: $X_3Y_2(ZO_4)_3$; $X=Mg$, Fe, Mn, Ca; $Y=Al$, Fe''', Cr, Ti, Mn'''; $Z=Si$, Ti in subordinate amount.

Almandite series:	$(Mg, Fe, Mn)_3Al_2(SiO_4)_3$
Pyrope	$Mg_3Al_2(SiO_4)_3$
Almandite	$Fe_3Al_2(SiO_4)_3$
Spessartite	$Mn_3Al_2(SiO_4)_3$
Andradite series:	$Ca_3(Al, Fe, Cr)_2(SiO_4)_3$
Grossularite	$Ca_3Al_2(SiO_4)_3$
Andradite	$Ca_3Fe_2(SiO_4)_3$
Uvarovite	$Ca_3Cr_2(SiO_4)_3$
Titanium garnet	$Ca_3(Al, Fe'', Fe''', Ti)_2[(Si, Ti)O_4]_3$

Sarcolite	$(Ca, Na_2)_3Al_2(SiO_4)_3$
Vesuvianite	$Ca_{10}Al_4(Mg, Fe)_2Si_9O_{34}(OH)_4$
Epidote group:	$W_2Y_3(ZO_4)_3(OH)$
Zoisite	$Ca_2Al_3(SiO_4)_3(OH)$
Epidote series:	$(Ca, Mn)_2(Al, Fe, Mn)_3(SiO_4)_3(OH)$
Clinozoisite	$Ca_2Al_3(SiO_4)_3(OH)$
Epidote	$Ca_2(Al, Fe)_3(SiO_4)_3(OH)$
Piedmontite	$Ca_2(Al, Fe, Mn)_3(SiO_4)_3(OH)$
Manganepidote	$(Ca, Mn'')_2(Al, Mn''')_3(SiO_4)_3(OH)$
Allanite series:	
Allanite	$(Ca, Ce, La, Na)_2(Al, Fe, Mn, Be, Mg)_3(SiO_4)_3(OH)$
Magnesium orthite	$CaCeMg_2Al[Si(O, OH)_4]_3F$
Nagatelite	$(Ca, Ce)_2(Al, Fe''', Fe'')_3[(P, Si)O_4]_3(OH)$

Hancockite	$(Ca, Pb, Sr, Mn)_2(Al, Fe, Mn)_3(SiO_4)_3(OH)$
Pumpellyite	$Ca_2Al_3(SiO_4)_3(OH) \cdot H_2O$
Zircon group:	$XSiO_4$
Zircon	$ZrSiO_4$
Thorite	$ThSiO_4$

WÖHLERITE FAMILY:

Wöhlerite group	$W_3X(ZO_4)_2(F, OH)$
Rosenbuschite	$(Na, Ca)_3(Fe, Ti, Zr)(SiO_4)_2F$
Wöhlerite	$(Ca, Na)_3(Zr, Cb)(SiO_4)_2F$
Hiortdahlite	$(Ca, Na)_3(Fe, Mn, Zr, Ti)(SiO_4)_2(F, OH)$
Guarinite	$(Ca, Na)_3(Fe, Mn, Zr, Cb)(SiO_4)_2(O, F, OH)$
Johnstrupite	$(Ca, Na, Ce)_3(Al, Mg, Ti, Ce)(SiO_4)_2(F, OH)$

Rinkite	$(Ca, Na)_{15}(Ce, Zr, Ti)_7(SiO_4)_{10}F_7$
Rinkolite	$(Ca, Na)_6(Ce, Ti)_3(SiO_4)_4(F, OH)_4$
Mosandrite	$(Ca, Na)_{12}Ce_3(Zr, Ti, Mg)_4(SiO_4)_{10}F_5$
Lâvenite	$(Ca, Na)(Zr, Cb, Fe, Ti, Mn)(SiO_4)F$
Britholite	$Ca_3Ce_4[(Si, P)O_4]_4(OH, F)_3$
Hellandite	$Ca_3(Y, Er)_4(Al, Fe''', Mn''')_5(SiO_4)_6(OH)_9$
Lessingite	$Ca_4(Ce, Y, Er, La)_7(SiO_4)_6(OH, F)_5$

DATOLITE FAMILY:

Datolite	$Ca_2B_2(SiO_4)_2(OH)_2$

Euclase	$Be_2Al_2(SiO_4)_2(OH)_2$
Homilite	$Ca_2Fe''B_2(SiO_4)_2O_2$
Gadolinite	$Y_2Fe''Be_2(SiO_4)_2O_2$

Miscellaneous orthosilicates:

Topaz	$Al_2SiO_4(F, OH)_2$
Axinite	$H(Ca, Mn, Fe)_3Al_2B(SiO_4)_4$
Ilvaite	$Ca(Fe, Mn)_2Fe'''(SiO_4)_2(OH)$
Tinzenite	$Ca_2Al_2Mn'''(SiO_4)_4$
Eulytite	$Bi_4(SiO_4)_3$
Zunyite	$Al_8(SiO_4)_3(F, Cl, OH)_{12}$

Subsilicates:

ALUMINUM SUBSILICATE FAMILY:

Andalusite	Al_2SiO_5
Sillimanite	Al_2SiO_5
Mullite	$Al_6Si_2O_{13}$
Kyanite	Al_2SiO_5
Staurolite	$Fe''Al_4Si_2O_{10}(OH)_2$

Kentrolite group:

Kentrolite	$Pb_3Mn_4'''Si_3O_{15}$
Melanotekite	$Pb_3Fe_4'''Si_3O_{15}$

Beckelite	$Ca_3(Ce, La, Di)_4Si_3O_{15}$

Titanium subsilicates:

Titanite	$CaTiSiO_5$
Lorenzenite	$Na_2(Zr, Ti)_2Si_2O_9$
Ramsayite	$Na_2Ti_2Si_2O_9$
Fersmanite	$Ca_4Na_2Ti_4Si_3O_{18}F_2$
Molengraafite	$Ca_4Na_4(Mg, Fe'')AlTi_4Si_6O_{28}(OH)$
Lamprophyllite	$Ca_2Na_6Ti_6Si_6O_{28}(OH, F)_2$

Miscellaneous subsilicates:

Dumortierite	$AlB_8Si_3O_{19}(OH)$
Serendibite	$Ca_2Mg_4Al_6B_2Si_4O_{26}$
Ardennite	$(Ca, Mn, Mg)_4Al_4(As, V)Si_4O_{18}(OH)_5$
Sapphirine	$Mg_5Al_{12}Si_2O_{27}$
Kornerupine	$MgAl_2SiO_6$
Cappelenite	$Ba(Y, Ce, La)_6B_6Si_3O_{24}(OH)_2$
Melanocerite	$Ca_{16}Na_4(Y, La)_3(Zr, Ce)_6B_3Si_{12}O_{57}F_{12}$
Mackintoshite	$(U, Ce, Th, La, Y, Pb)_2SiO_5$

URANIUM SILICATES:

Uranophane group:

Uranophane	$CaU_2Si_2O_{11} \cdot 7H_2O$
Sklowdowskite	$MgU_2Si_2O_{11} \cdot 7H_2O$
Kasolite	$Pb_2U_2Si_2O_{12} \cdot H_2O$
Soddyite	$U_5Si_2O_{19} \cdot 6H_2O$

III. DISCUSSION OF THE CLASSIFICATION

The writer is aware of the probability that a considerable number of minerals will be found, when more structural data are available, to have been misplaced in the classification. However, the general outline of the classification and the positions of the most important groups will probably stand as given. The chief uncertainties in the classification arise from insufficient data on rare minerals, many of which offer almost insurmountable difficulties in structural studies. The structures of these are not likely to be solved soon. In the meantime, the writer believes, the results of a new technique, and a newer and more adequate theory should be applied to the study of the silicates and to their classification. One must first have a classification in order that it may be modified and further improved. Further, an attempt to make the classification of all the silicates gives direction to future study since exceptions and modifications of the theory appear in the course of a systematic examination of the data.

The classification proceeds, in general, from the most siliceous types to those having the least amount of silica, namely the orthosilicates. At the end of the classification certain titano-silicates and boro-silicates are introduced. It is difficult to decide which of the low-silica compounds are no longer essentially silicates. The point of view here taken is that a mineral ceases to be a silicate when the SiO_4 tetrahedra are no longer the dominant motif in the structure. The classification, therefore, can have no sharp break at the end; it would naturally fit onto a similar grouping of titano-silicates and boro-silicates and some other rare, low-silica-content minerals.

SILICA TYPE

The minerals of this type, except the crystalline forms of silica, are composed almost exclusively of alkali or calcium aluminum silicates, the composition being such that $2(Al+Si)=0$. Apparently only a few exceptions to this composition are of this type, namely, danalite, helvite and cordierite. Another noteworthy feature of this type is the presence, in some of its groups, of such unusual components as Cl, S, SO_4 and CO_3. These are apparently held in the large spaces of the open network, which is characteristic of this structural type. It is to be noted that the structure of these minerals is analogous to that of the crystalline forms of silica, which are also three-dimensional networks of SiO_4 tetrahedra. These silicate structures differ from silica in that some of the tetrahedra in the cell are AlO_4. As a consequence of this, other atoms, usually the large alkali or alkaline earth atoms also enter into the structure, in order to balance the valence bonds of the oxygens. It is for this reason that

the total valences of the alkali or calcium atoms are always equal to the number of aluminum atoms in the general formula.

Since the three-dimensional network is the so-called open structure, the density of this type of silicate is lower than that of any other type, the range being from 2 to 3, with most of the members occupying an intermediate position. It is likewise true that the mean refractive index is also low for these silicates. Further, because of the nature of the three-dimensional network, the tendency of producing equidimensional crystals is shown in the type. Since the chemical and physical properties of this type are so distinctive, no particular difficulty is encountered in recognizing its members.

Silica group: SiO_2. The classification of the silicates properly begins with the crystalline forms of silica because these substances show in their structures the same silicon-oxygen tetrahedra as are found in the silicates. Further, in all the forms of silica which have thus far been studied (four out of the seven crystalline modifications) the tetrahedra are linked together in such a way as to share corners with four other tetrahedra to produce the three-dimensional network, which is the linkage of our first type.

Since the silica minerals show no appreciable variation from pure SiO_2, for the sake of brevity no discussion of other aspects of these minerals is attempted here.

Petalite group: W Z_5O_{10}. Petalite (Li, Na)$AlSi_4O_{10}$. The mineral is essentially a lithium compound. The only considerable substituting atom is Na. The range of the ratio Li:Na is from 15:1 to 2.3:1 (Dana 1892, p. 312, anal. 4).

Milarite 6(Ca, K)(Al, Be, Si)$_5O_{10}$ with Ca:K = 2:1 and Al:Be:Si = 1:2:12, the expanded form being: $Ca_4K_2Be_4Al_2Si_{24}O_{60}$ with a small amount of water possibly belonging in the formula. This is one of the few silicates in which the Be apparently plays the same role as Si in the structure. Incidentally it is only very recently that this old species was found to contain Be (Palache 1931).

Leifite $Na_4Al_2Si_9O_{22}F_2$. Because of its general physical characteristics and composition this little known mineral is placed here. It is perhaps more closely related to the members of this group than any other.

Feldspar group: W Z_4O_8, with W = Na, Ca, K, Ba and to some extent Na_2, and Z = Si−Al; Si:Al = 3:1 to 1:1. Since all feldspars contain a certain minimum amount of Al and Si the general formula may be somewhat more specifically stated as

$$W\ Al(Al,\ Si)Si_2O_8$$

with only one atom out of the four Al+Si atoms participating in the Al,

Si substitution found in some members of the feldspar series. The usual division into monoclinic and triclinic members is here made and the two symmetry types in the feldspars are retained because no new evidence to show that orthoclase is triclinic has been presented, and further evidence of some value (Taylor 1933) has shown that it is probably monoclinic.

The problem of miscibility in the monoclinic feldspars is rather complicated by the wide range of temperature of formation. It can be laid down as a general rule, in the feldspars as well as in other silicates, that a higher temperature of formation allows greater miscibility of the components. Thus K, Na, Ba may be, and very likely are, completely miscible at high temperatures of formation. The ordinary temperatures at which we study the minerals show miscibility ranges which are very different. It is because of this difference in miscibility that we have the so-called exsolution phenomena. Unmixing is probably a rather sluggish process in the feldspars so that we might expect certain members formed at high temperatures to exhibit greater miscibility than the same minerals formed at lower temperatures.

In the orthoclase series, K and Na are probably not miscible to any considerable extent at low temperatures of formation, as in low-grade metamorphism and in most vein deposits. However, analyses of higher temperature orthoclases indicate as much as 40 per cent Na may replace K (Alling 1921).

Barbierite, the supposed monoclinic soda-feldspar has not been shown to exist as such. The fact that Na replaces some K in orthoclase does not, of course, necessitate the supposition that a pure monoclinic sodium member exists. This fallacy is another example of the dangers of postulating so-called "end members."

Apparently a more or less complete series of the K, Ba monclinic feldspars is known. The mineral hyalophane has the composition $(K, Ba)Al(Al, Si)Si_2O_8$ with K:Ba in all proportions. However, some evidence (Taylor Darbyshire and Strunz 1934) indicates that celsian, the pure Ba feldspar, may be triclinic. If this is true, the K, Ba series may be strictly two overlapping series having physical properties sufficiently alike so that we cannot detect the break.

The triclinic feldspars are divided into two main series: the microclines, and the plagioclases.

The microclines, with the formula $(K, Na)AlSi_3O_8$ are generally homogeneous, even with considerable amounts of Na. Anorthoclase is often, however, not homogeneous, and as such cannot be considered as a definite mineral compound. In other words, Na does not enter into the composition of the microcline members to any large extent. This fact

may be an expression of the lower temperature range of formation of the microclines as compared with the orthoclases, and a consequent lessening of the miscibility of Na and K. In albite, $NaAlSi_3O_8$, we have only a moderate amount of K (15 per cent) as a maximum, so that we probably have no overlapping series from both ends.

