Nomenclature of pyroxenes

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Abstract

This is the final report on the nomenclature of pyroxenes by the Subcommittee on Pyroxenes established by the Commission on New Minerals and Mineral Names of the International Mineralogical Association. The recommendations of the Subcommittee as put forward in this report have been formally accepted by the Commission. Accepted and widely used names have been chemically defined, by combining new and conventional methods, to agree as far as possible with the consensus of present use. Twenty names are formally accepted, among which thirteen are used to represent the end-members of definite chemical compositions. In common binary solid-solution series, species names are given to the two end-members by the '50% rule'. Adjectival modifiers for pyroxene mineral names are defined to indicate unusual amounts of chemical constituents. This report includes a list of 105 previously used pyroxene names that have been formally discarded by the Commission.

KEYWORDS: nomenclature, pyroxenes, IMA.

Introduction

THE subcommittee on pyroxenes has, after a thorough evaluation of the group of pyroxene minerals, presented its recommendations for a new classification and nomenclature to the Commission on New Minerals and Mineral Names (hereafter abbreviated as CNMMN). These recommendations have been approved by the Commission by a formal vote (20th May, 1987).

The classification and nomenclature of the pyroxenes have been largely based on their crystal chemistry. In practice the chemical content of the pyroxene formula unit calculated to six oxygens, or to four cations (Vieten and Hamm, 1978), is essential for the classification. This formula unit corresponds to one quarter of the unit cell for the monoclinic pyroxenes and to one eighth of the unit cell for the orthorhombic pyroxenes. The basic principle adopted for amphibole nomenclature (Leake and Winchell, 1978) is to denote principal stoichiometries by generally well-established names, with adjectival modifiers to indicate the presence of substantial substitutions that are not essential constituents of the end-members; this has been followed as far as possible in the pyroxene nomenclature.

No new names have been introduced in the proposed nomenclature. Accepted and widely used names have been chemically defined by combining new and conventional methods to agree as far as possible with the consensus of present use. Two kinds of adjectival modifiers are used: one to specify a part of the compositional range shown by a mineral that forms a wide solid solution (e.g. magnesium-rich augite and iron-rich augite); the other to specify elemental substitutions that are not essential constituents (e.g. titanian augite). 105 previously used pyroxene names, mostly synonyms, obsolete or almost unused, recommended for rejection, have formally been discredited by the CNMMN.

General publications dealing with the pyroxene group include Rock-Forming Minerals (Deer *et al.*, 1978) (hereafter DHZ), the Special Papers (ed. Papike, 1969) and Reviews in Mineralogy (ed. Prewitt, 1980) of the Mineralogical Society of America, which provide references to the voluminous literature.

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Crystal chemistry of the pyroxenes

Pyroxenes are silicates that, in their simplest form, contain single SiO_3 chains of linked SiO_4 tetrahedra. Generally, small amounts of Si are replaced by Al and other small cations. The repeat along the chain (*c* axis) comprises two tetrahedra and is approximately 0.52 nm in length. The general chemical formula (formula unit) for all pyroxenes[1] is $M2M1T_2O_6$, where $M2$ refers to cations in a generally distorted octahedral coordination, $M1$ to cations in a regular octahedral coordination, and T to tetrahedrally coordinated cations.*

Any pyroxene belongs to either the orthorhombic or the monoclinic crystal system. There are two orthorhombic pyroxene types: orthopyroxene (*Pbca*) and orthopyroxene (*Pbcn*)[2]. Only the former has been found in nature. Monoclinic pyroxenes are called clinopyroxenes. Their space groups are $C2/c$, $P2_1/c$ and $P2/n$, depending on their chemical composition and genetic history.

Throughout this report, the standard pyroxene formula is used with superscripted Arabic numerals (e.g. Fe^{2+}) referring to charges, and subscripted numerals (e.g. Mg_2) to numbers of atoms.

In order to derive a pyroxene formula from a chemical analysis, the calculation should be based on six oxygen atoms, when Fe^{2+} and Fe^{3+} are both determined. In microprobe analyses, only total Fe is determined and the option of calculating to four cations should at least be permitted if not actually preferred. Vieten and Hamm (1978) show that calculation to four cations will be more reliable for microprobe analyses of the majority of pyroxenes. Therefore, for microprobe analyses it is recommended that the components be totalled to six oxygens and four cations by adjusting the ratios Fe^{2+}/Fe^{3+}, Ti^{4+}/Ti^{3+}, etc.

The standard pyroxene formula $M2M1T_2O_6$ contains two tetrahedral sites. In the allocation of the cations to obtain a pyroxene formula, the following procedure is recommended:

(1) Sum T to 2.000 using Si^{4+}, then Al^{3+}, then Fe^{3+}.

(2) Sum $M1$ to 1.000 using all Al^{3+} and Fe^{3+} in excess of that used to fill the T sites. If there is insufficient Al^{3+} and Fe^{3+} to sum to 1.000, then add Ti^{4+}, Cr^{3+}, V^{3+}, Ti^{3+}, Zr^{4+}, Sc^{3+}, Zn^{2+}, Mg^{2+}, Fe^{2+} and finally Mn^{2+} until the sum is 1.000.

(3) Sum $M2$ using all Mg^{2+}, Fe^{2+} and Mn^{2+} in excess of that used to fill the $M1$ sites. Then add Li^{+}, Ca^{2+} and Na^{+} so that the sum becomes 1.000 or close to it. If the sum is far from 1.000, one must be suspicious about the results of the analysis.

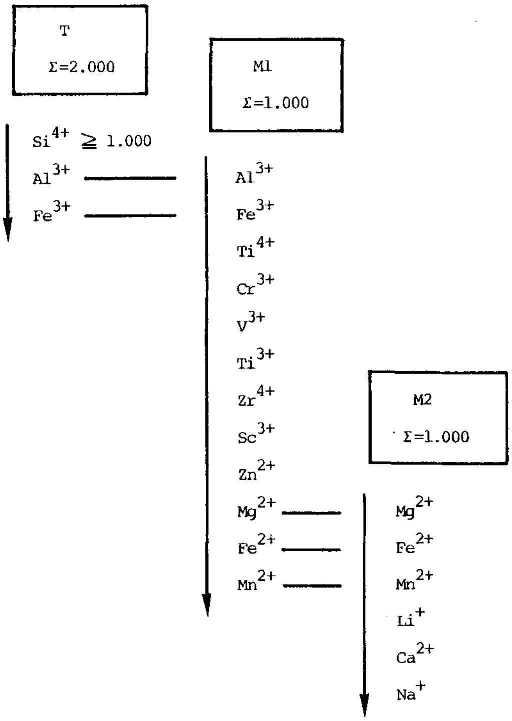

FIG. 1. Flow chart for ideal site occupancy of cations between the T, $M1$ and $M2$ sites of pyroxenes. Only representative cations are included. Arrows indicate order of filling of sites. Real site occupancy is usually slightly different from the ideal site occupancy.

A flow chart (Fig. 1) gives a diagrammatic representation of the site allocation of the principal cations in pyroxenes. However, because the distribution of cations among the $M1$, $M2$ and T sites in a given pyroxene is partly a function of temperature, the accurate site occupancy must be determined by structure determination. The site occupancy given in Fig. 1 is called ideal site occupancy to distinguish it from real occupancy. A method for classifying pyroxenes by their ideal site occupancies has been proposed by Bokij and Ginzburg (1985). In the present classification of pyroxenes, the $M1$ and $M2$ sites are considered together as a single M site in order to avoid the difference between the real and ideal site occupancies.

Starting from the most common pyroxene formula, $M2(R^{2+})M1(R^{2+})T_2(2R^{4+})O_6$, four coupled substitutions are possible if one assumes more than one R^{4+} in the T site. They are listed in Table 1, where the elements in parentheses are coupled substitutions.

