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Compression of Garnet to 100 Kilobars

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The compression of a natural Mg-rich garnet to pressures greater than 100 kb was studied by a high-pressure in situ X-ray powder-diffraction method. A quadratic least-squares fit to the data yields a rough value for the bulk modulus of 1750 kb. The results are in agreement with the compression data found by Takahashi and Liu (1970), who used a different high-pressure X-ray diffraction technique, and with the results of Soga (1967), who used an ultrasonic technique.

This study of the compression of an Mg-rich garnet is the second in a series of reports on the compression of minerals thought to be major constituents of the earth's upper mantle. The first was a study of the compression of Mg-rich olivine [*Olinger and Duba,* 1971]. Past investigations conducted on the members of the almandite-pyrope garnet series $(Fe, Mg)_3Al_2(SiO_4)_3$ are listed by *Birch* [1966, p. 132] and by *Takahashi and Liu* [1970]. Attention will be given here to two recent works, *Soga*'s [1967] investigation of the elastic constants and their pressure derivatives in an Fe-rich member of the series and *Takahashi and Liu*'s [1970] compression study of four members of the series using a high-pressure in situ X-ray powder-diffraction technique.

SPECIMEN AND EXPERIMENTAL METHOD

The specimen studied was a garnet crystal extracted from a serpentinized peridotite from Zöblitz, Czechoslovakia. The crystal was ground to a fine powder, its cell parameter (11.554 ± 0.009A) was determined from X-ray powder-diffraction film by using a 114.6-mm Debye-Scherrer camera and CuK_α radiation, and its chemical composition (Table 1) was determined by using a microprobe.

The high-pressure in situ X-ray diffraction technique used was described by *Jamieson* [1964, 1965]. Briefly, the powdered garnet sample was mixed with powdered NaF (2:1 by volume), pressed into a pellet 0.40 mm in diameter and 0.25 mm high, set into a powdered amorphous boron annulus, and this assembly was then pressed between two tungsten-carbide pistons by a small-tonnage hydraulic ram. A collimated, filtered MoK_α X-ray beam was passed through the sample perpendicular to the axis of the pistons, and the subsequent diffracted rays were recorded on a film mounted concentrically 114.6 mm from the sample. Pressures in the sample region were deduced from the compression of the NaF by referring to *Olinger and Jamieson* [1970]. Errors to be expected in correlating the NaF compression to pressure are within ±6 kb at 100 kb.

EXPERIMENTAL RESULTS

Two series of high-pressure runs yielded 34 diffraction patterns of the garnet and NaF. One series was made with a previously uncompressed boron annulus to achieve in situ diffraction patterns in the higher-pressure region (50–

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120 kb), and one series was made with a precompressed annulus so that patterns of the specimen could be obtained in the lower-pressure region (30–70 kb). From 19 of the patterns 3 garnet diffraction lines were measured (400, 420, 642), and from the remaining 15 patterns 4 or more lines were measured (400, 420, 642 and one or more of the following: 332, 611, 640, 842). From 12 of the patterns 2 NaF diffraction lines (200, 220) were measured, and from the remaining 22 patterns these 2 lines and an additional line (222) could be measured. The accuracy to which the compression (V_p/V_0) of garnet could be determined from each of the 34 patterns was $\sim\pm0.6\%$. (This percentage includes the accuracy to which the standard ambient garnet volume could be determined.) The accuracy to which the compression of NaF could be determined from each pattern was $\sim\pm0.4\%$.

The simultaneous volume compressions of pyrope and NaF observed here are listed in Table 2 with the pressures associated with the NaF compression [*Olinger and Jamieson,* 1970]. The compression data of pyrope are plotted in Figure 1; bars representative of the uncertainty of the data are shown for one data point. The curve shown in Figure 1 is the quadratic least-squares fit of the data with the V/V_0 pyrope as the dependent variable; the bars on the curve indicate the standard deviation. Compression data for four ferromagnesian garnets [*Takahashi and Liu,* 1970] found in the pressure region studied here are included in Figure 1.

DISCUSSION

The compression of ferromagnesian garnets has been studied by a different high-pressure in situ X-ray diffraction technique [*Takahashi and Liu,* 1970]. Their method involves passing a thin pencil of X rays through the high-pressure anvil axis instead of perpendicular to the axis as with the present technique. As can be seen from Figure 1, *Takahashi and Liu*'s [1970] compression data fall well within the standard deviation of the quadratic fit to the data. That fit is

$$V/V_0 = 1.002 - (5.72 \times 10^{-4}) \times P + (1.38 \times 10^{-6}) \times P^2 \pm 6.2 \times 10^{-3}$$

where P is measured kilobars.

TABLE 1. Chemical Analysis of Garnet Specimen

Compound	Wt %
SiO_2	41.4
Al_2O_3	22.4
MgO	18.2
FeO	9.1
CaO	4.8
TiO_2	2.1

Index of refraction is 1.73 (+).