The plagioclases are seemingly a straightforward, single isomorphous series with examples known throughout the range between albite and anorthite. Recent x-ray work (Taylor, Darbyshire and Strunz 1934) has shown, however, that the anorthite cell is double the albite cell and that the change occurs somewhere about $Ab_1 An_1$. This evidence seems to indicate that with respect to the x-ray properties there are really two series, an albite-labradorite portion, and a labradorite-anorthite part. Yet none of the other physical measurements in the plagioclases indicates that such a break occurs, so that one may infer from this that even though we have two series, they are so close in their physical properties that we do not find any measurable differences. When two such series are so closely related, for our purposes we may consider them as one.

Anemousite, the feldspar containing the so-called carnegeite molecule $Na_2Al_2Si_2O_8$, a supposed isomer of nepheline, has a composition which may be expressed as $(Ca, Na, Na_2)Al(Al, Si)Si_2O_8$; that is to say, some of the Ca is replaced in the structure by Na_2. This is possible in the open network in which spaces are available to accommodate an extra atom, but it is a rarity in the silicates as a whole. The carnegeite molecule is not a feldspar and we do not, therefore, include it in our list. Only a small amount of Na_2 has been found to enter into the feldspar composition.

Pollucite $(Cs, Na)_4Al_4Si_9O_{26} \cdot H_2O$ with $Cs:Na = 4:1$ somewhat variable. There are two formula weights of the above in the unit cell as determined by the writer ($a_0 = 13.66$ Å) and checked by recent work of Strunz (1936).

The formula is derived from the analyses in Dana (1892, p. 344) and the work by Wells (1891). It is perhaps stretching relations to group this mineral with leucite as is commonly done in textbooks. Presumably the fact that both are isometric is the only reason for grouping them together.

Leucite $WZ_3 O_6$, or more specifically $KAlSi_2O_6$; Na, Ca usually less than 1 per cent and Li, Rb, Cs in traces. Leucite is, as minerals go, a fairly pure specific compound with little variation in its composition. The zeolite analcite $NaAlSi_2O_6 \cdot H_2O$ is possibly closely related in structure, but no evidence is found of an isomorphous relationship between the two.

Nephelite group: WZ_2O_4. Nephelite $(Na, K)(Al, Si)_2O_4$, sometimes with Ca and Mg in very small amounts; $Na:K = 35:1$ to $3:1$; $Si:Al = 1.1:1$

rather uniformly. Bannister (1931) has shown that the unit cell contains 32 oxygen atoms so that the composition of the unit cell is eight times our formula.

One of the remarkable features about the chemistry of nephelite is the uniform failure of Al:Si ratio to be unity. There is nearly always a slight preponderance of Si so that the ratio is, as given above, 1.1:1. Corresponding with this slight deviation in the ratio of Si:Al in the natural nephelites, we have a decrease in the $(Na+K)$ atoms so that the formula is only approximately true. For a detailed account of the chemical and physical characteristics of the nephelites reference should be made to Bannister's excellent work (1931).

Kaliophilite WZ_2O_4, with $W=K$ predominantly, and Na subordinate; the ratio $K:Na=53:1$ to $4:1$; a trace of Ca in most cases; $Z=Si:Al = 1:1$. The unit cell probably contains 54 units of the above formula (Bannister 1931). The writer is inclined to agree with Bannister in his statement that a continuous isomorphous series (Bowen 1917) between kaliophilite and nephelite has not been definitely shown to exist in nature.

Eucryptite $WZ_2 O_4$, with $W=Li$; $Z=Si-Al$; $Si:Al=1:1$.

Cancrinite group: $W_{7-8}Z_{12}O_{24} \cdot N \cdot sH_2O$; $W=Na$, Ca, K with Na and Ca predominating; $Z=Si:Al=1:1$.

Cancrinite, which is here meant to include all of the minerals of the group except those containing Cl, is rather variable in composition within the limits indicated by the group formula. Since no study of the analyses has appeared in the form taken here, a résumé is given in the following table.

TABLE 3. CANCRINITE: ANALYSES (BÖRGSTROM 1930)

	Na	K	Ca	Al	Si	O	CO$_3$	SO$_4$	H$_2$O
Synthetic Friedel	7.17	.50		6.02	5.98	23.79	1.05		2.30
Brevig yellow	6.77	.07	.55	5.40	6.60	23.99	1.29		2.96
Litchfield	6.38	.02	.93	5.90	6.10	23.69	1.51		2.16
Litchfield	6.66	.06	.97	6.06	5.94	23.98	1.32		2.99
Miask	5.86	.04	1.09	5.92	6.08	23.63	1.47		2.96
Brevig Rose	6.23	.05	1.29	5.80	6.20	24.02	1.51		2.52
French River	5.10	.18	1.46	6.02	5.98	23.71	1.39		2.10
Colo.	5.19	.11	1.61	6.14	5.86	23.59	1.61		2.68
Beaver Creek	6.31	.32	.79	6.08	5.92	23.73	.76	.61	2.91

From this table of atomic ratios, on the basis of $Al+Si=12$, the compositional ranges may be stated as:

(a) $Na_8Al_6Si_6O_{24} \cdot CO_3 \cdot 2H_2O$

(b) $(Na, K)_6CaAl_6Si_6O_{24} \cdot CO_3 \cdot 2-3H_2O$

(c) $(Na, K)_6Ca_2Al_6Si_6O_{24} \cdot 2CO_3 \cdot 2-3H_2O$

The compositions of the most reliable analyses indicate a tendency for Ca to increase as Na+K decreases, and also for CO_3 to increase with the Ca. Water seems to bear no exact relation to the other constituents, varying from 2 to 3 per 24 oxygen atoms. The Al:Si ratio is fairly uniformly 1:1.

TABLE 4. MICROSOMMITE AND DAVYNE

	Na	K	Ca	Al	Si	O	CO_3	SO_4	Cl
Microsommite Vesuvius v. Rath	3.00	2.62	2.15	6.11	5.89	24.31		.22	2.76
Microsommite Vesuvius Scacci	3.23	1.80	2.09	6.42	5.58	23.44		.76	2.36
Davyne Mt. Somma	3.93	1.66	2.02	6.14	5.86	23.78	.36	.53	2.16

Microsommite and Davyne $W_8Z_{12}O_{24}(Cl, SO_4, CO_3)_3$; W = Na, Ca, K; Z = Al+Si; Al:Si = 1:1. $(Na, K)_6Ca_2Al_6Si_6O_{24} \cdot Cl_2 \cdot CO_3$ is the most common composition, but Na+K, with Na dominant, may vary from 5 to 6 with a consequent variation in the Cl:CO_3 ratio (Table 4). The chief differences between this series and the cancrinites are that in the former there are considerable quantities of Cl and some SO_4, and that much more K is present; water is absent.

Sodalite group: Sodalite series: $W_{7-8}Z_{12}O_{24}N_{1-2}$; W = Na predominantly, Ca common; Z = Si:Al = 1:1; N = Cl, S, SO_4, CO_3 rarely. This group might be said to be the isometric equivalent of the cancrinite group, with some modifications, as appears in the formulae in the classification.

There is no direct evidence that the compound $Ca_4Al_6Si_6O_{24} \cdot SO_4$ is a true member of this series. The analyses quoted (Barth 1932) do not support the contention, and Barth's general formula is here not used for that reason. Jaeger (1929) has shown that the artificial aquamarines have a composition which may be referred to our general formula.

Danalite series: $X_8Z_{12}O_{24} \cdot S_2$; X = Mn, Fe, Zn; Z = Si+Be; Si:Be = 1:1; or $(Mn, Fe, Zn)_8Be_6Si_6O_{24} \cdot S_2$. It is to be noted that the two species of this series (danalite with Zn, helvite without) are closely related to the sodalites. However, the elements (Mn, Fe″, Zn) are rarely found in this type of silicate; and further, Be apparently substitutes for Si in the tetrahedral network. The unit cell dimensions of danalite and sodalite are closely similar (Barth 1926).

Scapolite series: $W_4Z_{12}O_{24}N$; W = Ca, Na; K to $4\frac{1}{2}$ per cent; Z = Si+Al; Si:Al = 3:1 to 1:1; N = Cl, CO_3; SO_4 subordinate, (OH) rare. Intermediate members are mizzonite, dipyre, and wernerite. These are members of a series of which marialite and meionite are the end components; neither

of these two are, however, pure compounds as found in nature. In marialite $Na:Ca<4:1$ and in meionite $Ca:Na<8:1$. Most of the members of the series are higher in Ca than in $Na+K$. Incidentally it may be worth noting here that one of Barth's (1932) end components of the sodalite group is close in composition to the calcic end of the scapolite series. Presumably under the temperature conditions prevailing, the tetragonal form of calcium aluminum silicate is stable rather than the isometric form, sodalite.

The chief chemical differences of this series as contrasted with the preceding two groups are (1) the variability of the $Si:Al$ ratio, as in the feldspars; (2) the lower $Ca+Na$ molecular percentage. Structurally they are related in that they are made up of three dimensional networks of Si and Al tetrahedra.

Zeolite family: $W_mZ_rO_{2r}\cdot sH_2O$; $W=Na, Ca, K, Ba, Sr$; also rarely Mg, Mn; $Z=Si+Al$; $Si:Al>1$; s variable. A more specific and rather more complex statement of the composition of the zeolites is:

$$(Na, K)_m(Ca, Ba, Sr)_nAl_{2n+m}Si_rO_{2(2n+m+r)}\cdot sH_2O.$$

The zeolites have been the subject of investigation and theory since the earliest days of mineralogy because of the large number of species within a limited range of composition. Many studies have been made attempting to show the constitutional relations between the members of this family. Tschermak's classical work remains as the best example of the studies according to the older theories. Winchell (1925) has contributed a series of papers embodying some of the newer concepts. Bannister and Hey have made careful chemical and x-ray studies of many of the zeolites, which they have described in a series of nine splendid papers over a period of six years. The ideas presented below are to a large extent a digest of those expressed in the works above mentioned, with some modifications and additions, as indicated.

The zeolites, as well as the other members of this silicate type, have certain chemical characteristics, as expressed in the formula previously given.

The earliest noted relation (Tschermak 1917; 1918) was that indicated in the part of the formula having to do with the alkalies, calcium, and aluminum: $(Na, K)_m(Ca, Ba, Sr)_nAl_{2n+m}$. The number of Al atoms in the formula is equal to the combined valences of the univalent and bivalent elements.

The second important feature, first thoroughly investigated by Winchell (1925), had to do with the relation $Al_{2n+m}Si_rO_{2(n+m+r)}$ that is, the sum of $Al+Si$ is equal to half the number of oxygen atoms in the formula. This, it will be noted, is the fundamental chemical characteristic of all

the members of this silicate type, and it is our reason for placing the zeolites in this part of the classification. The two chemical characteristics above referred to are really fundamentally the same since the first relation follows from the second.

The writer in his investigations of zeolite compositions has found no instance where the ratio Al:Si is greater than 1; Al does not exceed Si in the formula. It is for this reason that some of the Winchell "end members" are not accepted here.

There is a definitely limited range of miscibility in the zeolites, so that the compositional range of a series is narrow. This probably means a narrow range of stability for most zeolites, and it may explain the large number of species in the family.

Most of the isomorphous substitutions are, as Winchell (1925) has shown, atom for atom, but there are undoubtedly cases where Na_2 (and perhaps K_2) replaces Ca. Hey (1930) has noted this same deviation from the usual silicate atom-for-atom replacement, and explains it as a replacement subsequent to the formation of the crystal, that is, a method analogous to the method of artificial base exchange in the zeolites.

Water seems to occupy definite positions in the crystal lattice of the zeolites (Taylor 1930), but because of the open structure of the network it is easily driven off giving a continuous dehydration curve in most cases. The framework of the structure is often preserved even after the water is driven off. For a detailed account of dehydration and rehydration see Hey (1930; 1935).

There are a few well-defined groups in the zeolites. These have long been recognized. On the whole, few series are known; and even where the compositions and crystal forms are close together, as in the natrolite group, we have little isomorphism. For the most part the formulae presented in the classification are rather complex. Recent x-ray work (Bannister) and Hey's careful study, as well as Winchell's papers agree that complex formulae are needed to express adequately the composition. The classification gives the zeolite formulae which, in the writer's opinion, express the composition and agree with recent chemical and x-ray work. A number of the species listed are not yet well defined. The precise relationships in all the groups are not well established. However, the general features as outlined in the classification are, it is believed, approximately correct.

Mordenite series: With $Ca:Na:K = 6:1:3$ to $3:6:1$; From the variations given it is evident that mordenite forms a rather extensive series between Ca, Na, and K members, with the K members subordinate. The formulae by Schaller (1932) are less complex. Hey (1934) has pointed out that the x-ray photographs of mordenite and ptilolite are identical.
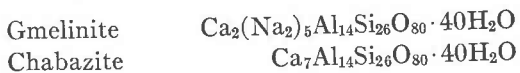
At any rate, the composition of ptilolite fits into the mordenite series and it is here considered as a member of that series.

The minerals of the heulandite group are apparently closely related crystallographically as well as chemically. The last three may form a series, but no direct evidence of this is available since the crystal data of the three species are not so closely similar as that usually associated with a serial relationship (Tschermak 1917 and Winchell 1925). Clinoptilolite, while it has a composition much like mordenite has been shown to be structurally identical with heulandite (Hey and Bannister 1934). Mordenite and heulandite have certain crystallographic and chemical similarities and they are probably related structurally; the former is essentially the Na mineral and the latter the mineral with dominant Ca

Stilbite group: This group is not particularly well defined. Certain crystallographic similarities have been noted by Tschermak (1917) and others, between the first five minerals listed here. Stilbite, epidesmine and harmotome are, in addition, obviously related chemically, as shown in the classification. Phillipsite, and the rare wellsite, are definitely related crystallographically to harmotome and stilbite, yet the compositions are widely different. This group probably consists of two main series which are isostructural but not isomorphous. This would mean structurally that some of the positions which are vacant in the stilbite structure are perhaps occupied by Ca or Na in the phillipsite structure.