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* Footnotes, indicated by superscript numbers, are to be found at the end of the paper.

Table 1. Four coupled substitutions of pyroxenes in the standard chemical fourmula $R^{2+}R^{2+}R_2^{4+}O_6$.

Substitution site	M2	M1	T	examples
standard	R^{2+}	R^{2+}	$2R^{4+}$	
substitution(1)	(R^{+})	(R^{3+})	$2R^{4+}$	Na-Al Na-Fe^{3+} Na-Cr^{3+} Na-Sc^{3+}
substitution(2)	(R^{+})	$R^{2+}_{0.5}(R^{4+}_{0.5})$	$2R^{4+}$	Na-(Ti^{4+}/2)
substitution(3)	R^{2+}	(R^{3+})	$(R^{3+})R^{4+}$	Al-Al Fe^{3+}-Al Cr^{3+}-Al
Substitution(4)	R^{2+}	$R^{2+}_{0.5}(R^{4+}_{0.5})$	$(R^{3+})R^{4+}$	(Ti^{4+}/2)-Al

Substitution (1) encompasses the end-members jadeite ($NaAlSi_2O_6$), aegirine[3] ($NaFe^{3+}Si_2O_6$), kosmochlor[4] ($NaCr^{3+}Si_2O_6$), and jervisite ($NaScSi_2O_6$). Substitution (2) results in components such as $NaFe^{2+}_{0.5}Ti^{4+}_{0.5}Si_2O_6$, but is less important than the other substitutions.

In substitution (3) the Al-Al couple is often referred to as ‘Tschermak's component’; $CaAlAlSiO_6$, in particular, is called ‘calcium Tschermak's component’. Substitution in esseneite[5], $CaFe^{3+}AlSiO_6$, is obtained by this type of substitution. This substitution is also important in ‘fassaite’[6]. Substitution resulting in $CaTi^{3+}AlSiO_6$ was reported by Dowty and Clark (1973) and Mason (1974) in pyroxenes from the Allende meteorite (Table 3, No. 4). In substitution (4) the component $CaMg_{0.5}Ti^{4+}_{0.5}AlSiO_6$ is found in some pyroxenes. There are a few instances of the component of substitution (2) or (4) amounting to nearly 50%, as described later (Table 3). However, no particular names are given for the end-member components of substitutions (2) and (4).

Mineral names of the pyroxenes

Twenty (20) mineral names and their grouping. The pyroxenes form extensive solid solutions by various types of ionic substitutions, some of which are described above. To cope with the problem of pyroxene nomenclature, it is necessary to subdivide the solid-solution series into ranges with specified compositions and names. Whenever there is a complete solid-solution series between two end members, it is customary in mineral nomenclature to use only two names, and the division between them should be at $A_{50}B_{50}$ (the ‘50% rule’). However, this ‘50% rule’ cannot be applied rigorously to the large groups of pyroxenes which show wide ranges of coupled substitutions. This is particularly so when the minerals concerned are abundant and widespread, and have a historically-established nomenclature in mineralogical and petrological circles. Taking this situation into consideration, 20 accepted and widely used names have been adopted as mineral species names of the pyroxenes (Table 2).

The definition of the pyroxene species has been based on thirteen end-members, or chemical components, listed in Table 2, and the component $Ca_2Si_2O_6$ (Wo)[7]. These end-members are given the names of the minerals whose compositions they most closely approximate. The 20 pyroxene species are grouped into six chemical subdivisions on the basis of the cation occupancy of the $M2$ sites and crystal chemical similarity. This classification is a slight modification of the widely used scheme proposed by DHZ (1978).

For the precise classification of the pyroxenes into 20 mineral species, however, the following characteristics of the pyroxenes must be considered. First of all, the Mg-Fe pyroxenes and some of the Ca pyroxenes are the most common rock-forming pyroxenes and form wide solid solutions which cover the pyroxene quadrilateral of the ternary $Ca_2Si_2O_6$ (Wo)-$Mg_2Si_2O_6$ (En)-$Fe_2Si_2O_6$ (Fs) system. Therefore, these pyroxenes are better treated together as the Ca-Mg-Fe or ‘quadrilateral’ pyroxenes. Secondly, Na pyroxenes form continuous solid-solution series with the Ca-Mg-Fe pyroxenes, forming the Na-Ca pyroxenes. Thirdly, donpeacorite and kanoite in the Mn-Mg pyroxenes, johannsenite, petedunnite and esseneite in the Ca pyroxenes, and spodumene, are rare in occurrence and unique in chemistry. For simplicity they are treated together as ‘other’ pyroxenes[8].

All the pyroxenes are thus divided into four

Table 2. Accepted pyroxene mineral names and their chemical subdivisions. Name, abbreviation and composition are given for any pyroxene that is used as an end-member of a pyroxene solid solution; such end-members are numbered between parentheses from 1 to 13. Main compositions are given for solid solutions. Space groups are also given.

mineral names	composition as end-member	main composition as solid solution	space group
I. Mg-Fe pyroxenes			
1. enstatite (En)(1)	$Mg_2Si_2O_6$	$(Mg,Fe)_2Si_2O_6$	$Pbca$
2. ferrosilite(Fs)(2)	$Fe^{2+}_2Si_2O_6$		
3. clinoenstatite		$(Mg,Fe)_2Si_2O_6$	$P2_1/c$
4. clinoferrosilite			
5. pigeonite		$(Mg,Fe,Ca)_2Si_2O_6$	$P2_1/c$
II. Mn-Mg pyroxenes			
6. donpeacorite		$(Mn,Mg)MgSi_2O_6$	$Pbca$
7. kanoite (Ka)(3)	$MnMgSi_2O_6$	$(Mn,Mg)MgSi_2O_6$	$P2_1/c$
III. Ca pyroxenes			
8. diopside (Di)(4)	$CaMgSi_2O_6$	$Ca(Mg,Fe)Si_2O_6$	$C2/c$
9. hedenbergite(Hd)(5)	$CaFe^{2+}Si_2O_6$		
10. augite		$(Ca,Mg,Fe)_2Si_2O_6$	$C2/c$
11. johannsenite(Jo)(6)	$CaMnSi_2O_6$		$C2/c$
12. petedunnite(Pe)(7)[*1]	$CaZnSi_2O_6$		$C2/c$
13. esseneite(Es)(8)[*2]	$CaFe^{3+}AlSiO_6$		$C2/c$
IV. Ca-Na pyroxenes			
14. omphacite		$(Ca,Na)(R^{2+},Al)Si_2O_6$	$C2/c$, $P2/n$
15. aegirine-augite		$(Ca,Na)(R^{2+},Fe^{3+})Si_2O_6$	$C2/c$
V. Na pyroxenes			
16. jadeite (Jd)(9)	$NaAlSi_2O_6$	$Na(Al,Fe^{3+})Si_2O_6$	$C2/c$
17. aegirine (Ae)(10)	$NaFe^{3+}Si_2O_6$		
18. kosmochlor(Ko)(11)	$NaCr^{3+}Si_2O_6$		$C2/c$
19. jervisite (Je)(12)[*3]	$NaSc^{3+}Si_2O_6$		$C2/c$
VI. Li pyroxene			
20. spodumene (Sp)(13)	$LiAlSi_2O_6$		$C2/c$

[*1] Petedunnite has been determined by Essene and Peacor (1987) to have the composition $(Ca_{0.92}Na_{0.06}Mn_{0.02})(Zn_{0.37}Mn_{0.19}Fe^{2+}_{0.19}Fe^{3+}_{0.12}Mg_{0.14})(Si_{1.94}Al_{0.06})O_6$ by means of an electron microprobe. This mineral was approved as a valid species CNMMN, IMA, in 1983.

