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X-RAY AND OPTICAL CHARACTERIZATION OF THE FORSTERITE–FAYALITE–TEPHROITE SERIES WITH COMMENTS ON KNEBELITE FROM BLUEBELL MINE, BRITISH COLUMBIA

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ABSTRACT

A combination of the n_β refractive index and d_{130} provides a good estimate of olivine composition throughout the forsterite-fayalite-tephroite series. The determinative curves are constructed, allowing a suitable correction for larnite, on the basis of 25 chemically analyzed olivines with CaO content <0.5 wt. %. The maximum difference between olivine compositions estimated using n_β and d_{130}, and those based on chemical analyses is about ±2.0 mol. %. Of four new microprobe analyses of manganiferous olivine from the Bluebell mine, three are of iron knebelites, and the fourth is of knebelite. None shows significant zoning.

SOMMAIRE

Les valeurs combinées de l'indice de réfraction n_β et de l'espacement d_{130} permettent d'estimer la composition d'une olivine de la série forstérite–fayalite–téphroïte. Les courbes déterminatives ont été construites, compte tenu de la présence de larnite, à partir de 25 analyses chimiques d'olivine dont la teneur en CaO n'atteint pas 0.5% (en poids). La différence la plus grande entre deux compositions d'une même olivine, l'une estimée en fonction de n_β et d_{130}, l'autre obtenue par analyse chimique, est d'environ ±2.0% (mol.). Sur quatre nouvelles analyses à la microsonde de l'olivine manganifère de la mine Bluebell, trois représentent des knebelites ferrifères et la quatrième correspond à la knebelite. Aucun des échantillons ne provient d'une olivine zonaire.

(Traduit par la Rédaction)

INTRODUCTION

The use of optical properties or *d*-values to establish the cation composition of olivines in the forsterite-fayalite series are familiar procedures. Other methods also have been applied to the determination of these and other varieties of olivine. The more significant methods are reviewed by Burns & Huggins (1972), who point out that most of the determination schemes are restricted to binary series. Their own determinative curves based on infrared vibrational spectra apply to Mg-Fe-Mn olivines.

Although in practice a strong pseudo-binary trend in olivine composition is observed, in theory, solid solution among the three main vareties of olivine — forsterite, fayalite and tephroite (Fo-Fa-Te) — closely approaches the ideal (Glasser & Osborn 1960; Thompson 1967; Louisnathan & Smith 1968; Fisher & Medaris 1969). Detailed terminologies describe varieties intermediate between Fo and Fa and between Fa and Te; compositions between Fo and Te are usually referred to as picrotephroite (Fig. 1).

Larnite (La—Ca_2SiO_4), forms complete solid solution series with Fa in kirschsteinite (Ki—$CaFeSiO_4$) and with Te in glaucochroite (Gl–$CaMnSiO_4$) (Bowen *et al.* 1933a,b), but it forms only a partial solid-solution series with Fo in monticellite (Mo—$CaMgSiO_4$) (Warner & Luth 1973). All three intermediate varieties occur in nature and, on the basis of experimental evidence (Schairer & Osborn 1950; Warner & Luth 1973), are believed to form complete solid solutions with each other. According to the experimental results of Bowen *et al.* (1933b), Ki forms limited solid solution with La. Limited solid solution between La and Mo seems likely. The exact relationship between Gl and La is unclear (Glasser 1961; Warner & Luth 1973).

Deer *et al.* (1962) note that monticellite may be distinguished from Fo-Fa-Te olivines by its lower birefringence.

According to the observations of Bowen *et al.* (1933a), synthetic Ca-Fe olivines can be distinguished from Fo-Fa olivines by much higher birefringence for a given mean index of refraction. Wyderko & Mazanek (1968) list a variety of X-ray and optical data that facilitate recognition of Ca-Fe olivines. Sahama & Hytönen (1958) showed that the Mo-Ki series can be distinguished from the Fo-Fa series either by measurement of d_{130} or by a combination of refractive indices, $2V_x$ and/or specific gravity.

Glasser (1961) supports the identity of glaucochroite as a separate compound and lists a number of distinguishing characteristics based on X-ray data.