The last three minerals listed under the stilbite group are related in composition to the other members of the group. Crystallographic similarities have been noted (Tschermak). Stellerite and erionite are rare species and have not been fully invesitgated. Tschermak lists erionite with stilbite, and stellerite has been shown to be very close to stilbite in its crystallographic properties.

Chabazite group: The first two minerals of this group are closely related in crystallographic properties. However, the compositions, as shown in the classification, are very different. The two minerals, as Winchell (1925) points out, are certainly not members of an isomorphous series. They are probably isostructural, with Na_2 of gmelinite occupying positions, half of which are occupied by Ca in chabazite. The probable isostructural relations can be shown by writing the formulae as follows:

$$\text{Gmelinite} \quad Ca_2(Na_2)_5Al_{14}Si_{26}O_{80} \cdot 40H_2O$$
$$\text{Chabazite} \quad Ca_7Al_{14}Si_{26}O_{80} \cdot 40H_2O$$

Thomsonite group: The members of this group probably do not form a series. There are some variations in the composition of thomsonite, as indicated in the formula, but the other members of the group are com-

paratively rare, and no variation has been shown to exist. The chemical compositions of gonnardite and arduinite indicate that the two species are probably identical. Optical and other physical data are lacking, in part, for these two species, so that further work must be done to establish their relation. Ashcroftine is the so-called kalithomsonite of Gordon (1924). Hey and Bannister (1933) have shown that this supposedly K-rich thomsonite is not really a member of the thomsonite series, but differs in having a very much larger unit cell (nine times) and truly tetragonal symmetry. Thomsonite and gonnardite are probably isostructural since their cell dimensions are similar (Hey and Bannister) as well as their compositions.

Natrolite group: The minerals of this group are closely related structurally as shown by the remarkable similarity of their x-ray diffraction patterns (Hey and Bannister 1933). The unit cells are, however, multiples of each other, and in detail the x-ray pictures differ somewhat, so that the minerals here placed in the group are not really members of a series, but are isostructural.

Natrolite has 80 oxygen atoms in the unit cell. Of the 16 Na atoms usually contained in the unit, one is sometimes K, thus Na:K = 15:1. There is also some substitution of Ca for Na_2 but only to a maximum of Na_4. The Al:Si ratio is essentially constant (Hey, with Bannister, 1932.)

Mesolite has a cell three times the volume of that of natrolite. Consequently the number of oxygen atoms is 240. The formula given represents $\frac{1}{8}$ of the unit cell contents. Few silicates are known with such huge unit cells. In fact, the zeolites in general have large units in comparison with most other silicates. Edingtonite is rather an exception among zeolites in having an average-sized unit cell, containing but 20 oxygen atoms, beside those in the H_2O.

Miscellaneous zeolites: The minerals listed are not in any sense a group; they are merely those zeolites which have no well-defined position in any of the previously discussed groups. Faujasite has been analysed but twice and its composition is not certain. Analcite is a well-established species with a fairly definite composition; only small amounts of Ca and K enter into the composition.

Laumontite shows some variation in composition from an almost pure Ca member to a member with the ratio Ca:Na = 5:2. It is to be noted here that laumontite has a composition almost identical with that of chabazite, except that the latter has more water.

Ferrierite $Mg_2Na_4Al_8Si_{32}O_{80} \cdot 20H_2O$? This mineral has an uncertain composition. It is unique among zeolites in carrying important amounts of Mg; as far as known it shows no definite relationship to any other zeolite in its physical and crystallographic properties.

Laubanite $Ca_2Al_2Si_5O_{15} \cdot 6H_2O$ is apparently a zeolite; but its composition, as given, does not conform with the general zeolite formula and is open to doubt. The writer has examined a specimen of this material from the type locality and finds that it is made up of an aggregate of at least two minerals. The study was carried no further, since the inhomogeneous material was finely intermixed and little hope was entertained of separating the individual constituents.

Didymolite, given as $Ca_2Al_6Si_8O_{27}$, has no water in the analysis (Ford, 1915). However, the optical properties as reported (Larsen and Berman 1934) cannot possibly be in agreement with this composition, since any calcium aluminum silicate would certainly have a mean index greater than 1.50. This substance, if its optics are correct, is probably a zeolite and the water has been overlooked.

Dachiardite has a doubtful composition, as given, since it is undoubtedly a zeolite and yet the relation between $Na+Ca$ and Al is not in agreement with the general zeolite formula-relations. A new analysis of this interesting zeolite is desirable but little material is available.

Cordierite $(Mg, Fe, Mn)_2(Al, Fe)_4Si_5O_{18} \cdot H_2O$. This mineral is apparently of the silica type. However, the presence of (Mg, Fe, Mn) is unusual in this type, and it is with some uncertainty that the writer places it here in the classification. With its low refractive index and low density, the mineral fits into this type; but until structural details are available, the classification of this mineral is uncertain.

Disilicate Type

This important silicate type has the following chief chemical characteristics:

The ratio of $Z:O=2:5$, where Z is predominantly Si, but in most of the families Al, with the co-ordination number 4, is a prominent element of the Z kind. The ratio $Si:Al$ is greater than $1:1$, with some important exceptions in the brittle micas. Since most of the members of this type are hexagonal or pseudo-hexagonal, in conformity with the pattern of the two-dimension network (Fig. 2), the smallest unit of the structure yields a composition Z_4O_{10} for the pseudo-hexagonal unit or Z_6O_{15} for the truly hexagonal units.

Another chemical characteristic of the type is the presence, in nearly all members, of hydroxyl or the equivalent fluorine. In friedelite Cl apparently plays the same role as the (OH) and F.

In many of the chloritic minerals, in addition to (OH) some H_2O is also found, thus there are two kinds of water in the composition. This dual role of water gives rise to the characteristic dehydration curves of the chlorites (Orcel 1927). The (OH) is more firmly held in the structure

and consequently is driven off at a higher temperature as compared with the more loosely held H_2O.

Physical properties of the disilicate type: The minerals of this type are particularly noteworthy in having a micaceous cleavage which is the most perfect cleavage known in crystals, with the possible exception of graphite. This cleavage is always taken as the basal plane {001}. It is assumed, and has been proved in many instances, that this cleavage plane represents the plane of the two-dimensional network which is the fundamental structural feature of the type (Fig. 2). Since this network as previously stated, is hexagonal in its pattern, the dominant habit in this type is a hexagonal plate, as exemplified in the micas, the chlorites, and the crystalline members of the kaolin group.

On the whole, the type is made up of minerals with medium hardness, but some members high in water content are soft. The Al-silicates are also softer than other members of the type. An interesting optical feature of these minerals is that the negative acute bisectrix is almost always normal, or nearly so, to the cleavage face. Ottrelite, chloritoid and some of the chlorites are exceptions to this rule. Wooster (1931) has discussed the structural basis of this optical behavior in platy substances.

A few platy silicates belong to the Pyrosilicate type.

Aluminum disilicates: $Y_p(Si_4O_{10})(OH)_{3p-4} \cdot sH_2O$; $Y = Al$, Fe''' subordinate, Cr rare; $p = 2$ to 4; $s = 0$ to 4. The aluminum silicate family is made up for the most part of rather finely crystalline species, whose fineness often borders on the submicroscopic. Some of the minerals in this family are so finely crystalline that they have been thought to be amorphous. However, x-ray powder pictures have shown these to be crystalline. A few Al silicates are probably truly amorphous. This may account for the considerable variability in composition as reported (Tomkeieff 1933).

The kaolins are made up of several members, all with the same composition. Halloysite has the kaolin formula plus H_2O. Volchonskite has $Y = Al$, Fe''', Cr.

Canbyite and batchelorite are close to the kaolins with some extra water. Chloropal is presumably an amorphous equivalent of batchelorite with Fe''' instead of Al.

Close to beidellite $Al_8(Si_4O_{10})_3(OH)_{12} \cdot 12H_2O$ is montmorillonite whose formula may be written as $(Al, Mg)_8(Si_4O_{10})_3(OH)_{10} \cdot 12H_2O$ with $Al : Mg = 6 : 2$, namely as a beidellite with part of the Al replaced by Mg. Nontronite is a member of the beidellite group (Gruner 1935). He writes these formulae somewhat differently.

Apparently little isomorphism exists in these minerals. The finely divided aluminum silicates do show a variation in composition but the

variability is not due to the formation of mixed crystals, but rather to a probable adsorption of water and gelatinous silica.

Talc shows little variation in composition from that given above. A small amount of Fe and Ni is often present, also Al in inappreciable amounts.

Antigorite series: The mineral antigorite is apparently a dimorphous form of serpentine which is distinctly fibrous and of the metasilicate type. Since the composition of this mineral corresponds to an aluminum-free chlorite (Tschermak 1890), it is currently considered as an "end member" of the chlorite series. The writer is not inclined so to consider antigorite, since a definite composition seems to be associated with the mineral. No continuous series has been shown to exist between antigorite and chlorite. As will be shown later, a certain minimum of $Al+Fe'''$ is always present in the chlorites; and it is, therefore, the writer's opinion, supported by a recent work by Selfridge (1936), that antigorite is not a chlorite.

Connarite is more hydrous than the other members of the group. Little is known of variations in its composition since so few analyses have been made.

The members of the *Freidelite group* are all rare minerals on which the data are not plentiful. However, in their physical properties they are undoubtedly closely related. They have all the characteristics of the typical platy silicates, including the micaceous cleavage. They are different from most platy silicates in that they are probably hexagonal or rhombohedral. Most other silicates of this type are pseudo-hexagonal, and really monoclinic or orthorhombic. The difference is expressed chemically in the Si_6O_{15} composition, since a hexagonal cell would probably have as its unit 6 silicons rather than the customary 4 of the other platy silicates.

Friedelite, it is to be noted, has some Cl in its composition, and apparently this element substitutes for (OH) in part. Some arsenic has been noted in this unusual mineral so that it probably forms a series with schallerite (Palache 1935). Fe is also reported in small amounts; a higher percentage of Fe enters into the isomorphously related pyrosmalite. We probably have a series varying to schallerite and to pyrosmalite. Ferroschallerite is a recently described equivalent of schallerite with Fe and Zn in considerable amounts (Bauer and Berman 1930).

Zeophyllite is apparently a Ca equivalent of friedelite, but no intermediate compounds are known and it is doubtful if a series could form. The only rhombohedral form found on zeophyllite corresponds in angle $(\rho = 78°)$ to the prominent form $t\{0.15 \cdot \overline{15}.2\}$ of friedelite. This mineral has heretofore been referred to the zeolites with which it has little in common, in the writer's opinion.

Centrallasite and truscottite from their compositions and physical properties are obviously closely reated. The writer is inclined to consider the two as varying only in the content of Mg. In truscottite $Ca:Mg = 4:1$; centrallasite is the Ca end component of the series (Larsen and Berman 1934, p. 158). Gyrolite is probably identical with centrallasite, although the water content is given as being different. A comparison of the optical properties of the two shows their essential identity.

Miscellaneous non-aluminum disilicates. The first two of the minerals listed in the classification are comparatively rare. Bementite has not been observed in crystals, but it is definitely a platy silicate. The negative acute bisectrix emerges on the best cleavage; the other cleavages noted for this mineral are districtly inferior to this perfect cleavage.

Errite is a rare species, recently described (Jakob 1923). A closely re- lated, and perhaps identical, mineral, parsettensite was described at the same time. These two are micaceous in habit and conform with the general physical criteria of this type.
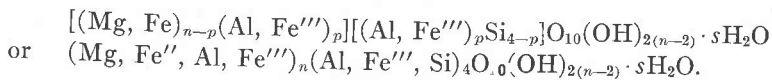
Apophyllite is often placed with the zeolites for several reasons. It is nearly always associated with zeolites and it has a considerable amount of water. However, no other mineral placed in the zeolite family lacks Al, and an x-ray structural study (Taylor and Naray-Szabo 1931) has shown that this mineral is of the platy silicate type.

Anhydrous non-aluminum disilicates: Gillespite and sanbornite, two rare minerals, occur together and have recently been so described (Rogers 1932). The exceedingly good micaceous cleavage and general optical properties, as well as the simple chemistry, are unmistakable evidence that these these minerals are properly placed here.

The chlorite family: $X_nZ_4O_{10}(OH)_{2(n-2)} \cdot sH_2O$. Pauling (1930 B) deduced a similar formula from structural considerations of the chlorite-like minerals. It is an important characteristic of the minerals of this family that Al and some Fe''' enter into both the X and Z parts of the above formula in equal amounts. Tschermak (1890; 1891) and later Winchell (1926) demonstrated this fact in another way. The general formula may be more specifically written:

$$(Mg, Fe'')_{n-p}(Al, Fe''')_{2p}Si_{4-p}O_{10}(OH)_{2(n-2)} \cdot sH_2O$$
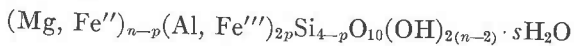
where the $(Al, Fe''')_{2p}$ is in part united with (Mg, Fe) and in part with the Si so that the resultant formula is, as given at the beginning of this section

$$[(Mg, Fe)_{n-p}(Al, Fe''')_p][(Al, Fe''')_pSi_{4-p}]O_{10}(OH)_{2(n-2)} \cdot sH_2O$$

or $(Mg, Fe'', Al, Fe''')_n(Al, Fe''', Si)_4O_{.0}(OH)_{2(n-2)} \cdot sH_2O$.

