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Chrome Pyrope: An Inclusion in Natural Diamond

Abstract. *Electron probe analyses of garnets that are rich in magnesium and that occur as inclusions in natural diamonds show that the chrome-garnet end member, $Mg_3Cr_2Si_3O_{12}$, is a major constituent (30 percent).*

The minerals that occur as inclusions in diamond are of interest because of the strong probability that they crystallized in the upper mantle. Natural diamonds have most probably crystallized within their stability field, and the high hydrostatic pressures required to form diamond can be sustained only within the mantle. This being so, inclusions in diamond are also samples of the mantle and can be expected to provide direct information on the mineralogy and geochemistry of the mantle. The inclusions might also provide information on the nucleation and growth of natural diamonds. Comparison of the chemistry of these inclusions with similar minerals in kimberlite and its associated ultramafic nodules should help in understanding the genesis of both groups.

The majority of mineral inclusions in diamonds are similar to minerals commonly found in ultramafic rocks—forsterite, enstatite, pyrope, diopside, and chrome spinel. Individual inclusions are invariably monomineralic, but occasionally several mineral species will occur as separate inclusions in one diamond; for example, olivine and garnet. The chemical compositions of several inclusions are demonstrably different from the normal kimberlite or nodule minerals, however. And a major difference is that the garnet inclusions contain up to 30 percent of the end member $Mg_3Cr_2Si_3O_{12}$, whereas the normal kimberlite garnets are considerably more aluminous.

The included garnets are generally claret colored; and, as their indices of refraction (1.759 to 1.781) and cell edges (11.535 to 11.698 Å) lie within the corresponding ranges for the pyrope-almandine-grossular series, mistaken identification can occur if standard methods are used without recourse to chemical analyses. Unfortunately, the inclusions average 50 μ in their longest dimension, and determination of their specific gravities is not feasible.

Chemical analyses (*1*) were made with a Materials Analysis Company model-400 electron probe on the inclusions after their removal from the host diamond (*2*). The inclusions were most reliably and easily removed by burning the diamond in air at 800°C for approximately 6 hours, a treatment which did not cause any apparent change in the appearance or composition of the garnet. Standards used in the analyses were predominantly glasses prepared by J. F. Schairer and by F. R. Boyd (*3*). The intensity ratios from the probe were reduced to chemical analyses with the use of computer programs written for the Univac 1108 in Fortran V (*4*). These programs correct the initial intensity ratios for drift, dead time, background, absorption, fluorescence, and atomic number effects.

Most of the figures for the analyses quoted in Table 1 are believed to be correct to better than ±2 percent of the amount of an element present. In the case of manganese, the CrKβ peak interfered with the background under the MnKα peak, and the consequent difficulty in estimating the true background resulted in errors up to 10 percent of the total amount of manganese. The ratio $\sigma/(\bar{N})^{1/2}$ (see Table 1) gives an indication of the homogeneity of the material being investigated—a number less than 3 shows no evidence of inhomogeneity. By this test the garnet inclusions show a remarkably high degree of homogeneity compared with many other minerals studied with the electron probe. Potassium is not reported in Table 1. Though present, it is minor, and analysis for potassium in garnet 1 showed a concentration of less than 100 parts per million. Since the electron probe can only determine total iron, the FeO contents were adjusted to give sufficient Fe_2O_3 to satisfy charge requirements. The percentages of oxides (by weight) in the analyses (Table 1) were first converted to corresponding number of cations on the basis of 12 oxygen ions. The ferrous ions were adjusted to give enough ferric ions to produce the correct garnet divalent to trivalent cation ration (that is, 3:2). The adjusted cation totals were then used to calculate the percentage of each end member in a unit formula of garnet in the order given (Table 1). Because of the small calcium content there is little difference whether the chromium is first assigned to uvarovite or to $Mg_3Cr_2Si_3O_{12}$.

These chrome-pyrope garnets are the most rich in magnesium yet found in nature (*5*). The name Hanléite was proposed by Sir Lewis Fermor (*6*) for a natural garnet approximating the composition $Mg_3Cr_2Si_3O_{12}$, which was reported by Mallet (*7*) to occur in association with chromite and serpentinite near

Table 1. Chrome-rich pyrope garnets. Diamonds from which garnets were obtained are probably from Africa, but the exact source is unknown. Inclusions 1 and 6 are from different diamonds; 15e and 15h are separate inclusions from the same diamond. Numbers in parentheses are the ratios $\sigma/(\bar{N})^{1/2}$, where σ is the standard deviation and $\bar{N}$ is the mean count.

	Chemical analyses of garnets in terms of percentages of constituent oxides (by weight)							
	1		6		15e		15h	
SiO_2	42.3	(3)	42.8	(2)	41.8	(3)	42.2	(2)
TiO_2	0.02	(1)	0.00		0.02	(1)	0.02	(2)
Al_2O_3	17.2	(1)	18.2	(2)	15.7	(2)	15.7	(2)
Cr_2O_3	8.93	(1)	7.9	(1)	10.9	(1)	10.7	(1)
FeO*	5.36	(1)	4.75	(2)	5.71	(1)	5.57	(1)
MgO	25.3	(1)	25.5	(2)	24.2	(1)	24.5	(1)
CaO	1.09	(1)	1.35	(1)	2.19	(1)	2.22	(2)
MnO	0.21	(1)	0.17	(1)	0.20	(1)	0.19	(1)
Total	100.41		100.67		100.72		101.10	
	Percentage of end members in unit formula†							
Spessartite	0.4		0.3		0.4		0.4	
Andradite‡	2.8		2.7		4.1		4.8	
Skiagite‡	1.1							
Uvarovite			0.7		1.4		0.8	
$Mg_3Cr_2Si_3O_{12}$	24.9		21.2		29.5		29.2	
Pyrope	63.9		67.7		56.2		57.0	
Almandine	6.9		7.4		8.4		7.8	

* Total Fe as FeO. † Calculated in order given (see text). ‡ Some FeO recalculated as Fe_2O_3 to satisfy charge requirements.