[*2] Esseneite has been determined by Cosca and Peacor (1987) to have the composition $(Ca_{1.01}Na_{0.01})(Fe^{3+}_{0.72}Mg_{0.16}Al_{0.04}Ti_{0.03}Fe^{2+}_{0.02})(Si_{1.19}Al_{0.81})O_{6.00}$ by means of an electron microprobe. This mineral was approved as a valid species by the CNMMN, IMA, in 1985.

[*3] Jervisite has been determined by M. Mellini *et al.* (1982) to have the composition $(Na_{0.43}Ca_{0.31}Fe^{2+}_{0.14}\ _{0.12})(Sc_{0.66}Fe^{2+}_{0.15}Mg_{0.19})Si_2O_6$ by means of an electron microprobe. This mineral was approved as a valid species by the CNMMN, IMA, in 1982.

chemical groups for the purpose of broad classification: Ca–Mg–Fe pyroxenes (**Quad**, 8); Ca–Na pyroxenes (**Ca–Na**, 2); Na pyroxenes (**Na**, 2) and 'other' pyroxenes (**Others**, 8). The abbreviations of the groups and the numbers of the accepted species are given between parentheses. **Quad** represents 'quadrilateral' for the Ca–Mg–Fe pyroxenes. The four chemical groups are further divided into 20 mineral species by using 12 components (using the Wo component for Di and Hd components). The composition ranges for the accepted names will be given later.

The pyroxene names may be qualified by one or more adjectival modifiers according to definite rules described later to specify important (though relatively minor) departures from the composition ranges. When the composition range of the mineral species is large, as in augite, one or more adjectival modifiers are used to specify the composition more clearly (e.g. subcalcic augite, Fe-rich augite).

Application of 50% rule. The 50% rule has been applied to complete solid-solution series between two end members as far as possible. They are the Mg–Fe pyroxene series (enstatite–ferrosilite and clinoenstatite–clinoferrosilite series), Ca pyroxene series (diopside–hedenbergite series) and Na pyroxene series (jadeite–aegirine series). Subdivision names of the intermediate solid solution ranges, such as bronzite, hypersthene and eulite of the enstatite–ferrosilite series and salite and ferrosalite of the diopside–hedenbergite series, have been discarded. However, the 50% rule was not applied rigorously to the Ca–Mg–Fe pyroxenes and Na–Ca pyroxenes. The widely accepted terms such as augite, pigeonite, omphacite and aegirine-augite[9] have been retained.

Gem names of spodumene. Two names, 'hiddenite' and 'kunzite', are often used respectively for (pale) emerald-green and lilac coloured spodumene of gem quality. They are not accepted as formal pyroxene names, but can be used as varietal gem names.

Relationships with the pyroxenoids. Pyroxenoids are closely related to pyroxenes in that they have a similar type of chemical composition and a structure that also consists of SiO_3 single chains. However, the repeat of the chains, which is two SiO_4 tetrahedra in the pyroxenes, is three or more SiO_4 tetrahedra in the pyroxenoids. Though the tetrahedral sites are mostly occupied by Si ions, the large cations are mostly Ca, Mn and Fe^{2+} ions in the pyroxenoids. The classification and nomenclature of the pyroxenoids are beyond the scope of this report. However, the following two points may be noted. Firstly, there is a polymorphic relationship with some pyroxenes such as ferrosilite, hedenbergite and johannsenite. These show pyroxenoid structures at high temperatures or pressures. Secondly, the wollastonite chemical component ($Ca_2Si_2O_6$) is used to express the composition of the Ca–Mg–Fe pyroxenes, though wollastonite belongs to the pyroxenoid structural group.

Classification and nomenclature of the pyroxenes

Preliminary classifications—construction of the Q–J diagram and application of pyroxene data. Before classifying the pyroxenes into the 20 mineral species listed in Table 2, the following procedure is recommended to divide them into four chemical groups: Ca–Mg–Fe pyroxenes (**Quad**), Na–Ca pyroxenes (**Na–Ca**), Na-pyroxenes (**Na**), and other pyroxenes (**Others**) (Morimoto and Kitamura, 1983).

In this procedure the pyroxenes are classified by using the total numbers of specified cations at the M ($M1$ and $M2$) sites on the basis of six oxygens. The $M1$ and $M2$ sites are considered together as M sites, without considering the site preference of atoms between the two sites.

The numbers of Ca, Mg, Fe^{2+} and Na cations in the M sites are plotted in the Q–J diagram (Fig. 2) as $Q = Ca+Mg+Fe^{2+}$ and $J = 2Na$. The lines representing the following equations are used to subdivide the Q–J diagram:

(1) $Q+J = 2.0$
(2) $Q+J = 1.5$
(3) $J/(Q+J) = 0.2$
(4) $J/(Q+J) = 0{\cdot}8$

The areas corresponding to the Ca–Mg–Fe pyroxenes, Ca–Na pyroxenes, Na pyroxenes and other pyroxenes are labelled (Fig. 2) **Quad**, **Ca–Na**, **Na**, and **Others**, respectively.

In this diagram, J is meant to include the total number of Na and R^{3+}, usually Al, Fe^{3+}, Cr^{3+} and Sc^{3+}, that couple with Na in substitution (1) mentioned in Table 1. When the coupling substitution in the pyroxene is not of type (1), but of type (2) or (3), the J value apparently does not represent the real numbers of Na and R^{3+} at the M sites. However, substitution (3) (e.g. Al-Al) works to move the J and Q values closer to the origin of the Q–J diagram, and substitution (2) (e.g. Na-Ti^{4+}) to move the J value farther away from the Q axis of ordinates. Therefore, the effects of substitutions (2) and (3) tend to cancel each other out in and near the Na pyroxenes area. Thus the J ($= 2Na$) values in the Na-rich pyroxenes represent, to a good approximation, the total number of Na and R^{3+} (Al, Fe^{3+}, Cr^{3+} and Sc^{3+}) at the M sites.

The boundary $Q+J = 2.0$ represents the upper limit of $Q+J$ at the M sites. The boundary

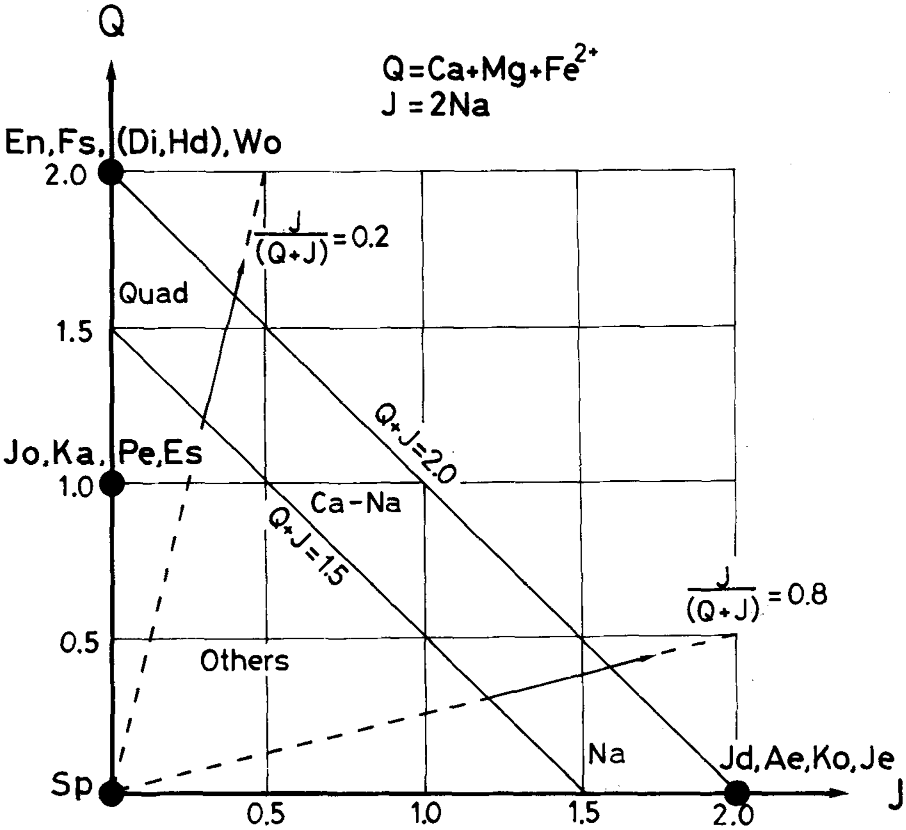

FIG. 2. *Q–J* diagram for the pyroxenes, on which the positions of the 13 accepted end-members have been indicated. Abbreviations and compositions of the end-members are listed in Table 2.