Variations in the number n give rise to the different groups of the

family. The different p values are, in general, responsible for the serial variations. The vermiculites differ from other groups of the family principally in having a higher s value. As will be shown, the terms n, p, and s, and the ratios Mg/Fe'', Al/Fe''' completely define any species of this family. Since the members of the family are so closely related chemically, it becomes a somewhat arbitrary procedure to divide them into groups on the basis of n values. However, a detailed examination of the minerals has shown that definite ranges of composition are found and that the minerals of the family are properly divided into the generally accepted groups.

The chlorite group: $(Mg, Fe)_{6-p}Al_{2p}Si_{4-p}O_{10}(OH)_8$. Typical members of this group are as given in the following table.

TABLE 5. CHLORITES

Orcel (1927) page	no.	Name	n	p	Mg/Fe''	Al/Fe'''
331	1	Amesite	6	1.6	2.25	Al
331	6	Corundophilite	6	1.6	6.5	12
192	—	Sheridanite	6	1.5	45	Al
346	35	Colerainite	6	1.4	Mg	Al
357	78	Ripidolite	6	1.45	1.9	7.5
247	—	Bavalite	6	1.46	0.09	52
221	—	Grochauite	6	1.35	10	Al
216	—	Prochlorite	6	1.37	5	67
228	—	Ripidolite	6	1.3	1.9	17
367	126	Metachlorite	6	1.3	0.2	4
347	38	Rumpfite	5.7	1.3	4.8	23
360	100	Ripidolite	6	1.4	0.51	Al
198	—	Leuchtenbergite	6	1.2	Mg	Al
201	—	Prochlorite	6	1.2	13	19
349	50	Rumpfite	6	1.18	Mg	Al
365	119	Pycnochlorite	6	1.15	1.1	13
365	120	Delessite	6	1.15	2.9	23
348	43	Leuchtenbergite	6	1.14	Mg	20
267	—	Clinochlore	6	1.08	12	15
382	185	Brunsvigite	6	1.05	0.47	14
269	—	Crome clinochlore	6	1.0	43	5.2*
380	166	Clinochlore	6	1.0	Mg	Al
380	172	Clinochlore	6	1.0	6.9	Al
387	200	Ripidolite	6	0.83	11	25
387	202	Pennine	6	0.79	20	14
389	217	Tabergite	6	0.76	Mg	Al Alkalies
408	275	Kotschubeite	6	0.91	Mg	5*
408	276	Kammererite	6	0.9	Mg	1*
409	278	Kammererite	6	0.87	Mg	3.33*
410	285	Kammererite	6	0.86	30	1.8*

* Al/Cr.

The minerals listed above are representative, well analysed chlorites. The analyses examined are among more than two hundred collected by Orcel (1927). More than twice the number given above were examined, because of their apparent superiority among the many analyses found in Orcel's paper. All have not been included in this table because they do not properly fall here in the classification, since the value n is less than 6. Tschermak (1890) recognized that chlorite-like minerals of a definitely different composition could not be grouped with the well-defined chlorites. These are here called Lepto-chlorites ($N<6$), as in Tschermak. Incidentally, the only important criticism of Orcel's work on the chlorites lies in his failure to recognize the significance of the variability of the divalent elements.

In order to define properly a member of the chlorite family it is necessary to give the values, n, p and the ratios Mg/Fe'', Al/Fe'''. The relation of these quantities to Orcel's symbols are $s=(4-p)/p$; $a=Fe'''/Al$; $f=Fe''/Mg$; where s, a, f, are symbols used by Orcel.

The relations to the Tschermak and Winchell symbols are:

$$50\ p = \%At = Amesite;\ 100-50p = \%Ant = Antigorite.$$

It is to be noted that the terms used by the writer can be directly placed in the general formula for the group. Ths single term serves the purpose of the two end member terms of Tschermak, and bears a simpler relation to the composition than the term $s=SiO_2/R_2O_3$ of Orcel. The term p, as the formula shows, is half the number of atoms of the (Al, Fe''') kind in the composition. Since the (Al, Fe''') content fixes both the Si and (Mg, Fe'') amounts, the single term is adequate.

In the above table a number of names usually associated with the chlorites, such as cronstedtite, thuringite, aphrosiderite, are missing. These are to be found on the following pages under the leptochlorites.

The leptochlorite group: $(Mg, Fe)_{n-p}(Al, Fe''')_{2p}Si_{4-p}O_{10}(OH)_{2(n-2)}$- $\cdot sH_2O$. Table 6 lists the leptochlorites taken from Orcel's collected analyses. The group is divided into three sections in the classification, the divisions being made on the basis of significant n differences. The first section is composed of chlorite-like minerals not very different from true chlorites. It may be that some of these minerals belong in the previous group and that the chemical analyses are somewhat defective. However, most of the minerals given are represented by recent analyses which are probably reliable. The second section shows a definite departure from the true chlorite composition not only in the n value, but also in the fact that many of the minerals have a higher p value than is found in the chlorites, and also much more Fe'' and Fe'''.

Cronstedtite, with the composition $Fe_3''Fe_4'''Si_2O_{10}(OH)_6$ is totally unlike any mineral of the chlorite group in its composition. The thuring-

ites are likewise definitely different chemically. It is worth noting here again that the species names, as given with the analyses, have not been changed, mainly because the writer is not inclined to enter here into a discussion of the suitability of certain names for specific portions of a series. In this paper the series is considered as the important unit, and the writer believes that the leptochlorites represent a more or less continuous series with the variations as indicated.

Whether there is a continuous series beteen the leptochlorites and the chlorite group cannot be shown by the chemical evidence. A serial relation seems, however, unlikely since the chlorites do have a definitely different composition and a constant n value. Further, optical properties of the leptochlorites do not fit well with the optics of normal chlorites. It is perhaps due to the failure to discriminate between the two groups that the optical properties of the chlorite group are so unsatisfactorily known.

A number of interesting possibilities for structural studies present themselves in the leptochlorites. It would be interesting to know whether the unit cell dimensions change in this group, as compared with the chlorites. Of greater interest is the mineral cronstedtite, $Fe_3''Fe_4'''Si_2O_{10}$-$(OH)_6$ or $(Fe_3''Fe_2''')(Fe_2'''Si_2O_{10})(OH)_6$, in which Fe''' is in the tetrahedral network and occupies half the positions, with Si in the other half. If true, this is the most important case of this sort in the silicates and there seems to be little doubt that this must be true, since no Al is available to enter into the network. It may be that this unusual condition in the tetrahedral network may account for the peculiar curved pyramidshaped crystals of this mineral, for the network under these conditions would certainly be distorted.

TABLE 6. LEPTOCHLORITES

Orcel (1927) page	no.	Name	n	p	Mg/Fe''	Al/Fe'''	s
335	14	Aphrosiderite	5.5	1.55	2.34	3.75	0
236	—	Ripidolite	5.6	1.38	1.1	3.1	0
238	—	Ripidolite	5.6	1.38	1.3	8.0	0
358	88	Ripidolite	5.7	1.39	1.67	Al	0
367	125	Chlorite	5.3	1.52	0.4	8.3	1
368	132	Daphnite	5.3	1.43	0.05	Al	0
371	139	Prochlorite	5.5	1.34	0.7	4.75	0
375	155	Cronstedtite	5.7	1.35	0.2	Fe'''	0
367	129	Chamosite	5.5	1.2	0.09	Al	1
373	153	Prochlorite	5.7	1.1	1.0	3.8	0
382	180	Delessite	5.5	1.06	2.3	7.7	0
363	122	Diabantite	5.7	1.08	1.03	6.2	0
385	189	Pseudophite	5.5	0.9	50	Al	0
387	197	Prochlorite	5.6	0.86	Mg	Al	0

| Orcel (1927) | | | | | | | |
page	no.	Name	n	p	Mg/Fe''	Al/Fe'''	s
376	160	Cronstedtite	4.95	1.93	Fe	Fe	0
375	159	Cronstedtite	4.85	1.55	low	Fe	0
257	—	Thuringite	5	1.5	0.32	2.7	0
337	28	Thuringite	5	1.48	0.3	2.1	0
337	26	Thuringite	4.8	1.5	0.1	2.1	1
335	18	Thuringite	4.75	1.64	0.07	1.74	1
358	84	Klementite	5.2	1.5	Mg	Al	0
373	152	Delessite	5.2	1.15	1.6	5.5	1
385	188	Pennine	5	0.89	Mg	25	1
393	219	Diabantite	5	0.72	2.78	6.5	1
334	9	Thuringite	4.67	1.6	0.67	17	0
334	12	Thuringite	4.5	1.7	0.05	1.46	$1\frac{1}{2}$
371	141	Delessite	4.6	1.28	1.8	3.5	$1\frac{1}{2}$
264	—	Thuringite	4.4	1.77	3.2	2	0
336	22	Thuringite	4.37	1.58	0.17	1.85	$2\frac{1}{2}$
368	136	Prochlorite	4.3	1.38	0.09	Al	2
395	234	Epichlorite	4.2	0.8	3.6	1.9	0
371	140	Delessite	4.1	1.34	8.4	1.4	1
382	184	Aphrosiderite	4	0.93	0.62	100	0

The vermiculites are, as stated before, chloritic minerals with a high water content, the latter probably accounting for the peculiar expansion properties. Saponite has not hitherto been placed with the vermiculites, but its chemical and physical properties indicate that it might well be considered a vermiculite-like mineral. Griffithite has been placed here for the same reason. The n values indicate that the unit cell must have at least three times the number of atoms here given in the formula, since any unit cell should have an integral number of n atoms. However, to show better the relations with other members of the family the fractional values of n are retained.

Brittle mica family: The minerals here listed are much like those of the chlorite family in that the same general formula applies to them and the same elements enter into their composition, except that Ca is found in considerable amounts in some members. It is to be noted, however, that the n values in these minerals are considerably lower than those found in the chlorite family, as is also the water content.

Physically these minerals differ from the chlorite family in being harder and, as the name of the family implies, more brittle. The cleavage is perhaps somewhat less perfect than in the chlorites. Optically some of these minerals differ from the other platy silicates in that the positive acute bisectrix emerges almost normal to the perfect cleavage (ottrelite, chloritoid, prehnite).

Chalcodite $(Mg, Fe)_{13}Al_4Si_{18}O_{50}(OH)_{10} \cdot 10H_2O$. The writer follows Hallimond (1924) in separating the two species, chalcodite and stilpnomelane. The chalcodites are definitely lower in $Al+Fe'''$ and higher in $Mg+Fe''$ (Analyses 7a and 7b in Hallimond's paper). There are at least five times as many atoms in the unit cell of chalcodite as we have given in the general family formula in the classification.

Epichlorite $(Mg, Fe)_{10}Al_6Si_{13}O_{40}(OH)_{10} \cdot 8H_2O$ yields the value n and p as given in the classification. The formula indicates that there are at least four of the general formulae in a unit cell (analysis number 233 in Orcel).

Stilpnomelane $(Mg, Fe)(Al, Fe''')_2Si_3O_{10} \cdot H_2O$. From a consideration of analyses in Hallimond's paper the simple formula is deduced for stilpnomelane. This mineral probably forms a series with certain of the ottrelites which differ only in having more Fe'' and some Mn'' in their composition (see classification).

Ekmannite is presumably similar in composition to members of this group. However, more chemical work is needed definitely to establish this species.

Ottrelite $(Fe'', Mn)(Al, Fe''')_2Si_3O_{10} \cdot H_2O$. The six analyses for this species listed in Dana (1892, p. 642) give the following values of n, p, and s (as used in the general formula):

Dana number	n	p	s
1	$2\frac{1}{2}$	1	1
2	2	$1\frac{1}{2}$	1
3	$2\frac{1}{2}$	$1\frac{1}{4}$	0
4	$2\frac{1}{2}$	$1\frac{1}{4}$	0
5	$2\frac{1}{2}$	$1\frac{1}{4}$	0
6	2	1	1

A new analysis of this mineral is needed to establish its composition since the analyses available are not in good agreement with each other. The writer believes that ottrelite is essentially similar to stilpnomelane.

Margarite $CaAl_4Si_2O_{10}(OH)_2$. This is a well-defined species of simple composition. The recently described ephesite is a supposed soda-margarite of composition $(Na, Li, Ca)_2Al_4Si_2O_{10}(O, OH, F)_2$, with Li and Ca subordinate. This mineral is probably isostructural with margarite. Although the latter contains some Na, the amount is small, and no evidence is found of a large $Ca-Na_2$ substitution.

Prehnite $Ca_2Al_2Si_3O_{10}(OH)_2$ is not usually associated with the platy silicates. However, it often has a distinctly platy habit, when in crystals; the basal cleavage is good, giving a pearly luster, and the acute bisectrix is normal to the plane of platy development. The platy cleavage is not inferior to that found in chloritoid or ottrelite, of this section. According

to Pauling (1930 A) the Ca members of the platy silicates should be the ones showing the least perfect cleavage and the greatest hardness because the bivalent Ca bonds interfere with easy separation of the layers.

Chloritoid (Fe, $Mg)_2Al_4Si_2O_{10}(OH)_4$, is chemically a rather well-defined brittle mica, not far removed in its composition from some of the leptochlorites. As much as 8 per cent of Mn is present in salmite, a manganiferous chloritoid. Most chloritoids carry some Mg, but Fe is the predominant constituent.

Clintonite series $X_4Z_4O_{10}$, $(OH)_2$ with $X = Mg:Ca:Al = 3:2:1$; $Z = Al:Si = 2:1$. The formula expanded yields $Mg_6Ca_4Al_{10}Si_4O_{30}(OH)_6$. This is the composition of the supposedly different species seybertite, brandisite, and xanthophyllite. The analyses as given for these three minerals (Dana, 1892, p. 638) indicate that they differ only in the Mg:Ca ratio, if at all. However, the difference in this ratio is no greater between the species than it is between different analyses of the same species. Since the composition of the three minerals is established on old analyses (1847, 1853, 1887) on material not definitely shown to be pure, the writer is inclined to consider that the variation in the Mg:Ca ratio is not sufficient to retain three species names for this single series.