During a study of olivine at the Bluebell mine, southeastern British Columbia, a con-

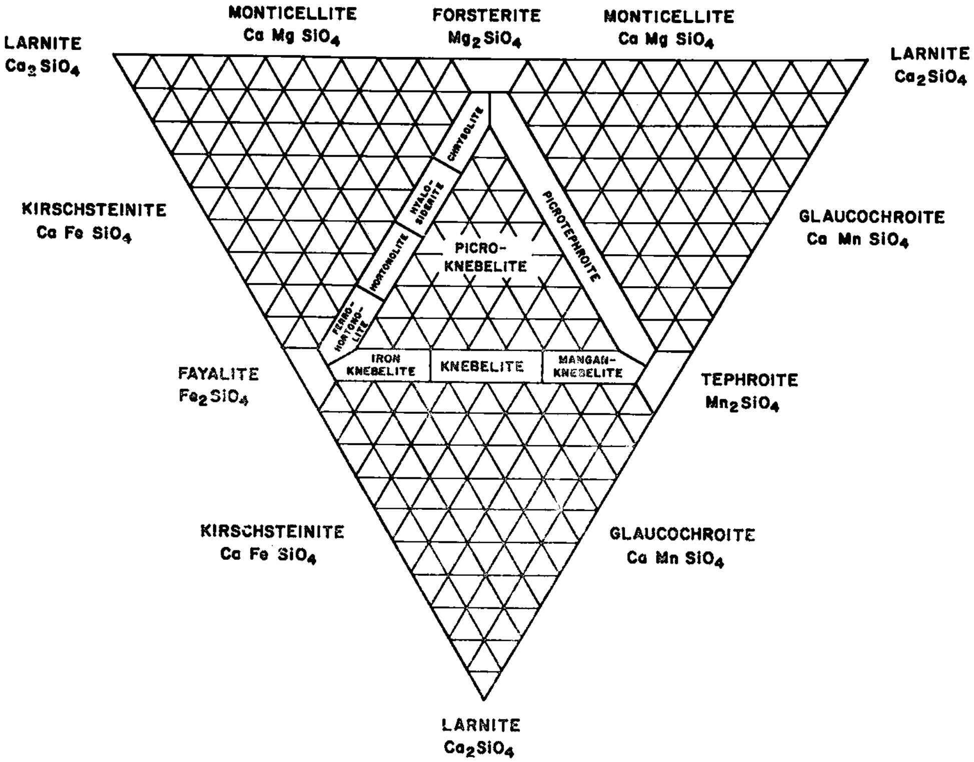

FIG. 1. Diagram showing the general compositional relationships among the olivines. Following Japanese practice, the term "picro-knebelite" is given to the central portion of the triangle Fo-Fa-Te. Solid solution is complete among Fo-Fa-Te; for details on the extent of solid solution among the various other species see text.

venient and reliable method was sought in order to determine the composition of the Mn-rich variety, knebelite. Determinative curves for Fo-Fa-Te presented by Winchell (1961) are unsatisfactory because curves for n_β and $2V_X$ are nearly parallel. Using optical data on knebelite-fayalite, Henriques (1956, 1957) constructed determinative graphs which suffer from substantial error in calculating refractive indices and unit-cell dimensions from chemical composition (Henriques 1957). Using a statistical procedure, Louisnathan & Smith (1968) suggested on the basis of cell dimensions that it is theoretically possible but impractical to estimate all three principal constituents in olivine. According to Burns & Huggins (1972), infrared spectroscopic determinations of olivine composition involve errors of only ±3 mol % Mg_2SiO_4. We decided to test whether comparable accuracy could be obtained using ". . . d_{130} and some other parameter . . ." as suggested by Yoder & Sahama (1957, p. 482). The "other" parameter that we selected is n_β.

MATERIALS AND METHOD OF INVESTIGATION

The d_{130} value and n_β of 25 analyzed olivines selected (Table 1) from the literature were used to construct the determinative diagram. Unless otherwise indicated, refractive index of each olivine is accurate to ±0.002. Probable error in measurement of d_{130} varies (Table 1) but in no case exceeds ±0.001Å.