$Q+J = 1.5$ represents the limit below which more than half of the $M1$ or $M2$ sites may be occupied by ions other than Q and J ions. In this case, the pyroxenes are considered as belonging to **'Others'**, which include the Mn–Mg and Li pyroxenes, johannsenite, petedunnite and esseneite. The third and fourth equations represent the lines dividing the area limited by the two above-mentioned $Q+J$ lines into Ca+Mg+Fe (**Quad**), **Ca–Na** and **Na** pyroxenes. The boundaries defined by $J/(Q+J) =$ 0.2 and 0.8 are used by DHZ (1978) and Cameron and Papike (1981).

Because the Mn–Mg pyroxenes and johannsenite (Table 2) have Mn ions occupying more than half of the $M2$ and $M1$ sites, respectively, they appear along the Q axis between 1.0 and 1.5 of the Q value in the Q–J diagram. Similarly, petedunnite and esseneite appear along the Q axis with its Q value between 1.0 and 1.5. Spodumene concentrates at the origin of the Q–J diagram because both Q and J are zero. Thus, the thirteen end-members (Table 2) and Wo are located in the Q–J diagram (Fig. 2).

Application of this classification procedure to 406 pyroxene analyses presented in DHZ has shown that most of the analyses, except those of johannsenite and spodumene, are included in the area between the lines $Q+J = 2.0$ and 1.5. The 103 DHZ pyroxenes selected by Cameron and Papike (1981), for which the Q values are less than 1.90 and Mn is less than 0.08 atoms per formula unit, are plotted in the Q–J diagram of Fig. 3. The 'CaMg TAL' pyroxene (Cameron and Papike, 1981) is included in the **Quad** area as described later (Table 3, No. 1). Only twenty analyses among 406 plot slightly over the line $Q+J = 2.0$, and most of these show unusual total numbers of cations. The results of the classification of the pyroxenes into the four chemical groups by this procedure are in almost complete agreement with the results obtained by DHZ (1978) and by Cameron and Papike (1981). A few unusual pyroxenes with Mn less than 0.08

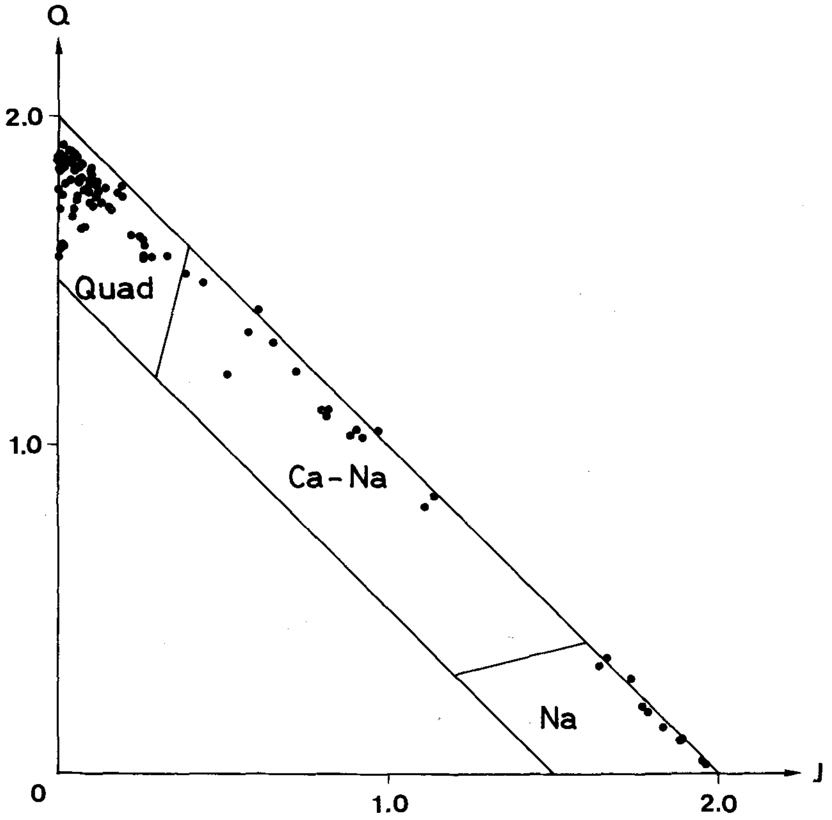

FIG. 3. The 103 DHZ pyroxenes selected by Cameron and Papike (1981) plotted on the Q-J diagram. For these pyroxenes the Q values are less than 1.90, and Mn is less than 0.08 atoms per formula unit.

atoms for the chemical formula unit have been found to lie outside the area between $Q+J = 2.0$ and $Q+J = 1.5$ lines in the Q-J diagram. The classification of these unusual pyroxenes will be discussed later.

The pyroxenes that plot in the area between $Q+J = 2.0$ and 1.5 have components other than Q and J ions at less than 25% of the M sites. Therefore, we can classify such pyroxenes on the basis of the normalized Q and J components, thereby neglecting the effects of the other components. The following procedures are adopted for further classification:

(1) The pyroxenes in the **Quad** area are classified on the pyroxene quadrilateral Wo-En-Fs diagram with normalized Ca, Mg and Fe ($= Fe^{2+} + Fe^{3+} +$ Mn) atoms.

(2) The pyroxenes in the **Na** area are jadeite, aegirine, kosmochlor and jervisite. Because kosmochlor and jervisite show little or no solid solution towards other end-members, they play no role in the classification. Jadeite and aegirine are classified on the Quad-Jd-Ae diagram together with the Ca-Na pyroxenes, aegirine-augite and omphacite.

The classification of the Ca-Mg-Fe 'quadrilateral' pyroxenes. The common rock-forming pyroxenes form wide ranges of solid solutions of the Ca-Mg-Fe pyroxenes and can be expressed by the pyroxene quadrilateral of the $Mg_2Si_2O_6$(En)-$Fe^{2+}_2Si_2O_6$ (Fs)-$CaMgSi_2O_6$(Di)-$CaFe^{2+}Si_2O_6$ (Hd) system. The Ca-Mg-Fe pyroxenes include varieties that have orthorhombic symmetry. They consist essentially of a simple chemical series $(Mg,Fe)_2Si_2O_6$, thus contrasting with the clinopyroxenes which have wide ranges of chemical composition in the Ca-Mg-Fe pyroxenes. Therefore, the Ca-Mg-Fe pyroxenes are defined on the basis of symmetry and relative amounts of $Ca_2Si_2O_6$(Wo), $Mg_2Si_2O_6$(En) and $Fe^{2+}_2Si_2O_6$(Fs). The composition ranges of the clinopyroxenes and orthopyroxenes are indicated in Figs. 4 and 5, respectively, where the