Kossmatite, a recently described mineral, has a composition $X_6Z_4O_{10}$-$(OH, F)_9$, with $X = Ca:Mg:Al = 3:1:2$; $Z = Al:Si = 1:3$; giving Ca_3-$MgAl_3Si_3O_{10}(OH, F)_9$.

Mica group: $W(X, Y)_{2-3}Z_4O_{10}(O, OH, F)_2$; $W = K$ predominantly, Na, Ba, Ca subordinate to rare; $X = Mg, Fe'', Mn'', Li$; $Y = Al, Fe'''$, Ti subordinate, Cr, Mn''', V rarely; $Z = Si:Al$ from 5:3 to 7:1.

	X	Y	$Z = 16$ Al:Si	OH:F	Formula
Muscovite series:					
Muscovite		8	2:6	8:0	$K_4Al_{12}Si_{12}O_{40}(OH)_8$
Phengite	2	6	1:7	8:0	$K_4Mg_2Al_8Si_{14}O_{40}(OH)_8$
Alurgite	3	5	1:7	9:0	$K_4Mg_3Al_7Si_{14}O_{39}(OH)_9$
Paragonite		8	2:6	8:0	$Na_4Al_{12}Si_{12}O_{40}(OH)_8$
Roscoelite		8	2:6	8:0	$K_4V_8Al_4Si_{12}O_{40}(OH)_8$
Biotite series:					
Biotite	12		2:6	8:0	$K_4(Mg, Fe)_{12}Al_4Si_{12}O_{40}(OH)_8$
Phlogopite	12		2:6	8:0	$K_4Mg_{12}Al_4Si_{12}O_{40}(OH)_8$
Siderophyllite	10	2	3:5	8:0	$K_4Mg_{10}Al_8Si_{10}O_{40}(OH)_8$
Biotite?	8	4	2:6	4:0	$K_4(Mg, Fe)_8Al_8Si_{12}O_{44}(OH)_4$
Biotite?	10	2	2:6	6:0	$K_4(Mg, Fe)_{10}Al_6Si_{12}O_{42}(OH)_6$
Lithia Micas:					
Lepidolite	8	4	2:6	4:4	$K_4Mg_4Li_4Al_8Si_{12}O_{40}(OH)_4F_4$
Lepidolite	6	6	1:7	4:2	$K_4Li_6Al_8Si_{14}O_{42}(OH)_4F_2$
Lepidolite	6	5	1:7	2:7	$K_4Li_6Al_7Si_{14}O_{39}(OH)_2F_7$

Zinnwaldite	8	4	2:6	4:4	$K_4Fe_4''Li_4Al_8Si_{12}O_{40}(OH)_4F_4$
Polylithionite	8	4	0:8	0:8	$K_4Li_8Al_4Si_{16}O_{40}F_8$
Cyrophyllite	8	4	1:7	2:6	$K_4Fe_2''Li_6Al_6Si_{14}O_{40}(OH, F)_8$

The muscovite series consists of members which are predominantly Al and Si compounds, with little Mg and Fe'', and rarely any F. Ba and Na replace some of the K, but rarely in notable amounts (except in paragonite). Special members of this group are fuchsite with small amounts of Cr replacing Al, and roscoelite with most of the Al replaced by V. Phengite and alurgite are members in this series having a larger than usual amount of Si.

The biotite series comprises those members wherein considerable amounts of Mg and Fe'', sometimes Mn'' in manganophyllite, are present, and part of the Al is replaced by Fe''' and Mn''' and minor amounts of Ti.

The lithia micas are those which have much Li and considerable F in place of OH.

The chief members of these mica series are arranged to show their variation, according to the formula. It must be noted in this connection that the X and Y portions of the formula are especially variable and consequently give rise to many compositions intermediate between those given here. Although there are probably hundreds of mica analyses, complete agreement as to the composition of some of them, especially in the Lithia mica groups, has not yet been reached. The formulae presented above are in good agreement with the analyses as well as with the structural relations established for the micas. These are, with some exceptions, in essential agreement with Winchell's latest conclusions, as expressed in his book (1933), but not with the conclusions of his earlier papers on the micas. Hallimond's views on the micas (1925) are not accepted.

The many recent analyses by Kunitz (1924) and Jakob (1925) have been utilized in this study. Early analyses of the micas were especially likely to be faulty since fluorine was often missed.

The structure of muscovite (Jackson and West 1930) has been fully determined. The lithia micas are most in need of structural investigation because the muscovite structure certainly needs some modification in order to meet the compositional differences of the lithia members of the group.

Since most of the examined analyses of the micas fall into some intermediate position in one or the other of the series given above, more details are not given here. The members of the series as given are to be considered as expressing the principal variations found. The species

names are those originally used with the particular analysis from which the formula was derived.

Miscellaneous disilicates: Glauconite $W_2(X, Y)_8(Z_4O_{10})_3(OH)_{12}$; $W = K$, Na subordinate; $X = Mg$, Fe''; $Y = Al$, Fe'''; $Z = Si$. More specifically the composition is $K_2Mg_2Al_6(Si_4O_{10})_3(OH)_{12}$. The composition of this mineral has been recently studied (Schneider 1927; Ross 1926; Hallimond 1922) and Gruner (1935 B) has proposed a structural arrangement similar to that of the micas.

Pholidolite is a mica-like mineral having a deficiency of K and an excess of water; it is probably an alteration product of a mica. Its formula is $KMg_6AlSi_7O_{20}(OH)_4 \cdot 3H_2O$; or $WX_6(Z_4O_{10})_2(OH)_4 \cdot 3H_2O$. This general formula, it will be seen by comparison, is not far from the mica formula.

Cookeite is a micaceous silicate having the composition: $LiAl_3Si_2O_9$- $+3H_2O$. Expressed as a platy silicate it gives the formula: $(XY)_4(Z_4O_{10})$ $(OH)_4 \cdot 2H_2O$; with $X:Y = Li:Al = 1:2$; and $Z = Al:Si = 1:2$.

Manandonite is presumably closely related to cookeite but has some oron in the composition.

Bityite $W_4(X, Y)_{12}(Z_4O_{10})_3(OH)_{20}$; $W = Ca$; $Z = Al:Si = 1:2$ (X, Y) $= Li:Be:Al = 2:1:6$; or $Ca_4(Li, Be)_4Al_8[(Al, Si)_4O_{10}]_3(OH)_{20}$.

Ganophyllite. An analysis of the light brown ganophyllite from Franklin (private contribution, L. H. Bauer 1936) yields the composition: $NaMn_6Al_2(Si_4O_{10})_2(OH)_{11}$. A recent description (Foshag 1936) of a somewhat different ganophyllite gave the composition $(Na, K, Ca)_2$- $Mn_5Al_3Si_{10}O_{32} \cdot 8H_2O$. These two compositions do not, in the writer's opinion, represent the same mineral. The mineral described by Foshag is perhaps more appropriately placed in the brittle micas, or the related leptochlorites. A further study of the two occurrences at Franklin should be made in order to reach some conclusion concerning the true constitution of ganophyllite.

METASILICATE TYPE

The metasilicates are those silicates which have a ratio of $Z:O = 1:3$, where Z is in most instances Si alone, and sometimes Si+Al with Si greatly predominating; O represents not only oxygen but OH, and F in small amounts. These silicates are divided into two principal subtypes, (A) the chain structure subtype, and (B) the ring structure subtype. The minerals with chain structures have Mg, Fe'', Ca, Mn, Al and Fe''' as the important elements of the composition. Those with the ring structures have the relation $Z:O = n:3n$, with $n = 3$ or 6, and are, in general, more unusual in their chemical composition. The members with chain structures are all characterized by a distinct prismatic habit

which often takes the accentuated fibrous form. This development is a consequence of the internal structure, which is the linking of tetrahedra to form continuous chains throughout the crystal. Presumably the chief differences in the various members of this type are due to the way the chains are tied together. Warren and Biscoe (1931) have demonstrated the relations between the pyroxenes and amphiboles in this respect. The full structural details of other chain structures are not yet known.

The ring structures are formed by SiO_4 tetrahedra joined in groups of three, as in benitoite (Zachariasen 1930 B), or in groups of six as in beryl (Bragg and West 1926). Some of the minerals grouped here are as yet not determined structurally. All the minerals placed in the ring structure type have trigonal or hexagonal symmetry, which is consistent with the structure of this type.

Amphibole group: There are, as shown in the classification, four distinct series in the amphiboles. Within each series there is isomorphism to the extent indicated in the formulae, but between these series little overlapping is found. Since Berman and Larsen (1931) have already discussed the composition of this group in some detail, the main points only need be cited here.

Anthophyllite and cummingtonite differ not only in crystal symmetry but also in that the orthorhombic members are high in Mg, and the monoclinic cummingtonite relatively high in Fe''.

The tremolite-actinolite series is perhaps the best known in the amphiboles. It was in this series that the importance of water in the amphibole composition was first recognized (Schaller 1916). Most of the members of this series are relatively high in Mg. Few reliable high Fe'' actinolites have been reported.

The hornblende series is perhaps the most complex series in the silicates. It varies more or less continuously with respect to the ratios Ca/Na, Mg/Fe'', Al/Fe''', Al/Si and OH/F. Most of the variations mentioned have been actually found in the amphiboles, of which there are hundreds of analyses. In view of this remarkable isomorphism, it is no wonder that so many species names have been proposed for members of the hornblende series. Unfortunately, some of the names in the literature are based on habit, or optical properties. For our purpose these names are of no value, since our classification is chemical and structural, and any other basis of classification cannot consistently be superimposed on it.

The species listed are fairly representative of the range in the series, but it must again be pointed out that this is not a list of so-called end members. It is a list of the most commonly found compositions in the series.

Narsarsukite $Na_8FeTi_3Si_{16}O_{43}F$, or $W_2X\ Si_4(O,\ F)_{11}$ has been shown by Warren and Amberg (1934) to be of this composition, and is presumably of a structural type closely related to the amphiboles.

Chrysotile $X_6Si_4O_{11}(OH)_6 \cdot H_2O$; $X = Mg$ predominantly; Fe'' minor amounts; Ni, Mn subordinate; Al small amounts. The species name chrysotile is here applied only to the fibrous mineral of this composition; another name which might equally well be used is serpentine. Serpentine has been shown to have the chain structure (Warren and Bragg 1930). The so-called antigorite (see previous structure type) is platy and presumably of the same composition as serpentine. These two substances are apparently dimorphous.

Pyroxene group: The pyroxenes are, in general, a well-understood group of minerals, mainly because of their relatively simple chemical composition. The similarity of composition and physical properties of the pyroxenes and amphiboles have been stressed in the textbooks. Actually, the compositions of the two groups are as widely different as almost any two groups in a particular silicate type. Warren and Biscoe (1931) have shown that the two structures are related in a rather simple way.

The orthorhombic enstatite-hypersthene series ranges from the pure Mg member to iron-rich hypersthenes with $Fe:Mg < 1$. The Fe end component is not known in nature. Small amounts of Al and Ca, and less often Ti, are present in some hypersthenes.

The pigeonite series ranges between clinoenstatite, an artificial monoclinic mineral of the composition of enstatite, and a somewhat calcic member called pigeonite. No evidence of a natural series extending from clinoenstatite to diopside has as yet been presented. Few good analyses of pigeonite are available.

The diopside-hedenbergite series is well established throughout the range $Mg–Fe''$. Rarer members of the series contain Mn, Zn, Cr, in addition to the usual Mg, Fe''. The so-called Tschermak molecule is an expression of the amount of Al present in this series. Because the oxygen is constant in the unit cell of the pyroxenes (as it is in most silicates) an introduction of Al into a diopside means that this Al must be shared equally by the Mg-like atoms and by the Si; otherwise the valence demands would not be satisfied. The member of the series having an Al substitution of this sort is called augite.

The Tschermak molecule was written as $CaAl_2SiO_6$, or $CaAl(AlSiO_6)$. This sort of "molecule" implies that half the Si could be replced by Al in the chain network. No actual pyroxene approaching this composition has been found in nature. This "end member" has therefore not been accepted.

The acmite-jadeite series is probably continuous through the Al–Fe‴ range and shows a relationship to the diopside series, with intermediate members such as aegirite.

Spodumene is a monoclinic pyroxene from all the available evidence. However, it forms no ismorphous series with other members of the pyroxene group, and Li is rarely reported in a pyroxene analysis. While we have placed spodumene in the pyroxene group, we must recognize that the other members are more closely related to each other structurally than is spodumene to any of them.

The so-called "triclinic pyroxenes" are not included here in the pyroxenes because the writer believes they are more properly considered as a separate group, with no isomorphous relations to any of the pyroxene minerals, and with physical and chemical properties clearly differing from those of the pyroxenes. To these pyroxene-like minerals we here give the name pyroxenoids.

The pyroxenoid family: The comparatively simple metasilicate composition, together with the fibrous or prismatic development of the pyroxenoid minerals, suggest strongly that a chain structure is the most likely internal arrangement. Chemical and physical analogies with the pyroxenes further suggest that the structure of these minerals should be somewhat similar to that of the pyroxenes. Because of the low symmetry no complete structural solution of any of the pyroxenoids has as yet been presented.

As shown in the table, there are two well-defined groups in the pyroxenoids, and a miscellaneous group of minerals, more or less related. The rhodonites are sufficiently close in their relations to be considered a series. The wollastonite group shows little variation in the composition of its individual members and is therefore not a series.

The rhodonite series has the simple metasilicate composition given in the classification. Rhodonite is the most important member of the series, the others are probably isomorphously related with part of the Mn replaced by a small amount of Ca, some Zn in fowlerite, Fe″ in iron rhodonite and Mg, Fe″ in sobralite. Sundius (1931) has shown the close optical and chemical relations between these minerals. Ca is not present in considerable amounts in this series, but in the wollastonite group Ca is essential.