The results of Smith's (1966) comparative study of chemical and electron microprobe analyses of Fo-Fa olivines suggest that any analysis with CaO greater than 0.5 wt. %, except for the monticellite group, is suspect and probably contains impurities (cf. Bowen *et al.* 1933a). In the present study only olivines with less than this limit are used, although it has not been established that a similar limit would apply to manganiferous olivines. Picrotephroites rich in CaO (>2.5 wt. %) are widely reported from Japan. Doubtlessly some of these result from solid solution rather than from impurities of calcium. Unfortunately, n_β and/or d_{130} are

TABLE 1. X-RAY AND OPTICAL DATA FOR ANALYZED NATURAL OLIVINES USED IN CONSTRUCTING THE DETERMINATIVE GRID (FIG. 2)

SAMPLE NUMBER	SOURCE*		COMPOSITION				n_β MEASURED	n_β CORRECTED**	d_{130} MEASURED	d_{130} CORRECTED**
			Fo	Fa	Te	La				
1	1	9232	90.9	9.0	0.0	0.1	1.672	1.672	2.7730 ± Not listed	2.772
2	"	4378	90.6	9.0	0.1	0.3	1.668	1.668	2.7722 "	2.771
3	"	9150	89.4	10.1	0.1	0.4	1.670	1.670	2.7719 "	2.769
4	"	9214	88.6	11.1	0.1	0.2	1.679	1.679	2.7752 "	2.774
5	"	9183	86.1	13.4	0.1	0.3	1.684	1.684	2.7756 "	2.773
6	"	7886	86.0	13.8	0.1	0.2	1.682	1.682	2.7752 "	2.774
7	2	5	87.3	12.6	0.0	0.1	1.682	1.682	2.772 "	2.771
8	3	63.1	63.2	36.5	0.3	0.0	1.733	1.733	2.7910 ± 0.0008	2.791
9	"	53.9	55.9	43.4	0.7	0.0	1.748	1.748	2.7959 "	2.796
10	"	40.0	40.0	59.5	0.5	0.0	1.781	1.781	2.8077 "	2.808
11	"	20.2	20.2	78.3	1.2	0.3	1.828	1.828	2.8213 "	2.820
12	"	0.0	0.0	98.9	1.1	0.0	1.864	1.864	2.8310 "	2.831
13	4	BAST.1	5.9	85.3	8.3	0.5	1.843	1.846	2.833 ± 0.001	2.831
14	"	BAST.2	2.9	81.9	14.5	0.6	1.843	1.846	2.838 "	2.835
15	"	HAGG.	29.5	50.4	19.7	0.4	1.784	1.785	2.825 "	2.823
16	"	SKIN.	9.7	62.2	27.9	0.1	1.824	1.825	2.841 "	2.841
17	"	V.SIL.	11.4	57.9	30.7	0.0	1.818	1.818	2.843 "	2.843
18	"	TU.HA.	5.4	53.8	40.3	0.5	1.822	1.824	2.850 "	2.848
19	"	DANN.1	2.6	52.2	45.0	0.2	1.821	2.824	2.855 "	2.854
20	"	DANN.2	3.7	44.5	51.5	0.3	1.821	1.822	2.857 "	2.856
21	5	5	6.7	1.2	92.0	0.1	1.800	1.800	2.861 "	2.861
22	"	2	13.9	6.3	79.7	0.1	1.795	1.795	2.850 "	2.850
23	"	7	24.2	3.0	72.8	0.0	1.775	1.775	2.844 "	2.844
24	"	1	26.1	6.7	67.2	0.0	1.775	1.775	2.840 "	2.840
25	"	4	44.7	2.2	52.9	0.2	1.743	1.743	2.827 "	2.826

* 1-Rogers & Brothers (1969); 2-Eliseev (1957); 3-Yoder & Sahama (1957); 4-Henriques (1956); 5-Hurlbut (1961)

** Corrected for calcium content (see text).

not reported with the published chemical analyses. Also, because analyses high in Fe_2O_3 are suspected of containing impurities, only analyses containing minor amounts of Fe^{3+} are used.

Calculations of the molecular proportions of Mg_2SiO_4, Fe_2SiO_4, Mn_2SiO_4 and Ca_2SiO_4 are obtained from the ratios Mg/A, Fe/B, Mn/C and Ca/D of atoms per formula A_2, B_2, C_2 and D_2SiO_4 and the composition recorded as Fo_A Fa_B Te_C La_D. Having thus obtained the quantity La for the purpose of correcting d-values and n_β curves, Fo, Fa and Te are recalculated to 100%.

