VIBRATIONAL SPECTRA OF HIGH-CALCIUM PYROXENES AND PYROXENOIDS

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ABSTRACT

IR and optical spectra have been measured on hydrothermally synthesized pyroxenes with compositions along the joins connecting the compositions CaSiO₃, MnSiO₃, CaMgSi₂O₆, CaMnSi₂O₆, and CaFeSi₂O₆. The objectives were to compare changes in the spectra with structural changes. The optical spectra are due to ferrous iron and appear insensitive to structural detail. The infrared spectra, particularly the Si-O stretching vibrations, vary markedly with small structural changes. Each structure type, diopside, wollastonite, bastamite and rhodonite has a distinct infrared spectrum. Spectral changes with composition are small. Two phase mixtures can be distinguished. IR evidence indicates that the high-temperature form of hedenbergite has the bastamite rather than the wollastonite structure.

INTRODUCTION

Infrared spectra of various pyroxenes have been published by numerous authors including Launer (1962), Lazarev and Tenisheva (1961a and 1961b), and Lyon (1967). Mostly these have been concerned with a comparison of the chain silicates with other silicate structures or of the main pyroxene families with each other. It has been recognized that the IR spectra of pyroxenes show distinct differences from one mineral to another but these do not seem to have been closely examined.

This paper is concerned with the high calcium apex of the CaSiO₃-MgSiO₃-FeSiO₃-MnSiO₃ tetrahedron. Compounds have been synthesized along the diopside-hedenbergite-bastamite triangle and along the tetrahedral edges connecting this triangle with the wollastonite apex. Our objective is to follow the changes in composition by infrared spectroscopy and to compare the spectral changes with structural changes.

EXPERIMENTAL METHODS

Phase Synthesis. Starting materials were reagent grade CaCO₃, MgO, Fe₂O₃, MnO₂, and silicic acid (SiO₂₋ₓH₂O) which were carefully dehydrated before weighing. These materials in the desired proportions were mixed for three hours in a mechanical shaker, fired in

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air at approximately 925° - 950°C for fifteen minutes in a silver foil-lined silica glass boat, and hand-ground under acetone in a synthetic sapphire mortar for approximately one hour. Compositions along the joins CaMgSi₂O₆-CaMnSiO₃, CaSiO₃-MnSiO₄, and CaSiO₃-CaFeSi₂O₆ were prepared in this manner. Compositions along the join CaMgSi₂O₆-CaFeSi₂O₆ were also prepared and were favorably compared to previously prepared similar compositions (Rutstein and Yund, 1969) to insure the reproducibility of method and technique.

Synthesis was carried out using standard hydrothermal techniques in Tuttle-type cold-seal pressure vessels, using the oxygen buffer technique of Eugster and Wones (1962). The QFM buffer was employed for all iron-bearing runs and some manganese-bearing runs. The majority of the manganese-bearing runs (without iron) were buffered by the pressure vessel (approximately NNO according to Eugster and Wones, 1962). The charges were placed in Ag₉₀ Pd₁₀ tubing. For (Ca, Fe)SiO₃ compositions the temperature of synthesis was 850°-995°C; for (Ca, Mn)SiO₃ compositions this was 750°C; for Ca(Mg, Fe)SiO₄ compositions, this was 750°C; and for Ca(Mg, Mn, Fe)SiO₄ compositions, this was 450°-550°C. All runs were made at 1 kb water pressure. Run duration was generally from seven to fourteen days for the higher temperatures and two to five weeks for the lower temperatures. Runs were quenched with an air blast. Only runs that showed negligible weight change, maintenance of the buffer at the conclusion of the run, and at least 98 weight percent yield of pyroxene or pyroxenoid (traces of SiO₂ and Mn₃O₄ were observed) were considered successful.

The run products were studied using standard oil immersion and X-ray techniques. Samples were examined using a Tem-Pres diffractometer with CuKα radiation. Rapid and sure distinction between pyroxenes and pyroxenoids was made possible by examination of reflections in the interval 24°-36° 2θ. Details of X-ray characterization will be presented elsewhere.

Spectral Measurements. Specimens for infrared measurement were prepared by grinding 1 mg of sample with 300 mg of KBr and cold-pressing the material under vacuum into a transparent disc. Spectra of these discs were obtained over the range of 4000 to 250 cm⁻¹ on a Perkin-Elmer Model 621 spectrophotometer. No difficulties were encountered with the spectral measurements.

Optical spectra were obtained from powders by diffuse reflectance spectroscopy. The powdered mineral was packed into a shallow aluminum holder. Light reflected from the powder surface was measured on a Beckman DK-2A spectrophotometer using a Kodak BaSO₄ paint in the reference beam. Background was determined using CaSiO₃ and CaMgSi₂O₆ standards. It should be noted that diffuse reflectance measurements yield an absorption spectrum directly; no mathematical transformations are necessary.