The wollastonite group is much more complex chemically than is the preceding series. In order to show better the variations in the composition of the members of the group the full cell contents (as determined by Warren and Biscoe 1931 for wollastonite) are used in the formulae. The wollastonite group of minerals does not form an isomorphous series, but most of the members are constant in composition. Although wollastonite

and pectolite are probably isostructural, no intermediate compounds are known. Margarosanite is chemically intermediate between wollastonite and alamosite, but its crytal form is like neither of them and it cannot be considered as an isomorphous mixed-crystal of a series.

The mineral bustamite $CaMnSi_2O_6$ has been assumed to be an end component of a rhodonite-bustamite series. However, it is not so placed here because, (1) x-ray powder patterns indicate that bustamite is more closely related structurally to wollastonite than to rhodonite (Bowen, Schairer and Posnjak 1933); (2) no continuous variation in the physical properties has been shown to exist in a presumed bustamite-rhodonite series; (3) Sundius has pointed out optical similarities between bustamite and wollastonite. A more detailed x-ray study of bustamite by the writer using cleavage prisms of the mineral has shown that the lattice constants of bustamite are close to those of wollastonite (paper read before the Mineralogical Society, 1936).

The compositions of wollastonite and pectolite present a problem in structural analysis. The two are related as follows:

Wollastonite $Ca_6\ Si_6\ O_{18}$
Pectolite $Ca_4Na_2\ Si_6\ O_{16}(OH)_2$
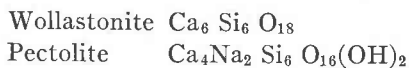
In pectolite the ratio $Si:O = 3:8$, in wollastonite it is $3:9$. If the two are isostructural, the chain must have either an Si_3O_8 or an Si_3O_9 composition for both minerals. In the former case, the most likely, the oxygen atoms of wollastonite are of two kinds; 16 are in the tetrahedral network and 2 are not. In the other alternative, $Si:O = 3:9$ (or $6:18$), the (OH) of pectolite would necessarily be in the tetrahedral network. This is unusual for silicates, although it has previously been reported (Zachariasen 1931). In a recent paper on the structure of wollastonite Barnick found that none of his chain arrangements would satisfy the x-ray data.

Alamosite is monoclinic (Palache and Merwin 1909) and shows only a partial relation to the triclinic wollastonite group. An intermediate mineral, margarosanite, is not similar crystallographically or in habit to either of the above mentioned minerals, and it cannot be placed in a series with them.

Under miscellaneous pyroxenoids are listed several minerals which have some relation, either in crystallography or in composition, or both, to the first two pyroxenoid groups.

Babingtonite is a mineral of definite composition and crystallographic properties close to those of rhodonite (Gossner and Brückl 1928). The composition would not lead one to expect a close structural relation between the two; yet Richmond (1937) shows that the two species have closely similar triclinic lattices, and are probably isostructural. The ex-

tent of the similarity of composition can be shown by comparing the cell formulas:

Rhodonite: $Mn_{10}Si_{10}O_{30}$
Babingtonite: $Ca_4Fe_2''Fe_2'''Si_{10}O_{28}(OH)_2$
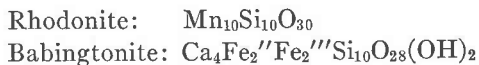
If these two species are isostructural, two positions in the cell of babingtonite are vacant where two manganese atoms would be found in the rhodonite cell.

Taramellite is a rare silicate, essentially a Ba babingtonite in composition. It is said to be orthorhombic in symmetry, and to have no H_2O in its composition so that it is probably not isostructural with babingtonite.

Hyalotekite is one of the rare Långban minerals, with a metasilicate composition and cleavages indicating a relationship to some of the minerals of this section.

Neptunite is a simple metasilicate of a composition and form not unlike the pyroxenoids or the pyroxenes. The Ti is not grouped here with the Si because the usual co-ordination number of Ti is not the same as that of Si in the silicates. In the formula for neptunite given in the classification $Fe''+Mn'':Ti$ is $1:1$.

The calcium metasilicates are of fibrous habit, rarely forming crystals suitable for measurement; data for these minerals are consequently scarce. Of those listed xonotlite has been studied by the writer crystallographically and by use of x-rays, and analysed recently by Bauer (in Palache 1935). Xonotlite is monoclinic and shows a relation to wollastonite in its unit cell dimensions. With two units of the formula $Ca_3Si_3O_8(OH)_2$ in the cell, the b_0 and c_0 values of wollastonite and xonotlite are almost identical. The a_0 value of xonotlite is somewhat greater than is the a_0 of wollastonite, as shown below:

Wollastonite (Warren) $a_0=7.88$Å; $b_0=7.27$Å; $c_0=7.03$Å
Xonotlite   (Berman) $a_0=8.55$Å; $b_0=7.34$Å; $c_0=7.03$Å
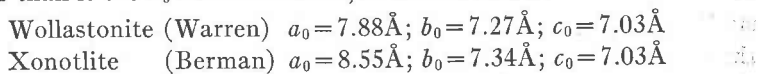
Wollastonite is triclinic and xonotlite is definitely monoclinic despite the fact that β is $90°$. Both minerals are elongated in the b-axis. There is little doubt that these minerals are structurally related, and perhaps both are made up of Si_3O_8 chains, for the xonotlite formula clearly suggests this type of chain. One might hazard the guess that the extra (OH) of the xonotlite lies along the a-axis, since that is the direction in which the cell is slightly increased in size over that of wollastonite.

Inesite is, as the formula indicates, closely related to xonotlite chemically. However, it is triclinic and differs optically from xonotlite.

The mineral foshagite has been shown to be identical with hillebrandite. This has been checked independently by the writer.

Jurupaite is presumably an equivalent of riversideite with the Ca:Mg ratio of 7:1. These are finely fibrous minerals and exact data for them is lacking.

Copper metasilicates: The copper metasilicates are all finely fibrous to cryptocrystalline. Chrysocolla is often amorphous and rather variable in composition. The other minerals of this family seem to have distinct optical properties and are therefore valid species.

Miscellaneous metasilicates. The chief reason for placing this list of miscellaneous minerals here is that they are fibrous or prismatic and their compositions can be expressed as metasilicates. They vary widely in their physical properties and have little in common. A division is made between those having the composition $(SiO_3)_n$ and the five minerals at the end of the list with a composition (Si_3O_8) (see pectolite and xonotlite). These latter minerals probably belong most properly in the metasilicate chain division of the classification, although their composition suggests a more complex chain arrangement than that of the other metasilicates. Some evidence of a complex chain has been presented for eudidymite and epididymite; the others have not been studied structurally.

Ring structures of the metasilicate type

Benitoite	WYZ_3O_9
Catapleiite series	$WYZ_3O.2H_2O$
Eudialyte series	$W_2(X, Y)Z_3O_8(OH, Cl)$
Steenstrupine	$W_4XY_6(Z_3O_9)_3(OH)_7 \cdot 3H_2O$
Tourmaline	$WX_3Y_6(Z_3O_9)_3(O, OH, F)_4$
Beryl	$X_3Y_2Z_6O_{18}$

The minerals of this sub-type have as their principal structural feature the closed metasilicate ring (Fig. 4, c, e). Benitoite and beryl have been studied and their structures show the two kinds of rings found, one of three tetrahedra to form a trigonal pattern, and the other of six to form the hexagonal pattern of beryl. From the structure data one would expect other members of this type to be either hexagonal or trigonal (or nearly so, in the case of pseudosymmetry). The members here listed are for the most part trigonal and thus far they fit the requirements. For those which have not been studied structurally the writer can only say that heretofore no simpler formulae have been proposed, and no adequate place in any classification has been found for these complex silicates.

Benitoite $BaTiSi_3O_9$. Zachariasen (1930B) has established the ring structure for this mineral.

Catapleiite series $(Na_2, Ca)ZrSi_3O_9 \cdot 2H_2O$. Catapleiite is pseudohexag-

onal at room temperature and hexagonal at 140°C. The formula is derived from the analyses in Dana (1892, p. 413). Natron-catapleiite gives the composition: $Na_2ZrSi_3O_9 \cdot 2H_2O$, which is much like that of eudialyte. Apparently in the ordinary catapleiite Ca substitutes for Na_2, a rather unusual substitution in the silicates where atom-for-atom replacement is the rule.

Eudialyte (eucolite) series $(Ca, Na)_2(Zr, Ce, Fe'', Mn'')Si_3O_8(OH, Cl)$. The composition of the series is much like that of catapleiite. The chief difference is the partial replacement of the Zr of catapleiite by Ce, Fe, Mn in eudialyte. In addition some Cl is found in eudialyte.

Steenstrupine $CaNa_3Mn(Ce, La, Al, Fe''')_6(Si, Ti)_9O_{27}(OH)_7 \cdot 3H_2O$. This complex mineral is not closely related chemically to the minerals just described. However, its composition can be expressed in the above formula. The Ti in small amount probably here enters into the tetrahedral network, as it probably also does in some garnets.

Tourmaline series: Tourmaline is the most complex of the minerals placed in this type. The composition of tourmaline has been thoroughly investigated over a long period. However, no generally accepted expression of the composition has as yet appeared. A ring structure in which the principal elements of the composition are arranged to give the trigonal symmetry is, in the writer's opinion, the most logical initial assumption to be made. The formula above offers strong confirmation of this assumption since the principal groups of atoms are actually grouped in sets of 3. It is to be noted also that the important variations in the composition of the tourmalines are all contained in the single term X of the formula, i.e., one can define a tourmaline simply by giving the Ca/Na ratio and the elements present in the X part of the formula. This interpretation of the tourmalines follows that of Larsen and Berman (1934, p. 247) and differs in detail from that of Kunitz (1929).

Beryl $Al_2Be_3Si_6O_{18}$ usually has this simple composition; some beryls, however, carry alkalies and water. One such analysis with considerable alkalies gave $(Li, Na, Cs)Be_{2\frac{1}{3}} Al_2Si_6O_{18} \cdot \frac{1}{2}H_2O$. Unfortunately few such complete analyses are available so that the role of the alkalies in beryl is not clear. Bragg and West (1926) concluded from a structural study that the alkalies and water were placed somewhere within the channels parallel to the c-axis and lying within the hexagonal ring of tetrahedra.

PYROSILICATE TYPE

The pyrosilicates are those which have the Si_2O_7 composition, resulting from two tetrahedra sharing an oxygen atom. Chemically the minerals of this type are characterized by a lack of Al, so that Al tetrahedra are not found in the structure, except in gehlenite, a member of the melilite

series. Furthermore, the atoms, other than Si and O, the W atoms of our classification, are generally large in radius. Such elements as Y, Sc, Ce, Ca, Ba, Pb are common in this type; Na and K are notably lacking; Be is sometimes present.

No specific physical characteristics distinguish the type. There is a tendency for the crystals of these minerals to be tabular, as in melilite, barysilite, hemimorphite and molybdophyllite. They are usually of high refractive index and high density as compared with silicates of the first three types, although this is not so much due to the structure as it is to the presence of such elements as Pb, Ba and some of the rare earths.

Thalenite group: Of the minerals in this group thortvietite is best known since Zachariasen (1930A) has worked out its structure. The others are related both chemically and physically.

Melilite group: The writer (1929) has discussed the chemical composition of the melilite group elsewhere. A complete series between åkermanite and gehlenite is known in nature, and has been produced in the laboratory (Buddington 1922). Na enters into the composition to a rather limited extent with the composition $CaNaAlSi_2O_7$ as the probable limit of the Ca-Na series.

Hardystonite has been shown (Warren and Trautz 1930) to be isostructural with melilite, and Zachariasen (1931) has pointed out the similarity of the cell dimensions of leucophanite with that of melilite. The minerals of this group are all tetragonal with the exception of leucophanite which is pseudo-tetragonal. The composition of leucophanite illustrates the possibility of F entering into the silicon-oxygen tetrahedron in place of one of the oxygens (Zachariasen).

Barysilite group: The three minerals of this group are closely related; barysilite is rhombohedral, the other two are hexagonal. The compositional relationship can best be shown by writing the formula for ganomalite as $[(Ca, Pb)_3Si_2O_7]_3 \cdot Pb(OH)_2$. There is no evidence, however, that the Pb has more than one structural position, and the writer prefers the formula as given in the classification.

Hemimorphite family: Hemimorphite has been shown to belong to this structural type (Ito and West 1932A). Bertrandite, a related mineral both crystallographically and chemically, has also been studied structurally but without much success (Ito and West 1932B; Wyckoff 1935, p. 117). Clinohedrite has undoubted chemical relations to these two minerals and is for that reason placed here. Cuspidine and its hydroxyl equivalent custerite, $Ca_4Si_2O_7(OH, F)_2$, are clearly of this chemical type. Complete crystallographic data are lacking for these minerals. Murmanite and molybdophyllite are rather platy in habit, like barysilite, but they cannot possibly be placed in the disilicate type. Since many of the

minerals in this type are tabular to platy, it is believed that these two are undoubtedly pyrosilicates, with a composition analogous to the members of the hemimorphite family. The minerals put together here as a family are so grouped mainly because they show chemical similarities. No close crystallographic relations have as yet been found.

Miscellaneous pyrosilicates. Barylite has a comparatively simple composition. Harstigite is a rare silicate of rather complex composition placed here with some uncertainty.

Lawsonite is of some special interest since its composition is similar to anorthite plus water: $CaAl_2Si_2O_8 \cdot 2H_2O$. If this mineral were of the silica type, as it well might be considering its composition, it would certainly have a low specific gravity and low refractive index as all of that type do. On the contrary it actually is an especially hard mineral with a specific gravity of 3.09 and mean refractive index of 1.67. These properties immediately rule it out of the silica type. The writer and Professor Warren of the Massachusetts Institute of Technology attempted to derive a structure of this mineral beginning with the assumption that it was an SiO_4 type, i.e., independent tetrahedra as the fundamental framework. This study failed to establish the structure, and the writer's opinion is that lawsonite probably has an Si_2O_7 structure, for this seems to be the only remaining possibility. A dehydration curve to determine the role of water is essential to reach some satisfactory solution of the structure.