There is general agreement (Fisher & Medaris 1969) that the divergence commonly observed between determinative curves for natural and synthetic (Fo-Fa) olivines is caused by the presence of minor amounts of various ions, mainly Mn and Ca. In the present study a correction for La is applied to both d_{130} and n_β determinative curves (Table 1). The correction is determined using the differences in refractive indices (n_β) as given in Deer *et al.* (1962) and d_{130} calculated by Smith & Stenstrom (1965) from cell edges of synthetic olivines. Data are as follows: Fo (1.651, 2.7661Å); Fa (1.869, 2.8293Å); Te (1.807, 2.8697Å); Mo (1.646, 2.9306Å), and for Ki, (1.734, 2.9573Å). Data for Ki are from Sahama & Hytönen (1958). For Gl, the data on material from Franklin, New Jersey, possibly the same as that studied by Palache (1937) and reported in Winchell (1961), are: (1.723, 2.96Å). Since substitution of Ca for Mn increases d_{130} and decreases n_β (Louisnathan & Smith 1968), a correction of $-(0.1645xFo + 0.1280xFa + 0.090xTe)$ (La/50) is applied to the measured d and a correction of $+(0.005xFo + 0.135xFa + 0.084xTe)$ (La/50) is applied to n_β. As a check on the accuracy of the measured values, d_{130} was calculated from cell-edge data for some of the specimens in Table 1.

Data for the curves consist of weighted values and interpolated points. The locations of the curves were determined by a standard method of least-squares curve fitting and goodness of fit was checked by polynomial regression analysis. The procedure followed is almost identical to that outlined in detail by Davis (1973).

Four new chemical analyses of knebelite from the Bluebell mine (Table 2) were obtained using an Acton (Cameca) M.S. 64 electron microprobe. Excitation voltage of 25kV and specimen

TABLE 2. ANALYSES OF KNEBELITE FROM BLUEBELL MINE, B.C.

Specimen	U.S. 4092[a]	U.S. 4094[b]	U.S. 4095[c]	U.S. 4096[d]	Gunning (1936)
SiO_2	31.57	31.50	31.54	31.89	28.93
TiO_2	0.03	0.0	0.02	0.05	—
Al_2O_3	0.05	0.04	0.06	0.02	Nil
Fe_2O_3	n.d.	n.d.	n.d.	n.d.	4.06
FeO	47.99	40.33	47.24	44.88	39.15
MnO	19.59	26.09	20.40	21.58	24.82
MgO	1.08	1.59	1.18	1.84	0.05
CaO	0.05	0.05	0.05	0.06	0.68
Na_2O	0.03	0.0	0.01	0.04	—
K_2O	0.01	0.01	0.02	0.00	—
H_2O+	0.05	0.05	0.05	0.02	2.01
H_2O-	n.d.	n.d.	n.d.	n.d.	0.10
TOTAL	100.45	99.66	100.57	100.38	99.80
Fo	2.8	4.0	3.0	4.7	—
Fa	68.8	58.0	67.5	64.1	—
Te	28.4	38.0	29.5	31.2	—
	Number of ions on basis of 4 (0)				
Si	1.037	1.038	1.035	1.040	
Al	0.0	0.0	0.0	0.0	
Ti	0.0	0.0	0.0	0.0	
Al	0.001	0.001	0.002	0.000	
Cr	0.0	0.0	0.0	0.0	
Ti	0.000	0.0	0.000	0.001	
Fe^{3+}	0.0	0.0	0.0	0.0	
Fe^{2+}	1.319	1.112	1.297	1.225	
Mn	0.545	0.728	0.567	0.596	
Mg	0.052	0.078	0.057	0.089	
Ca	0.001	0.001	0.001	0.002	
Na	0.001	0.0	0.000	0.002	
K	0.000	0.000	0.000	0.0	
d_{130} (obs)	2.8441	2.8473	2.8437	2.8462	
(calc)	2.8446	2.8459	2.8461	2.8423	—
$n\beta$ ± 0.002	1.834	1.828	1.832	1.830	1.81
aÅ ± 0.005	4.831	4.842	4.844	4.828	—
bÅ ± 0.005	10.558	10.552	10.552	10.549	—
cÅ ± 0.005	6.137	6.136	6.135	6.109	—
VÅ^3	313.075	313.558	313.563	311.135	—