Hanlé monastery in Kashmir. However, this name has since been discredited (*8*). Other reported occurrences of possible $Mg_3Cr_2Si_3O_{12}$-bearing garnets are in kimberlites from Lesotho, Basutoland (*9*) and the České Středohoří Mountains, Czechoslovakia (*10*), and in xenoliths from kimberlite pipes (South Africa) (*11*). In these three instances, the garnets are from olivine-bearing ultramafic rocks, and the $Mg_3Cr_2Si_3O_{12}$ end member constitutes less than 9 percent of the total garnet composition. Bagrowski (*12*) reported finding a red chrome-rich pyrope in the Stockdale kimberlite pipe (Kansas). This analysis has since been discredited in that the Cr_2O_3 content was too high and it did not have the correct cation ratios (*13*). However, Brookins (*13*) does note the existence of a green garnet, which may be chrome-rich, in the Stockdale pipe.

Nixon and coauthors (*9*) and Fiala (*10*) have independently plotted refractive index against the Cr_2O_3 content for chrome-rich pyrope garnets. Both studies show a linear relation between the two variables, but the curves differ in slope. Further work is necessary to define more closely the physical properties of chrome-rich pyrope garnets.

The stability field for $Mg_3Cr_2Si_3O_{12}$ garnet is unknown, although Coes (*14*) has reported synthesizing it at high pressures and temperatures. The chrome-bearing uvarovite garnet ($Ca_3Cr_2Si_3O_{12}$) has been synthesized at 1 atm (*15*). It may be that $Mg_3Cr_2Si_3O_{12}$ garnet is unstable at low pressures and alters to more stable phases when the pressure is decreased. For example, by analogy with the aluminum-bearing reaction studied by MacGregor (*16*), the reaction

$$\underset{\text{forsterite}}{Mg_2SiO_4} + \underset{\text{garnet}}{Mg_3Cr_2Si_3O_{12}} \rightleftarrows \underset{\substack{\text{magnesiochromite}\\\text{(chrome spinel)}}}{MgCr_2O_4} + \underset{\text{enstatite}}{4MgSiO_3}$$

is possible, and it is interesting that all the minerals of this reaction occur as inclusions in diamond, although not necessarily in the same crystal (*17*).

The differences in chemical composition between the garnet inclusions from diamond and the garnet (usually pyrope almandines) from the ultrabasic nodules in kimberlite are curious and as yet unexplained (*18*). With regard to the chemistry of the mantle, it should be noted that, besides chrome pyrope and chrome spinel, chrome diopside (*19*) also is an inclusion in diamond. These facts suggest that chromium plays an important role in the phase chemistry of the mantle and must be considered when proposing petrologic models for the mantle.

HENRY O. A. MEYER
Geophysical Laboratory,
Carnegie Institution of Washington,
Washington, D.C. 20008

References and Notes

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Galactic X-rays: Variable Sources in Hydromagnetic Waves

Abstract. *Galactic sources of x-rays fluctuating in intensity are explained as being small regions, of enhanced gas density and temperature, emitting thermal Coulomb bremsstrahlung of kiloelectron-volt energies. Hydromagnetic wave motions, of the magnetic fields in the galactic spiral arms, produce the enhanced regions by compressing the clouds of ionized gas to which they are tied by their high electrical conductivity. From the observed periods of fluctuation of a few months, together with the hydromagnetic velocity, it is estimated that the average size of sources does not exceed 10^{16} centimeters. By using the formula for Coulomb bremsstrahlung and requiring that the sources shall produce the observed x-ray fluxes, one finds a second estimate of size of sources in agreement at about 10^{16} centimeters. Such regions are too small to be observable radio sources with current radio telescopes.*

Good evidence is accumulating from balloon and rocket experiments that Cygnus X-1 is an x-ray source of variable intensity; for x-rays of from 1 to 100 kev its intensity varies by factors of from 2 to 6 within periods as brief as 18 months, and both decreases (*1*) and increases (*2*). Similar but less well-substantiated fluctuations of the Crab nebula are deduced (*3*), at energies above 20 kev, from balloon experiments; the fluctuations may be by factors of from 2 to 5 within as little as 1 month. Likewise Centaurus XR-2 is reported (*3*) to have decreased and perhaps to have increased its intensity. Some 20 galactic sources (*4*) of x-rays have been reported since the first discovery in 1963. Because so many have been discovered by a few rocket and balloon experiments searching a small fraction of the sky, many more sources probably will be found.

We now propose an explanation of these variable sources, of the near-equality of their x-ray intensity (the known sources have intensities comparable within a factor of about 20), of their small sizes, and of their ability to both increase and decrease in intensity within brief periods. We predict that they will be found in abundance in the galactic arms.

We propose that the plasma producing the x-rays is the ionized gas of the galactic arms themselves, with average particle density of about $1/cm^3$ and average magnetic field about 6×10^{-6} gauss at about 300°K (*5*), but with a distribution of lower and higher densities and magnetic fields, in regions of various dimensions.

Such enhancements probably are caused by sinusoidal motions of the magnetic lines of force, accompanied by compression and rarefaction of the gas masses in the spiral arms, these having a sufficiently high electrical conductivity to be attached to the magnetic lines of force (*5*). Oscillations of hydromagnetic waves traveling in the gas clouds create regions having fluctuating increases and decreases in gas pressure, in magnetic fields, and in their own