Danburite, with the composition of an orthosilicate $CaB_2Si_2O_8$ has presumably a pyrosilicate structure (Dunbar and Machatschki 1930) so that its formula may be written $CaB_2(Si_2O_7)O$. No other example of this sort has, as yet, been found among the silicates.

Astrophyllite has the somewhat complex formula given, for the originally analysed material and also for the more recently described occurrences of the Kola region. The ratio $Fe'':Al:Ti = 11:1:3$ to $8:3:4$.

Aenigmatite. The formula of aenigmatite has recently (Fleischer 1936) been given in the pyrosilicate form, as $W(X, Y)_{13}(Si_2O_7)_6$ or more specifically $(Na, Ca)_4(Fe'', Ti, Fe''', Mg, Al)_{13}(Si_2O_7)_6$. Since the physical properties are not too well established and the chemical variation is considerable, there may still be some question as to the adequacy of the formula of aenigmatite. Rhönite is said to be a calcium-aluminum rich aenigmatite but the best formula from the analyses bears no very close relation to the latter.

Orthosilicate Type

The orthosilicates are those in which independent SiO_4 tetrahedra are the characteristic feature of the fine structure. No tetrahedron shares

oxygen atoms with any other silicon-oxygen tetrahedron and the resulting ratio is $Si:O = 1:4$. When the ratio is less than $1:4$ it means that some of the oxygens of the structure are not in the tetrahedra. This last type therefore merges into non-silicate structures wherein the tetrahedra no longer play a dominant role, or even an important one, and the minerals can no longer be said to be silicates. The transition silicates are here called subsilicates. At the end of the classification it becomes difficult to draw the line. The mineral sapphirine, where less than a third of the oxygens are in the tetrahedra, should not perhaps have been included in a silicate classification.

The orthosilicates are chemically diverse and no particular tendency for certain elements to be absent is known. Na and K are notably scarce and the rare earth and other rare elements are notably present. Al is found in most of the members but not in tetrahedral co-ordination so that Al and Si do not substitute for each other in any minerals of the type.

The physical characteristics of the type are sufficiently definite to be of some diagnostic value in the classification. Most of the minerals placed here have no pronounced tendency to form fibrous or platy crystals; they generally form equidimensional crystals. This is in keeping with the structural features of the type which does not have extended units of structure. The members of the type are generally hard and of comparatively high specific gravity, since the chief elements in the composition are the denser atoms and the packing is close. The refractive indices of most of the members are also comparatively high, for the same reasons.

Chrysolite group: The olivine series has within it eight well-defined species corresponding to the principal variations within the series. In addition, three other species, listed in the classification, are recognized. All of the elements, excepting Ca and Pb, form continuous series with each other. The limit of miscibility of Ca in the olivines is as shown in such minerals as glaucochroite, $CaMgSiO_4$. A Ca end component, larnite, is apparently not a member of the olivine series (Tilley 1929). Larsenite, $PbZnSiO_4$, is an unusual member, with Pb replacing the Ca part of the regular formula. A pure Zn member of this series is unlikely since the pure Zn orthosilicate formed in nature is the rhombohedral mineral willemite. The olivine structure (Bragg and Brown 1926) shows the structural non-equivalence of the two types of Mg atoms, one of which may be replaced by Ca without unduly distorting the lattice. This explains the limited miscibility of Ca in the series.

The two species larnite and merwinite are not closely related to the olivine series crystallographically, but they have the same type of composition. Larnite, Ca_2SiO_4 is, as expected from the structural evidence

previously stated, not an olivine. The other mineral is equally rare and little is known of its properties.

Phenakite group: Phenakite and willemite are definitely related in both crystallographic and chemical properties. Dioptase, while it is close to the other two crystallographically, is less definitely related in its composition. No adequate structural work has as yet been done on dioptase. It would be particularly interesting to know the role of water in this mineral. The three minerals are in no sense a series since no mixed-crystals are known. Willemite does have some Mn in varying amounts in its composition, but some analyses are misleading because of the probable admixture of tephroite or some other Mn mineral. Trimerite $(Mn, Ca)BeSiO_4$ is pseudohexagonal and probably related in structure to the members of the phenakite group.

Humite group: To show the inter-relations of these minerals, their formulae may be written together with the forsterite formula, in a manner somewhat different from that given in the classification.

Forsterite	Mg_2SiO_4
Norbergite	$Mg_2SiO_4 \cdot Mg(OH, F)_2$
Chondrodite	$2Mg_2SiO_4 \cdot Mg(OH, F)_2$
Humite	$3Mg_2SiO_4 \cdot Mg(OH, F)_2$
Clinohumite	$4Mg_2SiO_4 \cdot Mg(OH, F)_2$

It has been found by x-ray studies that this remarkable group is structurally composed of segments similar to the olivine structure with interleaved segments of brucite layers $Mg(OH)_2$. Since these are packed in the direction of the c-axis, the length of that axis changes from one species to the other in a regular way, but the other two axes are essentially constant in absolute length. A detailed account of the structure may be found in Taylor and West (1928) and Taylor (1929).

Dana (1892, p. 534) shows that these species have essentially the same a- and b-axes and that the c-axes are proportional to the number of Mg atoms in the formula, as $5:7:9$ for chondrodite, humite and clinohumite respectively. The early crystallographic work thus anticipated in a measure the structural features found later.

Hodgkinsonite group: This group, in which no series are formed, is chemically similar to the preceding humite group, with Mn playing the role of Mg. The crystallographic and structural features of the group have not as yet been investigated from this point of view. Gageite is less certainly related to the group but it has no closer affinities and is therefore placed here.

Garnet group: The garnets have been studied from all points of view, and it is well recognized (Ford 1915) that there are two important series, as indicated above. For convenience in designating the series the

most prominent members of each are here chosen (Winchell 1933, uses Pyralspite and Ugrandite). There is a small amount of miscibility between the two series, while the members of each series show a more or less complete range of miscibility. However, in the almandite series Mg and Fe show mixed crystals in all proportions, Fe'' and Mn through a wide range, but Mg and Mn do not form mixed crystals throughout the range. In the andradite series Al and Fe''' are completely miscible, whereas Cr is only present in small amounts in mixed crystals. Rarer constituents such as Mn''' and Ti enter into some of the garnets in small amount. Ford (1915) has discussed the miscibility ranges in the garnets at some length.

Titanium garnets, the so-called schorlomites, are comparatively rare and very few modern analyses are available for study. There seems to be little doubt, however, that Ti substitutes in part for Si in the composition. This may be explained perhaps by assuming that the larger Ti atom may fit into the tetrahedral framework at the high temperature of formation of these garnets. The formula derived from the most recent analysis (Hoffman 1901) is as given in the table above. Here Si:Ti = 2:1, with Fe''' high as in most Ti garnets.

Sarcolite has a composition almost identical with that of grossularite. It is, however, tetragonal and has a very much lower refractive index and specific gravity. Little Na enters into the composition so that this slight variation cannot explain the physical differences. As a consequence of its comparatively low refractive index (1.61) and low specific gravity (2.9) the writer is not inclined to consider this mineral as a true orthosilicate. However, no better place in the classification is apparent. Certainly sarcolite has little in common with the scapolites with which it has been grouped (Gossner and Mussgnug 1928). The proper placing of this mineral must await an x-ray study.

Vesuvianite is variable in composition and a complete solution of its constitution is not yet available. Warren and Modell (1931) have investigated the complex structure and concluded that this mineral is related structurally to the garnets. Their study indicates that both Si_2O_7 and SiO_4 types of silicate structure are in the vesuvianite network. This is one of the few known structures where two types are found. An examination of the vesuvianite analyses shows that the formula given by Warren is not completely satisfactory. However, no better has been derived as yet, and Warren's formula is used here. The peculiar beryllium bearing vesuvianite recently described from Franklin, N. J. does not fit in any sense into the Warren formula, or any other which has ever been proposed for vesuvianite.

Epidote group: This group consists of an orthorhombic member, zoisite, which varies little from the composition given, and the more important monoclinic members which show considerable variation in composition. The group is divided into three series between which there is apparently no miscibility.

The epidote series has a little Mn'' in its composition (manganepidote); otherwise W is always Ca. Y is predominantly Al with a maximum of 40 atomic per cent of Fe'''; thus $Al:Fe''' \geqq 3:2$. In piedmontite Mn''' represents as much as one-half the Y component.

In the allanites, rare earth elements as well as Mg, Be, and Na enter into the composition. An allanite having considerable Mg (magnesium orthite) has been described (Geijer, 1926). Another allanite of unusual composition is nagatelite (Iimori, 1931), in which part of the Si is replaced by P in the ratio $Si:P=5:1$. The possibility of this kind of replacement in the silicates has been discussed by Machatschki (1931).

Hancockite is a rare member of the epidote group with Sr and Pb in its composition.

Pumpellyite, a recently described mineral (Palache and Vassar 1925) differs from epidote chemically in having an extra molecule of H_2O. In some of its physical properties it resembles the epidotes, but crystals are not available for study. An x-ray investigation of the fibers would probably yield data adequate for comparison with epidote.

Sursassite $Mn_5Al_4Si_5O_{21} \cdot 3H_2O$ (Jakob 1926) has optical properties near those of a manganese epidote (Barth and Berman 1930). In view of the complexity of the given composition and its total dissimilarity from that of epidote, it would seem desirable to reinvestigate this mineral.

Zircon group	$XSiO_4$
Zircon	$ZrSiO_4$
Thorite	$ThSiO_4$

The two minerals of this group are closely related in form, but no intermediate members are known. Zircon is essentially pure $ZrSiO_4$ with spectroscopic traces of many rare elements including Hf; Fe''' is often reported in small amounts. Thorite is rarely found unaltered. Many of the analyses show U, Fe''', Pb, Ca in rather small amounts. One variety has been called uranothorite. It is particularly noteworthy that Zr is not found in thorite.

Wöhlerite family: The minerals of this family are complex in composition and varied in crystallography. Brögger (1890) described most of these minerals in detail and has placed them in two existing groups, on the basis of rather elaborate constitutional formulae. Wöhlerite,

hiortdahlite and lavenite were placed in the pyroxenes; johnstrupite and mosandrite in the epidotes. There is no indication that any of these minerals are metasilicates, and the Si:O ratio is closely 1:4. Further, in order to place these in either the epidotes or pyroxenes one must make assumptions concerning the chemical relations wholly unacceptable to the writer. The simplicity of the formulae presented here as compared with Brögger's convinces the writer that they probably more nearly express the true composition. The essential difference between the members of the wöhlerite group lies in the X component of the formula. It is seen that the chief difference (if there is any real difference) between hiortdahlite and guarinite (Zambonini and Prior, 1909) is in the presence of Ti in one and Cb in the other. Wöhlerite is a Zr, Cb equivalent of the others. Johnstrupite has essential Ce as well as some Al. Brögger (1890) indicated certain crystallographic similarities between the members of this group. Peacock (1937) has re-investigated rosenbuschite and has discussed its systematic relations.

The other minerals placed in this family are very different in composition and probably not closely related in structure to the wöhlerite group. No closer relation to any other silicates, however, is apparent, and they are placed here for comparison. Gossner and Kraus (1933, 1934) have determined the cell dimensions and cell contents of several members of the wöhlerite family.

Låvenite has the composition as shown in the classification, $X = $ (Ca, Na); $Y = $ (Zr, Cb, Fe, Ti, Mn). It is an example of the complex substitutions possible in the rare earth and rare element silicates, as noted in the minerals of the preceding group as well as in some others previously discussed (eudialyte, steenstrupine, catapleiite, etc.). This mineral may perhaps, on chemical grounds be considered a member of the datolite family.

Datolite family: The four minerals in this family are closely related in crystallographic properties; they probably have some structural relations but no serial relation is known between them. The structure of euclase has been determined, but the others have not yet been worked out. It seems unlikely that datolite is very close to euclase in its structural features since Be or Al are considerably smaller than Ca in ionic radius (Fig. 5) and one or the other must have a position equivalent to that of Ca if the two minerals are isostructural. In homolite and gadolinite the indications of isostructural relations are more favorable, but it is unlikely that these are isostructural with either of the first two mentioned minerals.

Miscellaneous orthosilocates: The normal orthosilicates which do not readily fit into any of the previously discussed groups are placed here.

Topaz and eulytite have been studied by means of x-rays, and the independent SiO_4 tetrahedra have been established as the important structural feature. In ilvaite some Mn is found, $Fe'':Mn''=4:1$. Since zunyite has such a high F and Cl content for an orthosilicate, there must be some doubt as to its proper place in the classification. A supposedly monoclinic modification of eulytite is known as agricolite; this is a rare and little-studied mineral.

Subsilicates: This subtype consists of those silicates which, as before stated, have independent SiO_4 tetrahedra in the structure, but all of the oxygen atoms are not in these tetrahedra. In all of the previously described types all of the oxygen atoms were in the tetrahedra so that the ratio of $Si:O \leqq 1:4$. In these subsilicates the ratios are $1:5$ or less to such low silicon compounds as sapphirine where the ratio is $Si:O = 2:27$. The classification logically terminates with these low silicon minerals where Si plays a decreasingly important role in the structure. In any natural classification there is no sharp break, and here the silicates merge into the titanates, the borates and the rare earth minerals. The subsilicates are properly a sub-type of the orthosilicates since the SiO_4 tetrahedra are independent elements of the structure.