Theoretical Analyses

A factor group analysis was performed on the diopside structure to determine the number of expected infrared bands. The mathematical techniques are discussed in an earlier paper (White and DeAngelis, 1967).

Table 1 shows the invariance conditions for the diopside structure. Space group C2/c contains the C₂₉h factor group. Only the cations lie on elements of symmetry and are thus restricted in their vibrational motion. The invariance conditions yield a reducible character which contains the symmetry properties of the vibrational degrees of freedom of the entire unit cell. The reducible representation is decomposed into the irreducible representations of C₂₉h in the Table 2. The factor group has a center of
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Table 1. Invariance Conditions for Diopside

<table>
<thead>
<tr>
<th>C_{th}</th>
<th>E</th>
<th>C_{2}</th>
<th>t</th>
<th>σ_{h}</th>
</tr>
</thead>
<tbody>
<tr>
<td>8(f) C_{1}</td>
<td>E</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>24 O^{2+}+8 Si^{4+}</td>
<td>32</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4(e) C_{2}</td>
<td>E</td>
<td>C_{2}</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>4 Ca^{2+}+4 Mg^{2+}</td>
<td>8</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

symmetry and this breaks the vibrations into sets which vibrate symmetrically to the center and sets which vibrate antisymmetrically to it. The second column gives the total number of vibrations in each symmetry species. Out of these we can separate the internal vibrations of the two-tetrahedron links of the pyroxene chains. Since both silicon and oxygen are on general positions, these degrees of freedom distribute uniformly among the symmetry species with 9 vibrations in each. Structures of lower symmetry such as that of wollastonite or bustamite yield even less information. About the only conclusion to be drawn from this analysis is that there should be a total of 18 infrared active bands due to motions of the chain. Perhaps half of these will be of stretching character. The spectra were obtained on powders so both polarization directions are superimposed and will probably overlap. Thus there are perhaps 4 to 9 bands expected in the Si–O stretching region and this is, of course, what is observed. It does show that a great deal of information is not missing except for the polarization dependence. Polarized spectra from single crystals could double the number of observable modes.

Optical Spectra

The optical spectra of the iron-containing compositions are given in Figure 1. The high temperature hedenbergite spectrum is characteristic

Table 2. Normal Modes and Selection Rules

<table>
<thead>
<tr>
<th>C_{th}</th>
<th>Total Modes</th>
<th>Acoustic</th>
<th>Chain Vibrations</th>
<th>Lattice Vibrations</th>
<th>Selection Rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_{g}</td>
<td>14</td>
<td>9</td>
<td>5</td>
<td>Raman</td>
<td></td>
</tr>
<tr>
<td>B_{g}</td>
<td>16</td>
<td>9</td>
<td>7</td>
<td>Raman</td>
<td></td>
</tr>
<tr>
<td>A_{u}</td>
<td>14</td>
<td>1</td>
<td>4</td>
<td>IR, E∥b</td>
<td></td>
</tr>
<tr>
<td>B_{u}</td>
<td>16</td>
<td>2</td>
<td>5</td>
<td>IR E⊥b</td>
<td></td>
</tr>
</tbody>
</table>
of the diopside type structure (White and Keester, 1966) and is quite distinct from the wollastonite structure shown below. However, the bands do not shift much as a function of composition and do not yield much information.

**Infrared Spectra**

*Comparison of End Members.* The interpretation of the infrared spectra can be started with the spectrum of diopside shown in Figure 2. It has a very characteristic pattern with three strong bands in the range of 1050 to 850 cm⁻¹. This basic pattern can be designated the “diopside” type. The 5 modes at high frequencies are representative of stretching motions in the silicate chain. In comparison, the spectra of hedenbergite (Fig. 2) and johannsonite (Fig. 2) are very similar. One weak sharp band in diopside moves to lower frequencies as iron or manganese is added and becomes a shoulder of the lowest frequency band in both hedenbergite and johannsonite. The others remain nearly constant which suggests that the chain vibrations are not particularly sensitive to the population of the cation sites.

The spectrum of wollastonite is shown in Figure 3. There are two distinctive clusters of three bands each in the high-frequency region.

The spectrum of bustamite (Fig. 3) is the third distinctive pattern. The high-frequency group consists of two sets of two bands each. The basic pattern changes little with changing composition providing that no structural change takes place. The comparison with the spectrum of
Fig. 2. IR spectra of diopside structure pyroxenes. Johansenite was natural specimen from Italy. All others were synthetics.
Fig. 3. IR spectra of wollastonite and bustamite structure pyroxenoids.
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the high-temperature form of CaFeSi₂O₆ is interesting (Fig. 3). The spectrum is very similar to that of bustamite but is unlike that of wollastonite. The structure of high-temperature CaFeSi₂O₆ has long been considered to be a wollastonite solid solution (Bowen et al., 1933) as was formerly the case for bustamite. Peacor and Prewitt (1963) showed that bustamite has a structure distinct from that of wollastonite with space group $A2/m$ instead of $P2_1/m$ of wollastonite. The difference lies in the relative arrangement of the chains and this should manifest itself in the infrared spectrum. Based on the comparison in Figure 3, we suggest that the high-temperature CaFeSi₂O₆ also has the $A2/m$ bustamite structure.

