

Dispersion method for olivine, orthopyroxene, and augite

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Abstract

The dispersion, $\Delta n/\Delta\lambda$, has been determined by the dispersion method for natural plutonic olivine, orthopyroxene, and augite solid solutions. The quantity $\Delta n_{(F-C)}$ varies linearly as $wn_D + z$, where

	<i>w</i>	<i>z</i>
for olivine β	0.07911	-0.12265
for orthopyroxene γ	0.05047	-0.07526
and for augite β	0.06236	-0.09479.

When applied to standard determinative curves for olivine and orthopyroxene, and to a new curve for augite, the dispersion data can be used to construct or compute dispersion nets in Hartmann space for the rapid determination of these minerals by microscopy.

The dispersion nets are composed of a set of equations: $X_{Mg} = (n_0 - n)/\Delta n_\lambda$, where X_{Mg} is the mole fraction of the Mg end-member, n is the observed refractive index at a given λ , $n_0 = aL + b$, and $\Delta n_\lambda = cL + d$. The Hartmann transform L is equal to $10^5/(\lambda - 200)$. The constants of the nets are:

	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>
Ol, $n=\beta$	1.909123 E-4	1.81596	1.29627 E-4	0.18069
Opx, $n=\gamma$	1.151303 E-4	1.75903	4.83225 E-5	0.11121
Aug, $n=\beta$	1.074600 E-4	1.71710	3.29820 E-5	0.06017,

where "E-4" signifies " $\times 10^{-4}$ ".

Routine composition determinations to an accuracy of $\pm 1-2$ mole percent are feasible with this method, given plutonic material comparable to that examined in this study.

Introduction

The refractive index-wavelength dispersion method of Merwin, as improved by Tsuboi (1934), continues to be a valuable tool in rapid mineral determination (*e.g.*, Morse, 1968, 1978) as well as an extremely powerful tool in the precise characterization and study of individual mineral grains (Bloss, 1978). Our purpose here is to extend the advantages of rapid determination to olivine, orthopyroxene, and

augite that crystallized slowly from common mafic magmas. These advantages lie chiefly in the statistical information obtained with ten or more grains in grain mounts, speed, convenience, low cost, and acceptable precision and accuracy. This paper extends and somewhat modifies our preliminary notes on the subject (Morse and Berg, 1971; Morse, 1973; 1977), although the dispersion nets shown in the first two notes are still useful for reconnaissance work.

The basis for extending the dispersion method to

new mineral species is the measurement of the dispersion, $\Delta n/\Delta\lambda$, over the compositional range of interest in each species, and the determination of suitable constants for the equations relating dispersion, refractive index, and composition. We offer here a set of constants suitable for digital computation, and a non-exhaustive empirical test of the method for each species.

Experimental procedure

In this study, we used the dispersion method itself to determine $\Delta n/\Delta\lambda$ for selected natural samples of the three mineral series. Grains were immersed in three to five oils of different refractive index, and by varying the wavelength, the refractive index of the crystal was found at a discrete wavelength for each oil. Ten to 20 or more grains were matched in each oil, after verifying that each was so oriented as to yield the desired refractive index (beta or gamma). The dispersion curves of the oils were represented by the Hartmann equation, which linearizes n against $L = 10^5/(\lambda-200)$, λ being the wavelength in nm. A more accurate treatment would be obtained by use of the Sellmeier equation (Louisnathan *et al.*, 1978) but tests to be reported below indicate that the results obtained herein are adequate for routine composition determinations. For each sample, the dispersion curve was found by linear regression, in Hartmann (n vs. L) space, on the determined points.

The resulting dispersion equations for each sample were solved for n_D and $\Delta n_{(F-C)}$. The results, plotted against n_D , are shown in Figures 1–3 for 13 olivine, 12 orthopyroxene, and 20 augite grains. Also shown in the figures are the standard errors (1 s.d.) and the equations relating $\Delta n_{(F-C)}$ to n_D , assuming linear variation. The values of $\Delta n_{(F-C)}$ extrapolated to the end

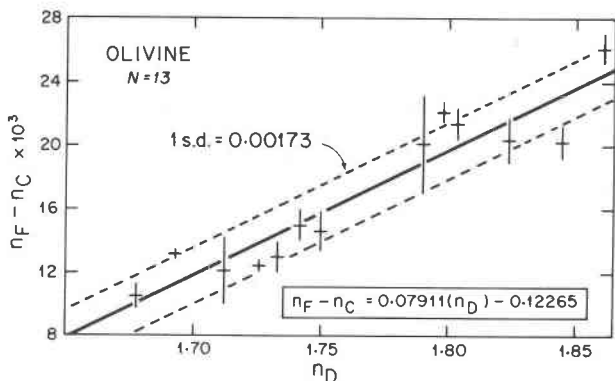


Fig. 1. Dispersion data for olivine. The simple correlation coefficient is 0.942.