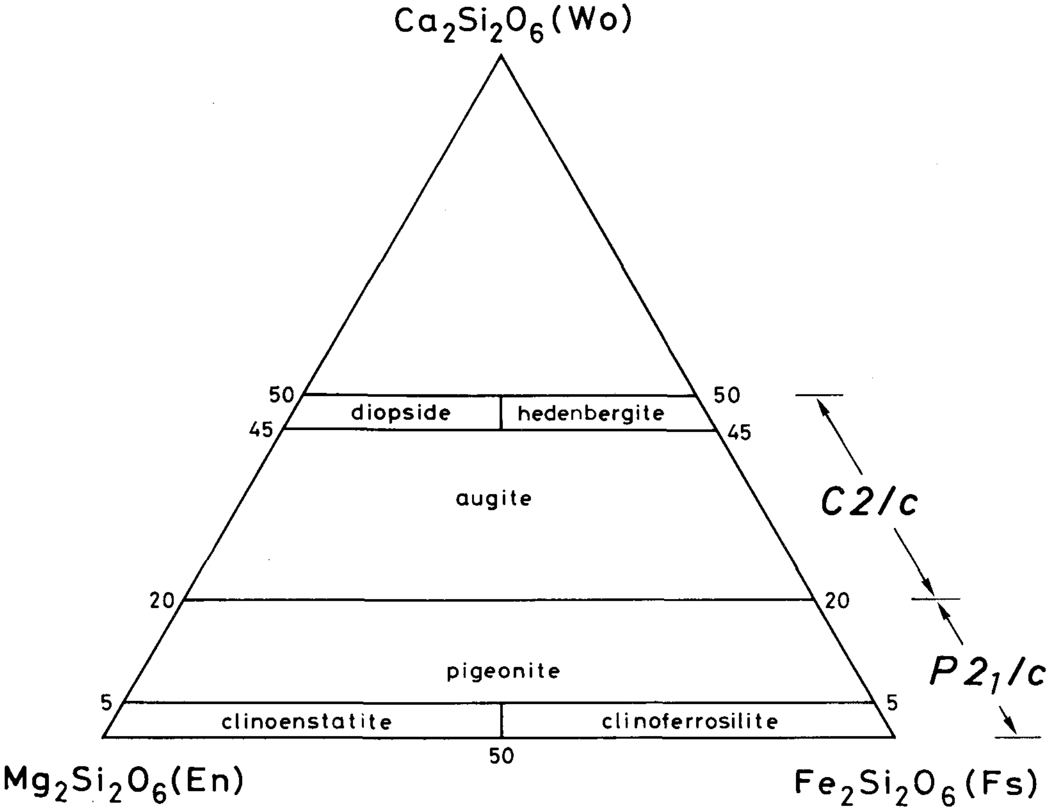

FIG. 4. Composition ranges of the Ca–Mg–Fe clinopyroxenes with accepted names.

composition is normalized to Ca+Mg+ΣFe = 100 with ΣFe = $Fe^{2+}+Fe^{3+}+Mn^{2+}$ [10].

The distinction between augite and pigeonite in the Ca-Mg-Fe pyroxenes is primarily structural, their space groups being *C*2/*c* and *P*2_1/*c* respectively. There is a miscibility gap between augite and pigeonite, and many pyroxenes with 15–25% Wo have proved to be mixtures of the two. Augite with less than about 25% Wo is often called subcalcic augite. On heating, pigeonite undergoes a rapid displacive transformation to a *C*2/*c* structure which cannot be quenched. Augite does not show this type of transformation.

The most calcium-rich orthopyroxene contains approximately 5% Wo. The high-temperature form of enstatite has the space group *Pbcn* and can be expressed as 'enstatite-*Pbcn*'. This form is not quenchable and has not been found in nature. 'Protoenstatite' has been used conventionally to describe this form, but this name is not adopted as a mineral name. The Wo value of 'enstatite-*Pbcn*' does not exceed 2% and the En value commonly

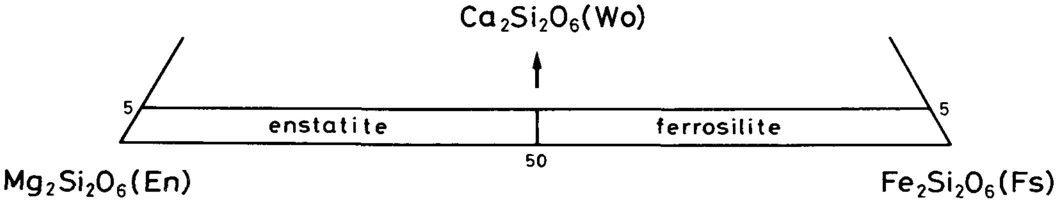

FIG. 5. Composition ranges of orthopyroxenes with accepted names.

exceeds 90%. Thus the composition field of 'enstatite-*Pbcn*' is different from that of enstatite-*Pbca*.

The classification of the Na and Ca–Na pyroxenes. The Na pyroxenes, jadeite and aegirine, commonly contain more than 90% of the $NaAlSi_2O_6$ or $NaFe^{3+}Si_2O_6$ component, respectively, but contain neither the Ko nor the Je component. Because kosmochlor is a rare accessory constituent of some iron meteorites and only one terrestrial locality is known for each of kosmochlor and jervisite, these two species are separately treated in the classification of the Na pyroxenes. Both jadeite and aegirine, however, show extensive solid solution with the Ca–Mg–Fe pyroxenes, especially with the diopside–hedenbergite series and augite, leading to the Ca–Na pyroxenes. The Na and Ca–Na pyroxenes are classified on the Quad-Jd-Ae diagram (Fig. 6) with normalized Q (Wo + En + Fs), Jd and Ae components[11]. The arbitrary divisions between the Ca–Mg–Fe pyroxenes, Na–Ca pyroxenes and Na pyroxenes are defined at 20 and 80% of Q = (Wo + En + Fs). Omphacite displays a $C2/c \rightleftharpoons P2/n$ polymorphic transition, and both high-temperature $C2/c$ and low-temperature $P2/n$ polymorphs appear in nature. Omphacite can thus be divided into two subspecies: omphacite-$C2/c$ and omphacite-$P2/n$. Because omphacite-$P2/n$ shows a unique crystal structure different from that of jadeite and augite, it is accepted as an independent pyroxene species. Aegirine-augite is also accepted as an independent species to keep balance with omphacite, though it is not known to occur with the $P2/n$ structure. The classification of the Ca–Na pyroxenes by Essene and Fyfe (1967) is not followed in this report.

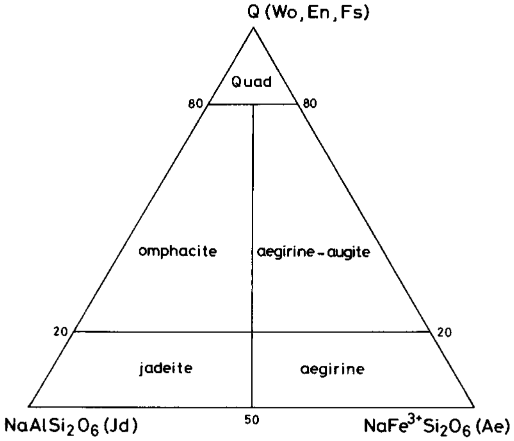

FIG. 6. Ca–Mg–Fe and Na pyroxenes with accepted names. Quad represents the Ca–Mg–Fe pyroxene area (see Fig. 4).

The classification of other pyroxenes. Most naturally occurring pyroxenes in the '**Others**' area are johannsenite ($CaMnSi_2O_6$), petedunnite ($CaZnSi_2O_6$) and spodumene ($LiAlSi_2O_6$) (Fig. 2). Recent investigations of natural manganese-bearing pyroxenes have yielded two new minerals, kanoite and its dimorph donpeacorite, $(Mn,Mg)MgSi_2O_6$, which seem to form a solid solution with En (Petersen *et al.*, 1984). They too occur in the '**Others**' area. These results suggest a possible Mn–Mg–Fe pyroxene quadrilateral. Esseneite ($CaFe^{3+}AlSiO_6$) is the first pyroxene with the substitution (3) as described in Table 1.