Attention should be called to the sharp weak bands near 700 cm⁻¹. Lazarev and Tenisheva (1961a) and later Ryall and Threadgold (1966) proposed that the number of these bands was determined by the number of tetrahedra in the chain repeat unit. This number would be 2 for pyroxenes and 3 for the pyroxenoids. The results of these spectra substantiate these conclusions. A detailed comparison of these spectra is shown in Figure 4. Because of their sharpness, these bands are useful for recognizing two-phase mixtures.

The Diopside Solid Solutions. Between diopside and hedenbergite is a complete solid solution with no evidence for phase separation or structural change (Rutstein and Yund, 1969). The infrared spectra reflect this and only minor shifts in band frequencies are observed. The characteristic diopside pattern is retained at all intermediate compositions.

Along the join between diopside and CaMnSi₂O₆ and between hedenbergite and CaMnSi₂O₆ changes occur because of the formation of the bustamite phase. Due to kinetic problems, johannsonite could not be synthesized pure under any conditions used. At 750°C, the infrared spectra show the characteristic pattern of the diopside structure out to CaMg₀.₇Mn₀.₃Si₂O₆. At the manganese-rich end, the characteristic bustamite pattern is observed from CaMnSi₂O₆ to CaMg₀.₅Mn₀.₅Si₂O₆. Intermediate compositions appear to be a mixture of the two. This is confirmed by X-ray and microscopic examination.

Along the hedenbergite to CaMnSi₂O₆ join, the characteristic pattern of the diopside structure persists at least to CaFe₀.₅Mn₀.₅Si₂O₆ with a two-phase region between this composition and CaFe₀.₃Mn₀.₇Si₂O₆ at 750°C. In general, the two-phase regions determined by infrared spectra and the two-phase regions observed by X-ray techniques were in agreement.

The Wollastonite Solid Solutions. As manganese is added to wollastonite, the characteristic wollastonite pattern remains intact to about Ca₀.₇₅Mn₀.₂₅SiO₃ and then changes over a very narrow composition range to
Fig. 4. Comparison of 700 cm⁻¹ region for pyroxene and pyroxenoid spectra.
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the characteristic bustamite pattern. It is here emphasized again that
the frequencies of these groups of bands change very little with com-
position (quite unlike the infrared spectra of most solid solutions) and
instead the patterns shift abruptly at phase boundaries. The bustamite
pattern remains throughout the composition range down to Ca_{0.10}Mn_{0.90}
where the rhodonite pattern appears.

The rhodonite pattern is defined for the MnSiO_3 end member in
Figure 5. The spectrum is more complex, presumably because of the 5
tetrahedron repeat unit. The 700 cm^{-1} region contains 5 sharp bands as
expected for the füinferketten structure. The MnSiO_3 end member, pre-
pared at 750°C, shows all of the complexity that might be expected from
the longer chain repeat length. The Ca_{0.1}Mn_{0.9}SiO_3 composition yields a
spectrum with less resolved detail and by Ca_{0.2}Mn_{0.8}SiO_3 [the "ideal"
rhodonite composition according to Peacor and Niizeki (1963)] the pat-
tern is very close to that of bustamite. Ca_{0.7}Mn_{0.3}SiO_3 has an unper-
turbed bustamite spectrum. These results are in good agreement with the
data of Glasser (1962) who found the upper stability limit of rhodonite
at 10 mole percent CaSiO_3 in the temperature range of 1000 to 1200°C.

As iron is added to CaSiO_3 at 850°C, the characteristic wollastonite
pattern persists to Ca_{0.88}Fe_{0.12}SiO_3. Then, over a composition range of
no more than a few percent, the wollastonite pattern gives way to the
bustamite pattern. Solid solutions more rich in iron then retain the same
bustamite-like infrared spectrum down to the CaFeSi_2O_6 composition.
This abrupt change in the infrared spectrum lends credibility to the
hypothesis proposed earlier that the high-temperature form of CaFeSi_2O_6
is a bustamite-like structure and is distinct from wollastonite. Wollas-
tonite, it appears, will accept only limited amounts of either iron or
manganese in solid solution before cation ordering takes place.

A summary of the composition limits of various structures encountered
in the infrared spectra is given in Figure 6.

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Fig. 5. IR spectra of various compositions near MnSiO$_3$. 
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