(a) sample obtained at 45 m in drillhole 2321, Comfort ore zone from the "knebelite ore zone" hosted by mineralized and silicified limestone; (b) 46.8 m, in drill hole 2321, Comfort ore zone from a mineralized zone in silicified limestone closely associated with dark green chloritic pegmatite; (c) & (d) from the "2R" stope, Kootenay Chief ore zone (analyst: D.J. Mossman).
Note: U.S. numbers refer to material housed in Dep. Geol. Sci., Univ. Saskatchewan, Saskatoon.

current of 50 nano-amps were employed. Machine drift was compensated by repeated measurements on appropriate natural standards before and after measurements on each specimen. The raw data were subsequently processed using the EMPADR VII computer program (Rucklidge & Gasparinni 1969).

Measurements of d_{130} on the Bluebell olivines were made by comparison with d_{111} of a silicon internal standard. In each case the result is the average of 10 traverses using Mn-filtered Fe$K\alpha$ radiation and a chart speed of ¼° 2θ/min. Error in measurement of d_{130} is less than 0.0005Å.

Refractive index n_β was determined in sodium light by the immersion method with an error ±0.002. The liquids employed are described by Meyrowitz & Larsen (1951). However it is more expedient at this high range of n_β to work with lower refractive indices and calculate n_β.

RESULTS AND DISCUSSION

The determinative scheme

The compositions of the 25 olivines (Table 1) and the curves of d_{130} and n_β corrected for calcium are shown in Figure 2 within the compositional triangle Fo-Fa-Te. The refractive-index curves generally correspond to those of Winchell (1961) and like the latter are unevenly spaced. However, they differ in that they are not linear. Although the exact reasons for this are unclear, the curvatures of n_β (and d_{130}) lines probably mainly reflect the changing proportions of the several cations (including Ca).

Other ions, notably Zn, Al, Fe^{3+}, Ti, Cr, and Ni, may also enter olivine in measurable amounts. In the case of the nickel olivine liebenbergite, d_{130} (diagnostically smaller in liebenbergite than in forsterite, fayalite, tephroite and monticellite) used in conjunction with either n_β or specific gravity provides an estimate of olivine composition within the Fo-Fa-liebenbergite compositional triangle (De Waal & Calk 1973). This is predictable in light of Simkin & Smith's (1970) study of element distribution in olivine which shows that Mn and Ni are dominantly related to major-element fractionation. They report that, in contrast to Mn and Ni, calcium content of olivine is largely determined by depth of crystallization and hence is dependent on P, T and cooling rate.

Hurlbut's work (1961) on the Fo-Te series indicated that Zn plays a very minor role as a substitute cation. This conclusion is substantiated by Mason (1973), who points out that the so-called zincian tephroite (roepperite) probably should be discredited as a mineral.

Yoder & Sahama (1957) maintained that Ca, Al and Fe^{3+} substitute only within narrow limits in the Fo-Fa series. Crystal-chemical studies suggest that most Fe^{3+} in olivines is the result of impurities, and that Fe^{3+} can enter olivine only by coupled substitution (Smith & Stenstrom 1965). Judging from the analyses selected from the literature, there seems to be a narrow range of substitution of Ti and Cr (see also Deer *et al.* 1962).

Compositions of the four manganiferous olivines from the Bluebell mine group closely together in Figure 2 but were not used in constructing the curves. The small differences (av. 1.0 mol. % olivine) between the chemically analyzed compositions and those based an d_{130} and n_β (Fig. 2) are exemplary. According to the classification given in Figure 1, three of the four