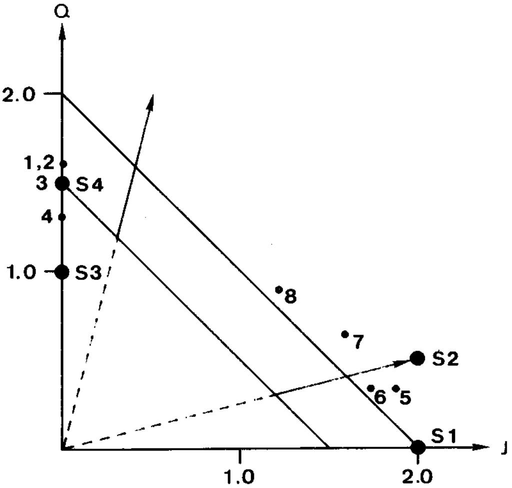

FIG. 7. Q–J diagram for eight unusual pyroxenes with Q-value less than 1.62 and Mn less than 0.08 atoms per formula unit (Table 3). The components formed by the substitutions (1) to (4), as indicated in Table 1, are plotted in the diagram. They represent the following compositions: $S1 = NaR^{3+}Si_2O_6$, $S2 = NaR^{2+}_{0.5}Ti^{4+}_{0.5}Si_2O_6$, $S3 = CaR^{3+}AlSiO_6$ and $S4 = CaR^{2+}_{0.5}Ti^{4+}_{0.5}AlSiO_6$.

The classification of unusual pyroxenes. Several pyroxenes with unusual chemical compositions (Table 3) appear outside the area between the $Q + J = 2.0$ and $Q + J = 1.5$ lines in the Q–J diagram, though they do not belong to the 'other' pyroxenes mentioned above (Fig. 7). They contain large amounts of chemical constituents of substitutions (2), (3) and (4) mentioned in Table 1 in the standard chemical formulae.

Table 3. Chemical composition and classification of eight unusual pyroxenes. Numbers such as 320-8, etc. represent pages and analysis number in DHZ (1978). Other references are in text. With the exception of 320-8 (=406-16), all the DHZ analyses in this table were not included in the 103 selected analyses of Cameron and Papike (1981). All pyroxenes in the table are shown with their numbers in the Q-J diagram (Fig. 7). S2, S3 and S4 represent the following components of substitutions (2), (3) and (4), respectively: S2=NaR$^{2+}_{0.5}$Ti$^{4+}_{0.5}$Si$_2$O$_6$, S3=CaR^{3+}AlSiO$_6$, and S4=CaR$^{2+}_{0.5}$Ti$^{4+}_{0.5}$AlSiO$_6$. To indicate R ions explicitly in these components, the notation S(R), such as S2(Mg) and S3(Al), is used. S3(Fe) is a new pyroxene, esseneite (Es).

a) Ca-rich group related to S3 and S4

No.	1. 320-8 (406-16)		2. 403-3		3. D and S*1		4. T and R*2	
Si	1.443	2.00	1.506	2.00	1.434	2.00	1.196	2.00
Al	.557		.494		.566		.804	
Al	.091	2.00	.171	2.02	.306	2.00	.186	2.00
Ti^{4+}	.165		.065		.022		Ti^{4+} .111	
Fe^{3+}	.128		.159		.218		Ti^{3+} .394	
Mg	.385		.570		.408		.289	
Fe^{2+}	.229		.063		.060			
Mn	.005		.007		.005			
Ca	.992		.975		.979		1.021	
Na	.006		.007		.002			
K	.000		.001		-			
Q	1.61		1.61		1.45		1.31	
J	0.01		0.01		0.00		0.00	
Mineral names	subsilicic titanian ferrian diopside		subsilicic aluminian ferrian diopside		subsilicic aluminian ferrian diopside		subsilicic titanoan aluminian pyroxene	
Names in literature	titanaugite (320-8) titanium-fassaite (406-16) CaMgTAL (C and P)*3		fassaite		fassaite		titanaugite	

Component ratios;

1. (Wo$_{22}$En$_{12}$Fs$_{10}$)$_{44}$S4(Mg)$_{18}$S4(Fe)$_{16}$Es$_{13}$S3(Al)$_9$
2. (Wo$_{26}$En$_{25}$Fs$_2$)$_{53}$S3(Al)$_{17}$Es$_{16}$S4(Mg)$_{12}$S4(Fe)$_2$
3. (Wo$_{22}$En$_{20}$Fs$_2$)$_{44}$S3(Al)$_{31}$Es$_{21}$S4(Mg)$_4$
4. S3(Ti)$_{39}$S4(Mg)$_{22}$(Wo$_{11}$Fs$_9$)$_{20}$S3(Al)$_{19}$

These pyroxenes can be divided into two groups: firstly Ca-rich pyroxenes with the $S3$ (CaR^{3+}Al SiO$_6$) and $S4$ (Ca$R^{2+}_{0.5}$Ti$^{4+}_{0.5}$AlSiO$_6$) components representing substitutions (3) and (4), respectively, and secondly Na-rich pyroxenes with the $S2$ component (Na$R^{2+}_{0.5}$Ti$^{4+}_{0.5}$Si$_2$O$_6$) representing substitution (2). The former shows a significant deficiency of Si atoms such as Si < 1.60 in the standard formula resulting in the Q-value close to or less than 1.5 (point $S4$ in Fig. 7). The latter appears outside the line $Q+J = 2.0$ approaching point $S2$ in Fig. 7. All these unusual pyroxenes are classified by using

b) Na-rich group related to S2

No.	5. 488-9		6. 491-14		7. 492-19 (C and G^{*4})		8. C and G^{*4}	
Si	1.994	2.00	2.024	2.02	2.026	2.03	2.009	2.01
Al	.032		.000		.000		.000	
Al	.000	2.00	.021	2.00	.098	1.98	.348	2.00
Ti^{4+}	.265		.023		.227		.104	
Fe^{3+}	.458		.728		.192		.031	
Mg	.150		.070		.070		.168	
Fe^{2+}	.107		.113		.420		.356	
Mn	.003		.006		.021		.011	
Na	.933		.872		.794		.610	
Ca	.083		.155		.152		.361	
K	-		.009		-		.006	
Q	0.34		0.34		0.64		0.89	
J	1.87		1.74		1.59		1.22	
Mineral names	titanian magnesian ferroan aegirine		calcian ferroan aegirine		titanian aegirine-augite		titanian ferroan omphacite	
Names in literature	titanian aegirine		aegirine-augite		titanian aegirine-augite (492-19) titanian aegirine (C and G^{*4})		titanian ferro-omphacite	

Component ratios;

5. $Ae_{46}S2(Mg)_{28}S2(Fe)_{20}\Delta_6$[*5]

6. $(Ae_{73}Jd_2Wo_8Fs_6En_3)_{92}S2_4\Delta_4$

7. $(Ae_{19}Jd_{10}Fs_{12}Wo_8En_2)_{51}S2(Fe)_{42}S2(Mg)_4\Delta_3$

8. $(Jd_{35}Ae_3Wo_{18}Fs_{15}En_7)_{78}S2(Fe)_{14}S2(Mg)_6\Delta_2$

[*1] Devine and Sigurdsson (1980), Table 1 for fassaite.

[*2] Tracy and Robinson (1977), Table 3, Analysis I for pyroxene from the Allende meteorite (Mason, 1974).