Aluminum subsilicate family. The three modifications of aluminum silicate save independent tetrahedra in the structure. Mullite has a structure apparently almost identical with sillimanite (Taylor 1928), and its cell dimensions are so close that only very accurate measurement can distinguish between the two. A comparison of unit cell compositions gives the following result:

$$\text{Sillimanite} \quad Al_8Si_4O_{20}$$
$$\text{Mullite} \qquad\; Al_8(AlSi_3)O_{19\frac{1}{2}}$$
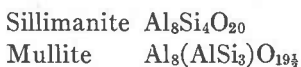
The interpretation of the relation between the two minerals is due to Wyckoff, Grieg and Bowen (1926), who believe that the mullite cell is actually twice the sillimanite cell and that one oxygen atom in forty is somehow missing in the structure. There are yet several discrepancies in the full mullite story. Artificial crystals have been measured by the writer. The forms [110] and [011], based on the sillimanite axial lengths, were the only important forms noted. This, in the writer's opinion indicates that the unit cell is possibly the same as that of sillimanite, and not some multiple thereof. X-ray pictures taken in this laboratory of single crystals of mullite have failed to show any doubling of the cell. The chemical analyses of mullite are uniformly lower in Al_2O_3 than the formula given. The calculated value of 71.8% of Al_2O_3 is to be compared with an average found value of about 70%. On pure material, as most of the artificial samples presumably were, this discrepancy is too

large. The actual composition is then somewhat nearer the sillimanite composition than the given formula indicates.

The composition of staurolite is such that it could be considered as two parts of kyanite to one part $Fe(OH)_2$. This is the structure derived for the mineral, which is a kyanite structure with interleaved layers of $Fe(OH)_2$.

Kentrolite group: The first two minerals in the group are orthorhombic and closely similar in their crystallographic properties. Beckelite is isometric and not closely related physically to the others. However, its structure is probably somewhat similar to that of the others, since its chemical elements are of the same sort and number as are those in the kentrolite group.

The titanium subsilicates are grouped together mainly because they presumably have independent SiO_4 tetrahedra and extra oxygen atoms as required for this sub-type. The writer has shown in another place (Barth and Berman 1930) that lorenzenite and ramsayite are members of a series. Molengraaffite and lamprophyllite are very close in their optical properties (Larsen and Berman 1934), and the writer is convinced that they are members of another series. Astrophyllite does not fit into the latter series according to the writer's interpretation, despite its apparent similarity in physical appearance.

Miscellaneous subsilicates. The minerals listed are, with one exception, (dumortierite), very rare, and their relations to other silicates are little understood because complete data are lacking. They are all low in Si, as the formulae show, and are therefore placed in this sub-type. Sapphirine is really an aluminate with some Si present. The writer believes that further data on these minerals will tend to show that some of the very complex compositions given are in error. In general, it can be said that all the minerals of this section are in need of further study.

The uranium silicate minerals are all low in silica and consequently come in this part of the classification. Uranophane and sklowdowskite are apparently closely similar in crystallographic properties as well as chemically and are possibly isostructural. Intermediate compounds are not known. Soddyite is the least siliceous of the uranium silicates and one of the least siliceous of the minerals placed in the silicates. Most of the oxygen atoms in this mineral are not associated with the Si tetrahedra.

REFERENCES

ALLING, H. L. (1921): *Jour. Geol.*, **29**, 193–295.
ASCH, W. and ASCH, D. (1914): *The silicates in chemistry and commerce*—New York.
BANNISTER, F. A., with HEY, M. H. (1931): *Min. Mag.*, **22**, 569–608.

BARTH, T. F. W. (1926): *Norsk Geol. Tidssk.*, **9**, 40–42.

———— (1932): *Amer. Min.*, **17**, 466–471.

———— and BERMAN, H. (1930): *Chemie der Erde*, **5**, 22–42.

BAUER, L. H. and BERMAN, H. (1930): *Amer. Min.*, **15**, 345.

BERMAN, H. (1929): *Amer. Min.*, **14**, 389–407.

———— and LARSEN, E. S. (1931): *Amer. Min.*, **16**, 140–144.

BÖRGSTROM, L. H. (1930): *Zeit. Krist.*, A, **74**, 117.

———— (1931): *Zeit. Krist.*, A, **76**, 481–499.

BOWEN, N. L. (1917): *Amer. Jour. Sci.*, **43**, 115–132.

————, SCHAIRER, J. F., and POSNJAK, E. (1933): *Amer. Jour. Sci.*, **26**, 193–234 (Bustamite, 270).

BRAGG, W. L. (1930): *Zeit. Krist.*, A, **74**, 237–305.

———— and BROWN, G. B. (1926): *Zeit. Krist.*, **63**, 538–556.

———— and WEST, J. (1926): *Proc. Royal Soc. London*, A, **3**, 691–714.

BRÖGGER, W. C. (1890): *Zeit. Krist.*, **16**.

BUDDINGTON, A. F. (1922): *Amer. Jour. Sci.*, **3**, 35–87.

CLARKE, F. W. (1914): *U. S. Geol. Surv.*, Bull. **588**.

DANA, E. S. (1892): *A System of Mineralogy*—New York.

———— (1932): *A Textbook of Mineralogy* (W. E. Ford)—New York.

DOELTER, C. (1914): *Handbuch der Mineralchemie*, **2** (1), 61–109.

DUNBAR, C. and MACHATSCHKI, F. (1930): *Zeit. Krist.*, A, **76**, 133–146.

FLEISCHER, M. (1936): *Amer. Jour. Sci.*, **32**, 343–348.

FORD, W. E. (1915 A): *Amer. Jour. Sci.*, **40**, 33–49.

———— (1915 B): *Third Appendix to Dana's System of Mineralogy*—New York.

FOSHAG, W. F. (1936): *Amer. Min.*, **21**, 63–67.

GEIJER, P. (1926): *Sveriges Geologiska Untersökning*, C, 343, Arsbok **20** (4).

GOLDSCHMIDT, V. M. (1926): *Sk. Norske Videns. Akad. Oslo*, 1 (2).

GORDON, S. G. (1924): *Proc. Acad. Nat. Sci. Philadelphia*, **76**, 249–268.

GOSSNER, B. and BRÜCKL, K. (1928): *Cbl. Min.*, A, 316–322.

———— and MUSSGNUG, F. (1928): *Cbl. Min.*, A, 129–138; 167–181.

GRUNER, J. W. (1935 A): *Amer. Min.*, **20**, 475–483.

———— (1935 B): *Amer. Min.*, **20**, 699–714.

HALLIMOND, A. F. (1922): *Min. Mag.*, **19**, 330–333.

———— (1924): *Min. Mag.*, **20**, 193–197.

———— (1925): *Min. Mag.*, **20**, 305–318.

HOFFMANN, G. (1901): *Amer. Jour. Sci.*, **11**, 150.

HEY, M. H., with BANNISTER, F. A. (1930): *Min. Mag.*, **22**, 422–427.

———— (1932 A): *Min. Mag.*, **23**, 51–125.

———— (1932 B): *Min. Mag.*, **23**, 243–289.

———— (1933 A): *Min. Mag.*, **23**, 305–308.

———— (1933 B): *Min. Mag.*, **23**, 421–447.

———— (1934 A): *Min. Mag.*, **23**, 483–494.

———— (1934 B): *Min. Mag.*, **23**, 556–559.

———— (1936): *Min. Mag.*, **24**, 227–253.

IIMORI, S. and others (1931): Abstract in *Min. Abs.*, **4**, 500.

ITO, I. and WEST, J. (1932 A): *Zeit. Krist.*, A, **83**, 1–8.

———— (1932 B): *Zeit. Krist.*, A, **83**, 384–393.

JACKSON, W. W. and WEST, J. (1930): *Zeit. Krist.* A, **76**, 211–227.

JAEGER, F. M. (1929): *Trans. Faraday Soc.*, **25**, 320–345.

JAKOB, J. (1923): *Schweiz. Min. Pet. Mitt.*, **3**, 227–237.

—— (1925): *Zeit. Krist.*, **62**, 443–453.
—— (1926): *Schweiz. Min. Pet. Mitt.*, **6**, 376–380.
KUNITZ, W. (1924): *N. Jb. Min.*, B.B.**50**, 365–413.
—— (1929): *Chemie der Erde*, **4**, 208–251.
—— (1930): *N. Jb. Min.*, A, **60**, 171–250.
LARSEN, E. S. and BERMAN, H. (1934): *U. S. Geol. Surv.*, Bull. **848.**
MACHATSCHKI, F. (1928): *Cbl. Min.*, A, 97–104.
—— (1931): *Cbl. Min.*, A, 343–347.
MITSCHERLICH, E. (1820): *Ann. Chim. Phys.*, **14**, 172–190; **19**, 350–419.
NARAY-SZABO, ST. v. (1930): *Zeit. Phys. Chem.*, B, **9**, 356–377.
ORCEL, M. J. (1927): *Recherches sur la Composition Chimique des Chlorites*, Thése-Paris.
PALACHE, C. (1931): *Amer. Min.*, **16**, 469–470.
—— (1935): *U. S. Geol. Surv.*, Prof. Paper **180.**
—— and MERWIN, H. E. (1909): *Amer. Jour. Sci.*, **27**, 399–401.
—— and VASSAR, H. E. (1925): *Amer. Min.*, **10**, 412–418.
PAULING, L. (1930 A): *Proc. Nat. Acad. Sci.*, **16**, 123–129.
—— (1930 B): *Proc. Nat. Acad. Sci.*, **16**, 578–582.
PEACOCK, M. A. (1935): *Amer. Jour. Sci.*, **30**, 495–529.
—— (1937): *Norsk Geol. Tidssk.* (in press).
RICHMOND, W. E. (1937): *Amer. Min.*, **22** (in press).
ROGERS, A. F. (1932): *Amer. Min.*, **17**, 161–172.
—— (1935): *Amer. Min.*, **20**, 25–35.
ROSS, C. S. (1926): *Proc. U. S. Nat. Mus.*, **69** (2), 1–15.
SCHALLER, W. T. (1916): *U. S. Geol. Surv.*, Bull. **610,** 133–136.
—— (1932): *Amer. Min.*, **17**, 128–134.
SCHNEIDER, H. (1927): *Jour. Geol.*, **35**, 289–310.
SELFRIDGE, G. C. (1936): *Amer. Min.*, **21**, 463–503.
STRUNZ, H. (1936): *Zeit. Krist.*, A, **95**, 1–8.
SUNDIUS, N. (1931): *Amer. Min.*, **16**, 411–429; 488–519.
TAYLOR, W. H. (1928): *Zeit. Krist.*, **68**, 503–521.
—— (1929): *Zeit. Krist.*, **70**, 461–474.
—— (1930): *Zeit. Krist.*, A, **74**, 1–19.
—— (1933): *Zeit. Krist.*, A, **85**, 425–442.
——, DARBYSHIRE, J. A., and STRUNZ, H. (1934): *Zeit. Krist.*, A, **87**, 464–498.
—— and NARAY-SZABO, ST. (1931): *Zeit. Krist.*, A, **77**, 146–158.
—— and WEST, J. (1928): *Proc. Roy. Soc. London*, (A) **117**, 517–532.
TILLEY, C. E. (1929): *Min. Mag.*, **22**, 77–86.
TOMKEIEFF, S. I. (1933): *Min. Mag.*, **23**, 463–476.
TSCHERMAK, G. (1864): *Ber. Kais. Akad. Wiss. Wien*, **50**, 1–48.
—— (1890): *Ber. Kais. Akad. Wiss. Wien*, **99**, 174–264.
—— (1891): *Ber. Kais. Akad. Wiss. Wien*, **100**, 29–107.
—— (1917): *Ber. Kais. Akad. Wiss. Wien*, (1) **126**, 1–66.
—— (1918): *Ber. Kais. Akad. Wiss. Wien*, (1) **127**, 1–113.
TUTTON, A. E. H. (1922): *Crystallography and Practical Crystal Measurement*—London.
VEGARD, L. and SCHJELDERUP, H. (1917): *Phys. Zeit.*, **18**, 93–96.
WARREN, B. E. (1929): *Zeit. Krist.*, **72**, 42–57.
—— (1930 A): *Zeit. Krist.*, **72**, 493–517.
—— (1930 B): *Zeit. Krist.*, A, **74**, 131–138.
WARREN, B. E., and AMBERG, C. R. (1934): *Amer. Min.* **19**, 546–548.
—— and BISCOE, J. (1931): *Zeit. Krist.*, A, **80**, 391–401.

WARREN, B. E., and BRAGG, W. L. (1928): *Zeit. Krist.*, **69,** 168–193.

——— (1930): *Zeit. Krist.*, A, **76,** 201–210.

——— and MODELL, D. I. (1931): *Zeit. Krist.*, A, **78,** 422–432.

——— and TRAUTZ, O. R. (1930): *Zeit. Krist.*, A, **75,** 525–528.

WELLS, H. L. (1891): *Amer. Jour. Sci.*, **41,** 213–220.

WHERRY, E. T. (1923): *Amer. Min.*, **8,** 1–8.

WINCHELL, A. N. (1925): *Amer. Min.*, **10,** 88–99; 112–117; 145–152; 166–174.

——— (1926): *Amer. Jour. Sci.*, **11,** 283–300.

——— (1933): *Elements of Optical Mineralogy* (Part II)—New York.

WOOSTER, W. A. (1931): *Zeit. Krist.*, A, **80,** 495–503.

WYCKOFF, R. W. G. (1931): *The structure of crystals*—New York.

——— (1935): *The structure of crystals*, Supplement—New York.

———, GREIG, J. W., and BOWEN, N. L. (1926): *Amer. Jour. Sci.*, **11,** 459–472.

ZACHARIASEN, W. H. (1929): *Norsk Geol. Tidssk.*, **10,** 449–453.

——— (1930 A): *Zeit. Krist.*, A, **73,** 1–6.

——— (1930 B): *Zeit. Krist.*, A, **74,** 139–146.

——— (1930 C): *Norsk Geol. Tidssk.*, **11,** 1–3.

——— (1931): *Norsk Geol. Tidssk.*, **12,** 577–581.

ZAMBONINI, F. (1923): (Abstract by H. S. WASHINGTON) *Amer. Min.*, **8,** 81–85.

——— and PRIOR, G. T. (1909): *Min. Mag.*, **15,** 247–259.

INDEX OF SPECIES