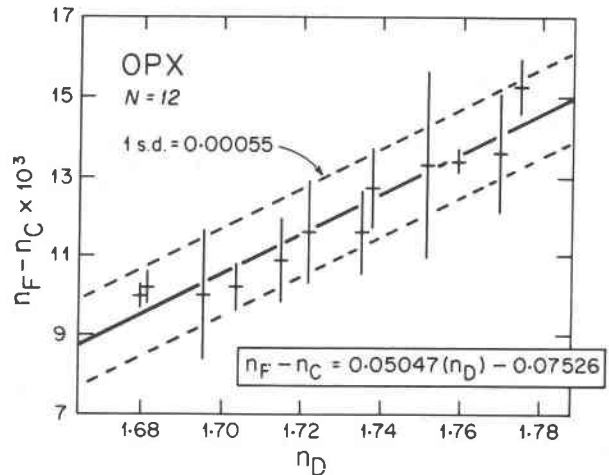


Fig. 2. Dispersion data for orthopyroxene. The simple correlation coefficient is 0.955.

members are listed in Table 1, where the fifth decimal is retained to reduce rounding errors.

All the samples studied were collected from plutonic rocks, including the Kiglapait and Hettasch intrusions, Labrador (Morse, 1969; Berg, 1980) and other North American localities. All of the augite samples were collected from the Kiglapait intrusion; they were analyzed chemically by K. Aoki, and details of their chemistry and physical properties will be reported separately.

The compositions of the olivines studied lie in the range Fo_2 to Fo_{87} , those of orthopyroxene in the range En_{12} to En_{88} , and those of augite in the range En_0 to En_{71} (where En is normalized to $En + Fs$). Although we expect the dispersions to yield valid extrapolations to the Mg end-members, we cannot, of course, comment objectively on their actual validity beyond $X_{Mg} = 0.71$ for augite and 0.88 for the other two groups.

For determinative curves at the D line, we have used the end-member data compiled in Tröger (1971) for olivine and orthopyroxene. For the Kiglapait augite series, however, we developed a new determinative curve, with an error bracket of 1 s. d. that corresponds to 0.7 mole % En (details to be published). This curve compares favorably with earlier determinations in the literature except near the iron-rich end, where the scarce older data fall away from the curve.

Synthesis of data

The results of the dispersion determinations are summarized in Figures 1–3 and in Table 1. The table

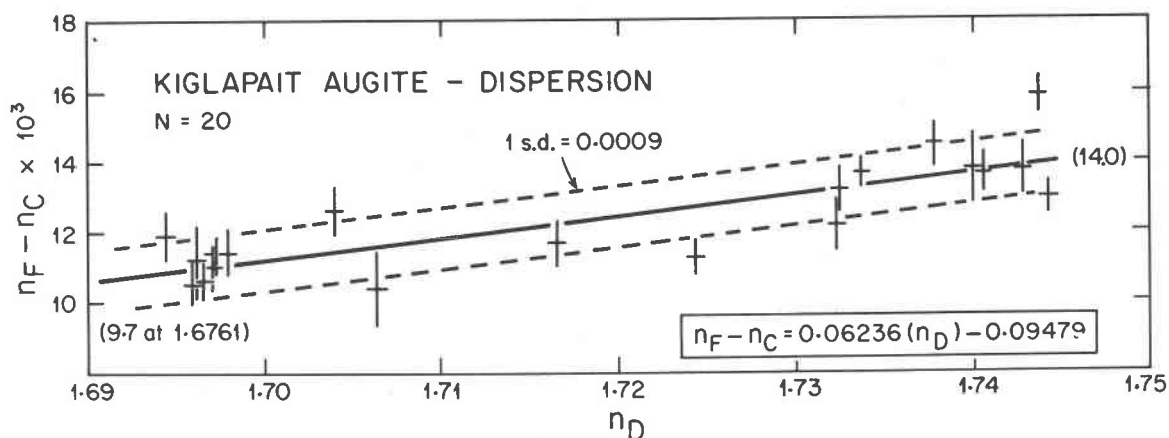


Fig. 3. Dispersion data for augite.

contains two sets of input data, namely the extrapolated dispersions $\Delta n_{(F-C)}$ for the end members and the end-point refractive indices n_D . All other entries are generated as described below. Reference to Figure 4 may aid in understanding how the equations for the full dispersion net are derived.