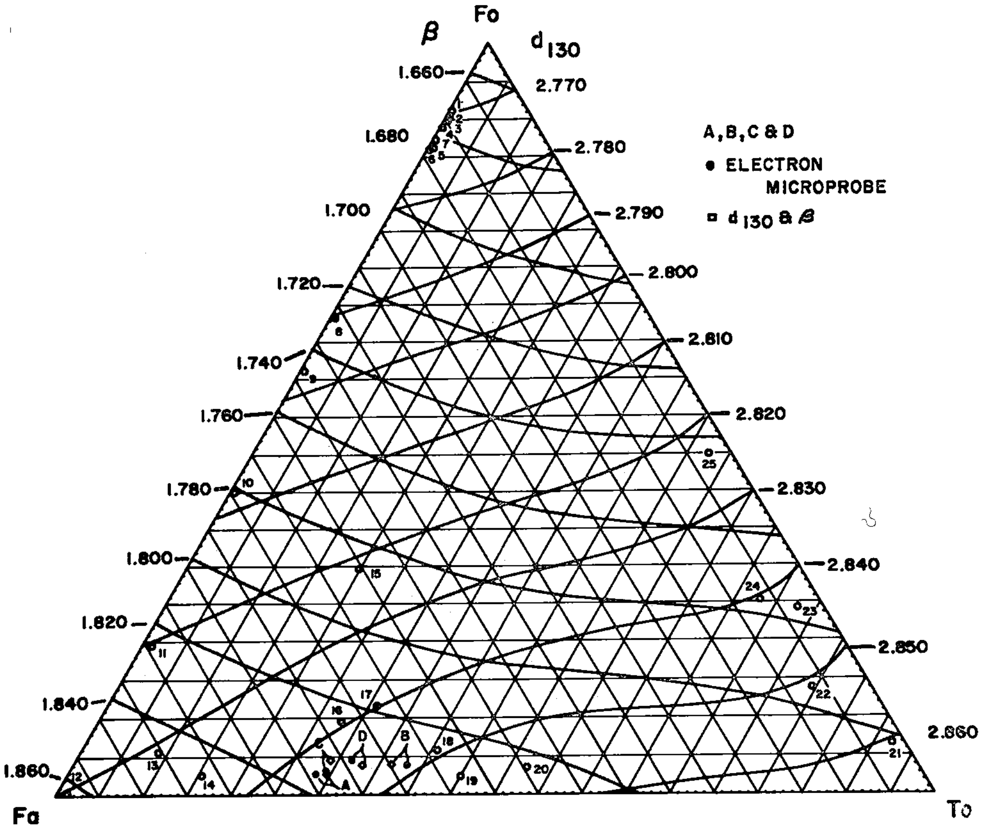

FIG. 2. Composition determinative grid for olivines of the Fo-Fa-Te series based on d_{130} and n_β. Compositions (mol. %) of the 25 analyzed olivines used in constructing this grid are indicated. Points A (U.S. 4092), B (U.S. 4094), C (U.S. 4095) and D (U.S. 4096) refer to the four knebelites (Table 2) from the Bluebell mine.

specimens are iron knebelites and the fourth is knebelite.

A large number of olivines for which only n_β or d_{130} is available were employed to estimate the probable error in these curves. For 13 analyzed olivines, difference between measured and estimated n_β averages ±0.0012 (Table 3), equivalent to an error of <0.7 mol. % Fo. For 31 analyzed olivines, difference between measured and estimated d_{130} averages ±0.0011Å; this represents approximately ±1.25 mol. % Fo. For practical purposes, assuming that the estimated errors are cumulative, the sum of the two averaged differences, as given above, is ±2.0 mol. % Fo.

It appears therefore that the method provides a satisfactory estimate of olivine composition in the Fo-Fa-Te mineral series. It compares favorably with Burns & Huggins' (1972) reported ±3 % error in the Mg_2SiO_4 components on the basis of infrared spectra. Refinement of the n_β and d_{130} curves is possible as further analyses become available, especially those in the picroknebelite field. However, neither of the above methods can compete with the electron microprobe for accuracy or possibly even for speed.

KNEBELITE FROM THE BLUEBELL MINE

Westervelt (1960) reported that knebelite occurs at the Bluebell mine in cross fractures and in massive bedded mineralized deposits within the Bluebell limestone. He considered it the earliest replacement mineral. Ohmoto & Rye (1970) also place it early in the paragenetic sequence (e.g., 450±35°C to 370±30°C) and assign it a hydrothermal replacement origin.