[*3] Cameron and Papike (1981), Table A3, Analysis 320-8 and 406-16.

[*4] Curtis and Gittins (1979), Table 2, Analysis 5 for No.7 and Table 5, Analysis 5 for No.8.

[*5] Δ represents minor components, some of which have unusual metal ratios for the pyroxene structure.

the accepted pyroxene names and the adjectival modifiers mentioned below, except the Allende pyroxene (Table 3, No. 4) which is called subsilicic titanoan aluminian pyroxene.

The Allende pyroxene (No. 4) contains 39% of the *S*3(Ti) component and can be considered as a new mineral. However, we have decided only to use the accepted names in this report and if a species has not yet been approved, we use *pyroxene* as for No. 4 in Table 3. The names used in literature for the unusual pyroxenes are listed in Table 3 in comparison with those in this report. The 'CaMgTAL' pyroxene (No. 1) is diopside in this classification.

Adjectival modifiers

Adjectival modifiers for mineral names are used to indicate unusual amounts of chemical constituents. In order to define the unusual amounts for the pyroxene mineral group quantitatively, extreme compositions of pyroxenes have been listed in Table 4, where the values for the main

Table 4 Extreme chemical compositions of pyroxenes in DHZ (1978). Number of cations per formula unit, minimum values for Si and maximum values for other cations. Bold numbers are for the main constituent elements. Numbers in the parentheses such as 42-9, etc. indicate pages and analysis numbers in DHZ (1978). Other references are in text.

	Mg-Fe pyroxenes	Ca pyroxenes	Na pyroxenes
Si	**1.76** (42-9)	**1.44** (320-8)*1	**1.94** (488-9)
Al^{3+}	0.24 (42-9)	0.56 (320-8)	0.07 (488-8)
Fe^{3+}	0.04 (49-8)	0.09 (320-11)	0.02 (488-9)
Al^{3+}	0.15 (49-6)	0.35 (320-11)	**0.98** (464-1)
Ti^{4+}	0.04 (40-30)	0.17 (320-8)*2	0.27 (488-9)*3
Fe^{3+}	0.12 (170-8)	0.37 (321-5)*4	**0.97** (487-1)
Mg^{2+}	**1.99** (41-1)	**1.27** (208-4)	0.15 (488-9)
Fe^{2+}	**1.72** (47-33)*5	**1.09** (220-13)	0.11 (488-9)
Mn^{2+}	0.27 (45-21)*6	0.36 (217-5)*7	0.03 (487-4)
Cr^{2+}	0.02 (36-9)	0.06 (207-11)	- *8
Ni^{2+}	-	0.003 (317-1)	-
Zn^{2+}	-	0.21 (216-11)*9	-
Ca^{2+}	0.26 (169-2)	**1.03** (202-4)	0.16 (466-14)
Na^{+}	0.10 (169-2)	0.31 (323-7)	**0.98** (464-1)

*1 Table 3, No. 1. Table 3, No. 4: Pyroxene from the Allende meteorite 1.20 (Mason, 1974; Tracy and Robinson, 1977).

*2 Probe analysis 0.252 & 0.282, half of $CaR^{2+}_{0.5}Ti^{4+}_{0.5}AlSiO_6$ (S4) (Tracy and Robinson, 1977; Robinson, 1980).

*3 Table 3, No. 5. Half of $NaR^{2+}_{0.5}Ti^{4+}_{0.5}Si_2O_6$ (S2).

*4 406-15 0.67, omitted because of possible errors in chemical analysis.

*5 Probe analysis 1.880 (Jaffe et al., 1978).

*6 Probe analysis 0.301 (Robinson, 1980), Kanoite 1.04 (Kobayashi, 1977).

*7 Johannsenite 0.963 (417-2).

*8 Kosmochlor 0.90 (522-1).

*9 Petedunnite 0.37 (Table 2, remark *1).

cations are shown as well as those for the accessory cations. The table was constructed using data from DHZ (1978) and Robinson (1980).

An element specified as a modifier should be present as a general rule in a quantity larger than 0.1 or 0.01 atoms in the standard chemical formula of 6 O or 4 metal atoms (Table 5) depending on the maximum content in Table 4.

The suffixes are those proposed by Schaller (1930) and adapted by CNMMN (Nickel and Mandarino, 1988). The suffix -ian is used for the higher valence state (e.g. ferrian) or for an element with a non-variable state (e.g. lithian). The suffix -oan implies the lower valence state (e.g. ferroan). It is recommended that such modifiers never be used for main cations normally contained in the named mineral, for example, in terms like calcian augite, aluminian omphacite, and sodian aegirine-augite, in which the modifiers are obviously superfluous.

If there is less than the amount necessary for the assignment of the modifiers such as 'aluminian' in Table 5, or 0.1 Al, but if the increased content of the element must be stressed, a modifier 'aluminium-bearing' may be used. This second type of modifier should be used also (1) if only an incomplete analysis is available preventing the calculation of a full chemical formula or (2) for pyroxenes where the valence state of a cation is unknown. With regard to the Si content in pyroxenes, it is suggested that $Si < 1.75$ is a suitable limit for use of the term 'subsilicic', though one should bear in mind that the $Si < 5.75$ limit for 'subsilicic' in amphiboles corresponds to $Si < 1.5$ for pyroxenes.

Table 5. List of adjectival modifiers to be used for pyroxene mineral names. The limit of the content is determined based on the values listed in Table 4.

cation	content*1	name
Al^{3+}	>0.10	aluminian
Ca^{2+}	>0.10	calcian
Cr^{3+}	>0.01	chromian
Fe^{2+}	>0.10	ferroan
Fe^{3+}	>0.10	ferrian
Li^{+}	>0.01	lithian
Mg^{2+}	>0.10	magnesian
Mn^{2+}	>0.10	manganoan
Mn^{3+}	>0.01	manganian
Na^{+}	>0.10	sodian
Ni^{2+}	>0.01	nickeloan
Si^{4+}	<1.75	subsilicic
Ti^{3+}	>0.01	titanoan
Ti^{4+}	>0.10	titanian
Zn^{2+}	>0.01	zincian

*1 Number of cations per formula unit $M2M1T_2O_6$. If the mineral name itself implies the presence of certain cations, adjectival modifiers for these cations should not be used ('subsilicic' is an exception).

In certain cases, particularly for the augite series, it is convenient to use the following adjectival modifiers: iron-rich, magnesium-rich, and sub-calcic. A prefix actually attached or hyphenated to a mineral name, however, is incorrect and should be avoided (Nickel and Mandarino, 1988), because it would cause the mineral to be indexed alphabetically under the prefix rather than the proper mineral name. This is why such terms as 'ferro-pigeonite', 'ferro-augite', etc., should not be used as mineral names.

It is often useful to give the space group of the mineral, particularly when it can occur in two or more forms. For example, we could distinguish between the two forms of omphacite by adding the space group symbol, i.e. omphacite-*C*2/*c*, omphacite-*P*2/*n*, or by adding the lattice-type symbol, i.e. omphacite-*C*, omphacite-*P* (Bailey, 1977).

Obsolete pyroxene names

The names of 105 pyroxenes or altered pyroxenes listed in Table 6 have formally been discarded by the CNMMN and are therefore obsolete. The preferred name is underlined in the same table.

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We are grateful to Professor J. H. D. Donnay, McGill University, Montreal, who contributed greatly to the improvement of the report by his careful review. We also appreciate criticisms and comments by Dr A. Kato, National Science Museum, Tokyo, Dr M. Kitamura, Kyoto University, Kyoto, and the members of the Commission on New Minerals and Mineral Names, IMA.