The slope a of the dispersion curve in Hartmann space is obtained from the relation:

$$a = \Delta n_{(F-C)} / \Delta L_{(F-C)}, \quad (1)$$

and the intercept b is then found by solving for the known n_D . The dispersion equation

$$n = aL + b, \quad (2)$$

is then solved for the F and C lines. Finally Δn_λ is found by subtraction at each of the lines F, D, and C. The quantity Δn_λ is the refractive index difference, at constant wavelength, between end members of the mineral series (Fig. 4). Because composition is normalized to $X_{Mg} = 1.0$, the quantity Δn_λ is simply the slope of the determinative curve for the mineral at a given wavelength. If we let n_0 be the refractive index of the Fe end-member at a given wavelength, and n be the refractive index of the crystal, then the equation of the determinative curve is:

$$X_{Mg} = (n_0 - n) / \Delta n_\lambda. \quad (3)$$

The constants n_0 (rows Fa and Fs) and Δn_λ for the three selected wavelengths corresponding to the F, D, and C lines are listed in Table 1. From these, a Tsuboi-style dispersion net can be constructed on Hartmann graph paper, thus facilitating rapid graphical application of the dispersion method (see Morse, 1968, for some practical details).

The Hartmann dispersion net for a given mineral series consists of the complete family of equations 3 for all λ . In order to generate the entire net, we need only provide expressions for the variation of n_0 and Δn_λ with wavelength. We already have the former in Table 1, constants a and b , and equation 2. Note that for n_0 , we use only the lines for the Fe-end members. The end points for the variation of Δn_λ also occur in Table 1, and from these we can generate constants c and d for the equation:

$$\Delta n_\lambda = cL + d. \quad (4)$$

All the required constants are grouped for convenience in Table 2, from which the entire determinative equation 3 can be written for each of the mineral series.

Table 1. Derived refractive indices for the F and C lines

$\Delta n_{(F-C)}$	$n_F, 486.1$	$n_D, 589.3$	$n_C, 656.3$	a	b
OLIVINE BETA					
Fo: 0.00796	1.65666	1.6510	1.64870	6.105512 E-5	1.63532
Fa: 0.02489	1.88269	1.8650	1.85780	1.909123 E-4	1.81596
Δn_λ	0.22603	0.2140	0.20910		
ORTHOPIYROXENE GAMMA					
En: 0.00877	1.67123	1.6650	1.66246	6.726801 E-5	1.64772
Fs: 0.01501	1.79927	1.7886	1.78426	1.151303 E-4	1.75903
Δn_λ	0.12804	0.1236	0.12180		
AUGITE BETA					
En: 0.00973	1.68302	1.6761	1.67329	7.46314 E-5	1.65693
Fs: 0.01401	1.75466	1.7447	1.74065	1.07460 E-4	1.71710
Δn_λ	0.07164	0.0686	0.06736		
$\Delta L=130.374$	$L=349.528$	256.871	219.154		

Notes: $L = 10^5 / (\lambda - 200)$. Constants a and b are the slope and intercept, respectively, for the dispersion curve of the crystal in Hartmann space; $a = \Delta n_{(F-C)} / \Delta L$. Each dispersion curve has the form $n = aL + b$. The quantity $\Delta n_{(F-C)}$ is from this study. For "E-5" etc. read "x10-5" etc.

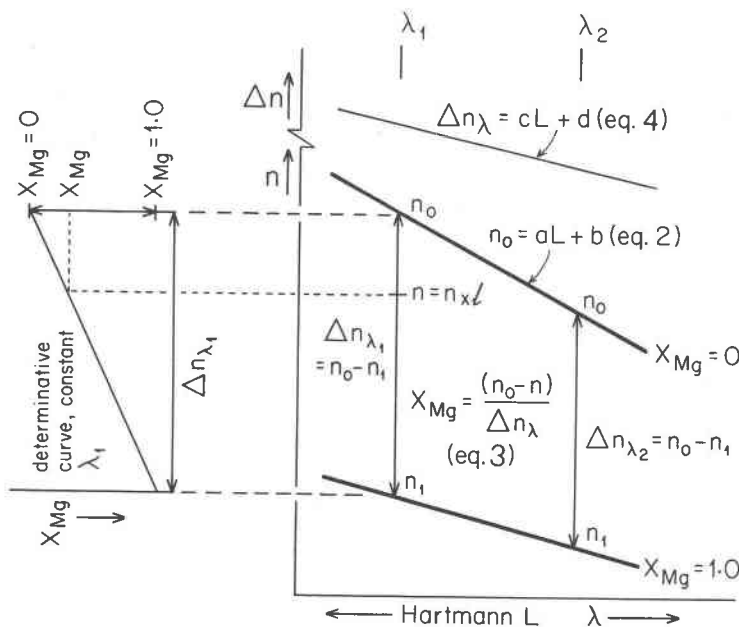


Fig 4. Derivation of the dispersion net equations for a binary Mg-Fe mineral series. Heavy lines are the dispersion curves in Hartmann space for the Mg and Fe end members of the series. Vertical double arrows show the difference in n between the end members at two selected wavelengths, λ_1 and λ_2 . The map along λ_1 is carried into a section showing the n - X relation (determinative curve) at the left. The dispersion net consists of an infinite number of such determinative curves, whose slope Δn_{λ} is graphed in the upper part of the diagram and whose upper intercept n_0 is given by the dispersion curve for $X_{Mg} = 0$.