Knebelite reported in this study was not obtained from obvious cross fractures. The samples typically feature radiating sheaf-like clusters of long black crystals up to 5 cm in diameter (Fig. 3). A weak basal parting is present in addition to a good {110} cleavage. Most crystals are < 1mm thick, but widths

TABLE 3. LIST OF SOME CHEMICALLY ANALYZED OLIVINES FOR WHICH EITHER n_β OR d_{130} IS KNOWN

SOURCE	COMPOSITION				d_{130}		DIFFERENCE
	Fo	Fa	Te	La	MEAS.	EST.	
Alberti (1970)	18	82			2.819±?	2.820	0.001
	26	74			2.815 "	2.817	0.002
	34	66			2.810 "	2.812	0.002
	42	58			2.804 "	2.808	0.004
	50	50			2.799 "	2.801	0.002
	58	42			2.796 "	2.796	0.000
	66	34			2.789 "	2.789	0.000
	74	26			2.785 "	2.784	0.001
	82	18			2.780 "	2.778	0.002
Hurlbut (1961)	0		100		2.867±0.001	2.867	0.000
	50		50		2.820 "	2.820	0.000
	60		40		2.810 "	2.810	0.000
Jahanbagloo (1969)	0	100			2.831 "	2.831	0.000
	20	80			2.818 "	2.820	0.002
	40	60			2.805 "	2.809	0.004
	60	40			2.791 "	2.793	0.002
	80	20			2.778 "	2.778	0.000
	100	0			2.764 "	2.764	0.000
Yoder & Sahama (1957)	5.5	88.1	6.2	0.2	2.830±0.0008	2.830	0.000
	68.7	30.9	0.1	0.2	2.787 "	2.787	0.000
	76.5	23.1	0.2	0.2	2.780 "	2.781	0.001
	76.5	22.7	0.3	0.5	2.781 "	2.781	0.000
	78.1	21.2	0.3	0.4	2.778 "	2.780	0.002
	82.5	17.2	0.3	0.0	2.779 "	2.777	0.002
	88.8	10.8	0.2	0.2	2.773 "	2.772	0.001
	89.0	10.7	0.3	0.0	2.774 "	2.772	0.002
	89.2	10.6	0.1	0.1	2.772 "	2.772	0.000
	90.3	9.6	0.1	0.0	2.773 "	2.771	0.002
	92.0	7.8	0.2	0.0	2.772 "	2.769	0.003
	90.8	8.9	0.2	0.1	2.771 "	2.770	0.001
	91.9	7.5	0.2	0.4	2.769 "	2.769	0.000
					AVERAGE DIFFERENCE		= 0.0011
					n_β		DIFFERENCE
					MEAS.	EST.	
Bowen & Schairer (1935)	0	100			1.864	1.865	0.001
	13.9	86.1			1.835	1.836	0.001
	32.6	67.4			1.794	1.794	0.000
	59.2	40.8			1.738	1.738	0.000
	100	0			1.651	1.651	0.000
Carmichael (1960)	14.6	82.7	2.2	0.5	1.833	1.834	0.001
	13.2	82.9	3.3	0.7	1.837	1.837	0.000
	12.2	84.8	2.5	0.5	1.837	1.840	0.003
	11.2	85.0	3.0	0.7	1.842	1.842	0.000
Hurlbut (1961)	0		100		1.805±0.001	1.806	0.001
	50		50		1.732 "	1.734	0.002
	60		40		1.712 "	1.716	0.004
Foss & Kerr (1932)	4.1	5.0	90.8		1.803	1.803	0.000
					AVERAGE DIFFERENCE		= 0.0010

For comparative purposes some data on synthetic olivines are included: (Alberti 1970; Jahanbagloo 1969; Hurlbut 1961).
Note: ESTIMATED values are those indicated on the basis of Figure 2. Where there is a larnite component the MEASURED value orrected accordingly.

of several cm are common. In thin section their shapes are vaguely reminiscent of olivines of plate-like and branching habits (Figs. 4A, B) characteristic of harrisite and spinifex varieties such as those figured by Donaldson (1974).