Footnotes

1. In omphacite-*P*2/*n*, the *M*1 and *M*2 sites are further divided into *M*1*a* and *M*1*b* (for *M*1) and *M*2*a* and *M*2*b* (for *M*2).
2. Orthopyroxene (*Pbcn*) is stable only at elevated temperatures for a limited composition near $MgSiO_3$.
3. Aegirine is used in preference to 'acmite' in this report. It is in common usage in the literature, and is consistent with the almost universal use of aegirine-augite for minerals of intermediate compositions, though 'acmite' has priority by 14 years (Dana, 1892). Common practice in experimental petrology has been to use the abbreviation Ac for $NaFe^{3+}Si_2O_6$; Ae should now be used instead.
4. The CNMMN, IMA, has recently voted in favour of the name kosmochlor instead of 'ureyite' for the pyroxene of generalized composition $NaCrSi_2O_6$.
5. Esseneite is a new pyroxene with the composition $CaFe^{3+}AlSiO_6$ (Table 2, No. 13).
6. 'Fassaite' has the general formula $Ca(Mg,Fe^{3+},Al)(Si,Al)_2O_6$. This name has been rejected as a formal name in this report.
7. $Ca_2Si_2O_6$ exists as wollastonite in nature, which belongs not to the pyroxenes but to the pyroxenoids. To represent the compositions of the Ca-Mg-Fe pyroxenes, the ternary $Ca_2Si_2O_6$(Wo)-$Mg_2Si_2O_6$(En)-$Fe_2Si_2O_6$(Fs) system has been used, e.g. $En_{20}Fs_{38}Wo_{42}$.
8. Definition of the '**Other**' pyroxenes is different from that given by Cameron and Papike (1981).
9. The name aegirine-augite appears to be in more common usage than 'aegirineaugite' and 'acmite-augite'.

Table 6. Obsolete pyroxene names. The following pyroxene mineral names, or names which refer to altered pyroxenes, have been formally discarded by the CNMMN. The correct names are underlined. The original form of this table was compiled by Malcolm Ross using the following references: Dana (1892); Tschermak (1897); Chester (1886); Ford (1932); Winchell and Winchell (1951); Deer, Howie, and Zussman (1963, 1978); Strunz (1970); and the unpublished Thesaurus of Mineralogical Terms of the International Mineralogical Association, which has been available since August 1974.

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acmite = aegirine
aegirite (aegyrite) = aegirine
aegerine-hedenbergite = augite
agalite = probably enstatite partly altered to talc
aglaite = altered spodumene
alalite = diopside
alkali augite = aegirine-augite
amblystegite = enstatite
anthochroite = augite
asteroite = iron-rich augite
baikalite = diopside
bastite = enstatite which has altered to serpentine, talc, or perhaps anthophyllite
blanfordite = manganoan aegirine-augite
bronzite = enstatite
calc-clinobronzite = pigeonite
calc-clinoenstatite = pigeonite
calc-clinohypersthene = pigeonite
calc-pigeonite = subcalcic augite
canaanite = diopside
chladnite = enstatite
chloromelanite = omphacite or aegirine-augite
chrome-acmite = chromian aegirine
chromejadeite = chromian jadeite
clinohypersthene = clinoenstatite or clinoferrosilite
coccolite (kokkolith) = iron-rich augite
cymatolite = altered spodumene
diaclasite = altered enstatite
diallage = diopside which has altered or which has good (100) parting; also used for alteration products of other pyroxenes
diopsidjadeite = omphacite
endiopside = magnesium-rich augite
enstatite-diopside = magnesium-rich augite
eulite = ferrosilite
eulysite = ferrosilite
fassaite = ferrian aluminian diopside or augite
fedorovite = diopside
ferroaugite = augite
ferrohedenbergite = augite
ferrohypersthene = ferrosilite
ferro-johannsenite = iron-rich johannsenite
ferropigeonite = iron-rich pigeonite
ferrosalite = hedenbergite
ficinite = enstatite
funkite = hedenbergite
germarite = altered enstatite
hiddenite = spodumene
hudsonite = hedenbergite
hypersthene = enstatite *or* ferrosilite
jadeite-aegirine (jadeite-aegirite) = jadeite or aegirine
jeffersonite = zincian manganoan diopside or augite
killinite = altered spodumene
korea-augite = augite
kunzite = spodumene
lavroffite = diopside
lavrovite= diopside
lawrowite = diopside
leucaugite = diopside
lime-bronzite = probably pigeonite or enstatite plus augite, ("inverted" pigeonite)
loganite = diopside + actinolite + talc
lotalite = hedenbergite
malacolite = diopside with good (001) parting, also diopside from Sala, Sweden
mansjoite = augite or diopside or hedenbergite
mayaite = omphacite
mellcrite = orthopyroxene
mondradite =probably an altered pyroxene
mussite = diopside
orthobronzite = enstatite
orthoenstatite = enstatite
orthoeulite = ferrosilite
orthoferrosilite = ferrosilite
orthohypersthene = enstatite or ferrosilite
paulite = enstatite
peckhamite = enstatite
phastine = altered enstatite
picrophyll = altered pyroxene ?

pigeonite-augite = probably subcalcic augite

pitkarantite = pyroxene ?

potash-aegirine = synthetic product, probably not properly characterized

protheite = augite

protobastite = enstatite

pyrallolite = altered pyroxene ?, talc ?

pyrgom = pyroxene

sahlite = diopside

salite = diopside

schefferite = manganoan diopside

schillerspar (schillerspat) = enstatite which is altered to serpentine, talc, or anthophyllite

shepardite = enstatite

soda-spodumene = sodian spodumene

strakonitzite = altered pyroxene, steatite ?

szaboite = partly altered enstatite

titanaugite = titanian augite

titandiopside = titanian diopside

titanpigeonite = titanian pigeonite

trachyaugite = augite

traversellite = diopside

triphane = spodumene

tuxtlite = omphacite

uralite = pseudomorph of amphibole after pyroxenes

urbanite = iron-rich augite or aegirine-augite

ureyite = kosmochlor

vanadinaugite = vanadium-bearing augite

vanadinbronzite = vanadium-bearing enstatite

vargasite = altered pyroxene ?

victorite = enstatite

violaite = augite

violan = magnesium-rich augite or diopside

10. For the nomenclature of the Ca–Mg–Fe pyroxenes, normalization must be made to $Ca+Mg+\Sigma Fe = 100$, where $\Sigma Fe = Fe^{2+}+Fe^{3+}+Mn$. Hereafter the mol percent of the end-member components is always used without remark and is represented simply by %. If the mole % quadrilateral components are calculated by the atomic % of Ca to the total cations at the *M* sites, no pyroxenes should contain more than 50% $Ca_2Si_2O_6$. However, if Ca, Mg and Fe are normalized, or, calculated as $100Ca/(Ca+Mg+\Sigma Fe)$, $100Mg/(Ca+Mg+\Sigma Fe)$ and $100\Sigma Fe/(Ca+Mg+\Sigma Fe)$, respectively, then some augites will plot on a Wo–En–Fs triangular diagram above the 50% $Ca_2Si_2O_6$ line. Especially, when the plot in the *Q–J* diagram is very close to or outside of the boundary $Q+J = 1.5$, the effect of johannsenite and petedunnite components must be considered. If the effect is negligible, the pyroxene must be considered to have an unusual composition and must be referred to the section of unusual pyroxenes.

11. To normalize *Q*, Jd and Ae components, $Ca+Mg+Fe^{2+}+2Na$ at the *M* sites must be made to total 100%. Then the normalized 2Na% must be divided to the ratio of Al/Fe^{3+} to give the ratio of Jd/Ae. Thus $Q+Jd+Ae$ must always give 100%. When the plot in the *Q–J* diagram is significantly outside the boundary $Q+J = 2.0$, the effect of substitution (2) must be considered, as in the section of unusual pyroxenes.

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