Application

In practice, data are collected for λ_{match} and T_{match} (the temperature of the stage) for each grain, and the dispersion equation (Hartmann or Sellmeier) for the oil is solved to obtain $n_{oil} = n_{x1}$ at $T^{\circ}C$. This value of n , and the wavelength, are then used to solve for composition via the constants of Table 2 and equation 3. The entire procedure is readily programmed for a digital computer, and can result in an output showing the compositions for an assembly of grains, with standard deviation and standard error of the mean. The results then contain useful information on sample variability as well as mean composition.

Olivine grains showing beta are best recognized by their low interference colors; however, one need not be restricted to optic axis sections, as both (010) and (100) cleavages contain Y and can occasionally be recognized. Orthopyroxene grains showing gamma are ubiquitous as (210) cleavage fragments, and need only be oriented with their prominent zone parallel to the polarizer, when they will show a green rather than pink pleochroic color. Augite grains showing beta, chiefly (100) partings, are easily recognized by their parallel extinction with respect to

cleavage or inclusions, which are set normal to the polarizer.

In all cases, it is wise to verify that a primary rather than partial value of the refractive index is available, by observing that an isogyre coincides with the crosshair normal to the polarizer. Note, however, that an isogyre offset of about 1/3 the field radius would be required to cause a mis-estimate of one

Table 2. Constants for the determination of X_{Mg}

	a	b	c	d
<i>Olivine Beta, X_{Fo}</i>				
1.909123 E-4	1.81596	1.29627 E-4	0.18069	
<i>Orthopyroxene Gamma, X_{En}</i>				
1.151303 E-4	1.75903	4.83225 E-5	0.11121	
<i>Augite Beta, X_{En}</i>				
1.074600 E-4	1.71710	3.29820 E-5	0.06017	

Notes: $X_{Mg} = (n_0 - n) / \Delta n_{\lambda}$, where $n_0 = aL + b$, n is the refractive index of liquid and crystal at the wavelength of match and $25^{\circ}C$, $\Delta n_{\lambda} = cL + d$, and $L = 10^{\circ} / (\lambda - 200)$.

mole percent En in augite, so the method is quite forgiving except in olivine.

Tests of the method

Inasmuch as the data are generated from natural samples, any test of the entire method incorporates uncertainties in the dispersion of the mineral, the assumed determinative curve for n_D , and the treatment of $\Delta n/\Delta \lambda$ for the oils. It is assumed, probably with justice, that the Hartmann treatment for the crystals introduces no significant error, but some systematic error arises from the use of the Hartmann rather than the Sellmeier equation for the oils. We have made a few tests of the olivine and orthopyroxene determinations by comparison with electron probe analyses of grain mounts. In eight samples of olivine and in six samples of orthopyroxene, we find a standard deviation of ± 1.2 mole percent Fo or En. The olivine samples tested span the range Fo = 2 to 80, and the orthopyroxene samples span the range En = 12 to 76. Twenty samples of Kiglapait augite analyzed by wet chemistry were each examined in four or five different oils. Taking only data from the centrally located oil in each set, the standard deviation is ± 1.0 mole percent En, using an average of 13 grains per sample. In short, the evidence suggests that an accuracy in the range of 1–2 mole percent is readily attainable if 10 grains per sample of comparable material are measured. Volcanic, alkalic, or very deep-seated mafic minerals may contain important minor constituents which could raise the uncertainty to unacceptable levels.

Notes on microscopy

Refractive index liquids used in this study were standard (Cargille) liquids, calibrated frequently with a temperature-controlled Abbe refractometer. For liquids above $n = 1.78$, dispersions given by the manufacturer were used; below that value the dispersions were determined directly.

The monochromator used was a Leitz-Schott wedge interference filter mounted in a loose shuttle that can be rapidly oscillated to and fro, thus facilitating determination of a null point (match between crystal and liquid) as the shadow in oblique illumination jumps from one side of the grain to the other.

Given this method of rapidly variable wavelength, the oblique illumination method is generally more sensitive than the Becke line test, contrary to the conventional wisdom (Saylor, 1935).

Temperatures were recorded to 0.1°C from a thermometer placed within 1 cm of the microscope stage.

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