The analyses of the two specimens from the "2 R" stope are similar, but differ substantially in MnO and FeO from specimens U.S. 4096 and U.S. 4094 obtained from a drill hole more than 1000 m to the north, and down dip from the "2 R" stope (see Shannon 1970, for details of regional and mine geology). The analysis of knebelite collected from the surface of the Kootenay Chief claim, and reported by Gunning (1936), more nearly resembles samples U.S. 4096 and U.S. 4094, but clearly requires adjustment for CaO and high Fe_2O_3 which probably result from myriad tiny inclusions of carbonate and iron oxides.

Early suspicions that zoning might inhibit reliable analysis proved unfounded because of the paucity of zoning revealed by electron microprobe traverses for Mg, Fe, and Mn, across knebelite crystals of various orientations. Lack of appreciable zoning in the Bluebell knebelite is unusual in view of the metasomatic origin commonly reported for the mineral (e.g., Henriques 1956). One notable exception to this mode of origin is the iron knebelite reported by Frisch (1972) from nordmarkite. Numerous

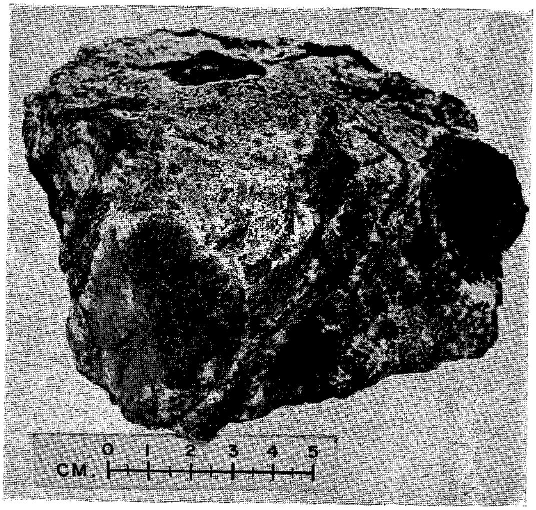

FIG. 3. Characteristic radiating sheaf-like clusters of knebelite crystals interleaved with a host of sulfide minerals which include pyrite, pyrrhotite, several varieties of sphalerite, arsenopyrite, galena along with magnetite, hematite, calcite, kutnahorite, plagioclase and quartz; host rock is the Bluebell limestone.

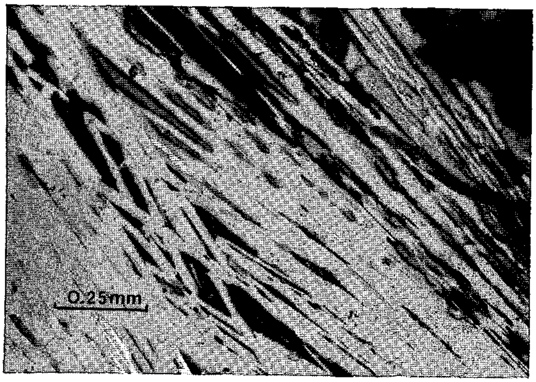

FIG. 4A. Bundles of knebelite crystals (light grey) crosscut other plates. Several branching crystals (upper right) are also present. Bright specks are included sulfide and oxide grains; accompanying silicate and carbonate minerals are in various shades of grey. Black holes are pits. (Reflected light).

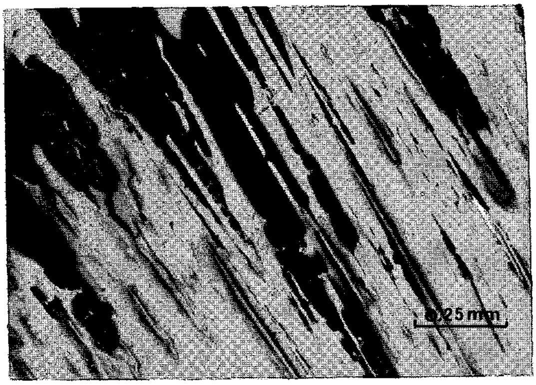

FIG. 4B. Skeletal platy crystals of knebelite contain scattered inclusions of opaque (bright) minerals. Some branching, and "budding" characteristics of knebelite are evident in center of photo. (Reflected light).

other examples of compositional overlap among olivines of different origin severely limit the extent to which mode of origin is indicated by chemical composition.

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