The value calculated for the isothermal bulk modulus of pyrope from this least-squares fit is $K_0 = 1750$ kb. Because the scatter is large and few low-pressure (0–20 kb) data were collected, this modulus has a large uncertainty. But this value is in agreement with the results

TABLE 2. Compression of Pyrope Sample at 23°C

Film No.	V/V_0 Pyrope*	V/V_0 NaF†	Pressure,§ kb
587-1	1.007	0.998	1.0
587-3	0.991	0.989	5.0
587-4	0.999	0.984	8.0
587-5	0.982	0.935	37.5
587-6	0.977	0.925	44.5
587-7	0.983	0.899	65.0
587-8	0.969	0.868	94.5
587-9	0.958	0.871	91.5
587-12	0.988	0.937	36.0
587-13	1.003	1.005	-2.5
587-14	0.999	0.993	3.5
587-15	0.993	0.959	22.0
587-16	0.980	0.934	38.0
587-17	0.980	0.922	46.5
587-18	0.996	0.901	63.5
587-19	0.954	0.882	80.5
587-20	0.966	0.884	78.5
587-21	0.954	0.881	81.5
587-22	0.969	0.929	41.5
587-23	0.998	1.004	-2.0
588-1	1.000	1.000	0.0
588-2	0.979	0.895	68.5
588-3	0.970	0.888	75.0
588-4	0.960	0.881	81.5
588-5	0.952	0.861	102.0
588-6	0.962	0.848	116.0
588-7	0.958	0.852	111.5
588-9	0.947	0.854	109.0
588-10	0.964	0.863	99.5
588-11	0.960	0.872	90.0
588-12	0.961	0.873	89.0
588-13	0.960	0.879	83.5
588-14	0.998	0.954	25.0
588-15	1.002	1.000	0.0

*Standard deviation of V/V_0 pyrope is $\sim\pm0.006$.
†Standard deviation of V/V_0 NaF is $\sim\pm0.004$.
§The uncertainty of the pressure is $\sim\pm6$ kb at 100 kb. The conversion of $V/V_0 \cdot$NaF to pressure is from *Olinger and Jamieson* [1970].

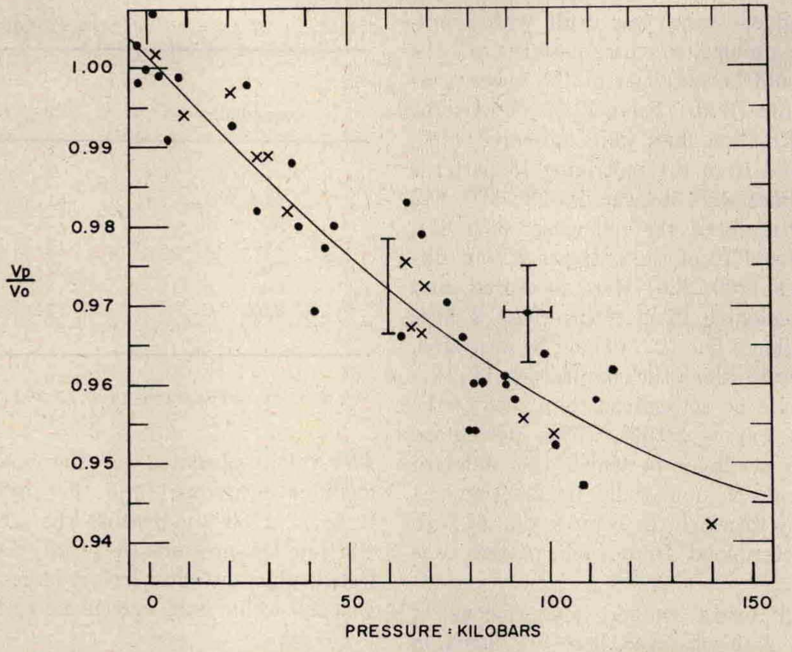

Fig. 1. Volume compression (V_p/V_0) data of Mg-rich garnet ($a = 11.554 \pm 0.009$A) found by using the present high-pressure in situ X-ray diffraction technique (dots). Volume compression data of various members of the ferromagnesian garnet series found by using a different high-pressure in situ X-ray diffraction technique [*Takahashi and Liu,* 1970] (crosses) and a quadratic least-squares fit to the present data are also shown. Representative uncertainty of the data is shown as bars on one data point. The standard deviation of the fit is shown as bars on the curve.

of *Takahashi and Liu* [1970], who report 1770 $\pm$ 60 kb for the bulk modulus of natural pyrope and values ranging from 1900 to 1700 kb for the entire ferromagnesian garnet series. These values were calculated from their data by using a Birch-Murnaghan least-squares fit and assuming $dK_0/dP = 5.45$ [*Soga,* 1967]. The scatter in the present data is larger than that of the *Takahashi and Liu* [1970] data because their X-ray beam, being thinner than the one used here, yields more highly defined diffraction patterns and their beam diffracts from a small volume in the high-pressure region whereas our beam diffracts from the whole sample. Our sample, although held totally in a high-pressure region, may have larger pressure gradients in the beam region than does the volume from which *Takahashi and Liu* [1970] diffract. Also in the present work many more data were collected in the pressure region under discussion than were collected by Takahashi and Liu. These data reveal effects observed by *Jamieson and Olinger* [1971] in a study of the simultaneous compressions of Nb and NaCl. Despite the excellent quality of the patterns in that study, plots of the simultaneous compressions showed that successive data 'wandered about.' Ambient patterns showed that the sample remained centered in the present study and in the study by Jamieson and Olinger.

Soga [1967] found by using the ultrasonic pulse-superposition method that the bulk modulus of natural almandite (Fe end member of the natural ferromagnesian garnet series) is 1757 kb. The results of the present compression study agree with this value since *Takahashi and Liu* [1970] showed that the difference in the bulk moduli of natural pyrope and almandite is only about 40 kb. Thus the results obtained here agree within the resolving power of the technique with the compressibility of Fe-Mg natural garnets determined by a different X-ray technique and inferred from elastic constant data.

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