
GEM GARNETS IN THE RED-TO-VIOLET COLOR RANGE

By D. Vincent Manson and Carol M. Stockton

The gemological classification of garnets has been thrown into question with the appearance on the market of new types of garnets that do not fit into the traditional system of description. The question of what criteria should be used to classify both old and new types of garnets is approached in this article through the study of 96 red-to-violet gem garnets. While the color of gem garnets is of paramount importance, color being both their most obvious feature as well as their principal claim to beauty, this article shows that the characteristic of color appears to have little correlation with variations in bulk (not trace) composition or physical properties. Analysis of the gemological properties, chemical composition, and CIE color coordinates of the stones studied led to the more specific definition of the widely accepted terms pyrope, almandine, and rhodolite for meaningful gemological classification. This article represents the first in a series of studies aimed at developing an effective terminology for the characterization of gem garnets.

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The garnet group of minerals encompasses both complex variations in chemical composition and a wide range of physical and optical properties among its members. As a result, the garnets have been subjected to various classification schemes by mineralogists and gemologists over the years. While the mineralogist usually has the instrumentation available to perform detailed chemical analyses, the gemologist is limited, for practical purposes, to a few basic tests that measure optical and physical properties of gemstones and that may or may not accurately reflect the bulk chemical composition of a complex material such as garnet. An effective gemological classification is one that enables the gemologist to employ readily available tests to reflect the differences in appearance and the chemical interrelationships that exist in a group such as garnets. For this reason, we have undertaken a review of all the gem garnets, with special attention to the needs and restrictions of the gemologist, in order to provide a viable gemological classification of this group. As the first in a series, this article looks particularly at garnets in the general hue range of red to violet (excluding those stones that are obviously orangish red), including for the most part those gem specimens whose chemical compositions consist primarily of combinations of pyrope and almandine (see figure 1). We selected this fairly familiar area in order to show that even the well-documented types of garnets still have problems that need to be addressed. In addition, this gives us an opportunity to introduce the methods of analysis that will be used throughout our ongoing study of garnets.

A representative example of a mineralogical classification of garnets is the hierarchical terminology given in Deer, Howie, and Zussman (1963), which includes group (garnet), series (pyrope and ugrandite), and species (pyrope, almandine, etc.). Many of these terms, such as *pyrope*, are still in use even though more recent de-

Figure 1. Examples of garnets in the red-to-violet color range used in this study.



scriptions of the compositions of garnets (Meagher, 1980) have contradicted the premises on which the terms were originally based (Winchell and Winchell, 1933). In agreement with most of the relevant literature, however, Deer, Howie, and Zussman list six species as being of major importance: pyrope, almandine, spessartine, uvarovite, grossular, and andradite. Another classification refers to these same terms as subspecies of the group garnet (Hurlbut and Switzer, 1979). To some extent, this may be due to a difference in interpretation by mineralogists of the meaning of the term *species* with regard to the members of a mineral group. Some equate species with a chemically pure end member (discussed later in this article), while for others it refers to a range of chemical variations. Hurlbut and Switzer, in fact, mention that the subspecies names are applied more loosely and cite an example in which "for convenience, gems near the end of the almandine-pyrope solid solution series are called almandine," but nowhere could we find that such a stone is specifically referred to as a member of the species almandine. Because of the influence of color on the appreciation of gemstones, an additional vital requirement of a complete gemological classification goes beyond the identification of species or bulk chemical composition to the definition of varieties. An excellent example is the invaluable distinction of ruby from pink sapphire, let alone from other corundums; all are of the same species and bulk chemical composition, but the types and quantities of trace elements present make a difference in color. Garnets do have an assortment of varietal names such as rhodolite, hessonite, and the like, but these are not rigorously defined and so lead to further confusion.

Garnets of the red-to-violet color range gen-

erally associated with the pyrope-almandine series reflect the problems associated with gem garnets in general. The importance of color in gems has led to the association by gemologists of very particular colors with the various types of garnets: any deep, pure red garnet is usually regarded as pyrope, any violetish-red garnet has been automatically assumed to be rhodolite, and so on. Such assumptions are not necessarily valid. What is a pyrope, an almandine, a rhodolite? What criteria enable us to delimit the ranges of their properties? How well do the commonly employed gemological tests (refractive index, specific gravity, and absorption spectrum) enable us to define and identify species and varieties? To what extent is the chemical composition of a garnet relevant to the gemologist? Are there natural breaks in the chemical continuum that we might use to advantage in defining these gem garnet species and varieties? What do we do with garnets that do not fit the currently defined categories? To what extent do we need definable nomenclature and how rigorous should the classifications be? How should color enter into these definitions?

THE GEMOLOGICAL PROPERTIES OF THE PYROPE-ALMANDINE SERIES

According to traditional gemological usage, this series includes three loosely defined types of garnets: pyrope, almandine, and rhodolite. Pyrope has been characterized as a dark to very dark pure red magnesium-aluminum garnet with a refractive index of approximately 1.74, a specific gravity of about 3.78, and no characteristic spectrum; almandine is described as a medium to very dark brownish-red iron-aluminum garnet with a refractive index around 1.79, a specific gravity of about 4.05, and a characteristic spectrum with

bands at 4360, 4700, 5050, 5270, 5760, and 6180 Å. Rhodolite lies between pyrope and almandine and has been less well characterized. The original description by Hidden and Pratt (1898) of rhodolite from North Carolina states that "the predominant color is a pale rosy tint inclining to purple . . ." and that "the ratio of MgO to FeO is almost exactly 2:1. . . ." The refractive index and specific gravity are, respectively, about 1.76 and 3.84, but their upper and lower limits are in question. The spectrum is essentially the same as that for almandine. It should be noted that there are other pyrope-almandine garnets in the same range of chemical, optical, and physical properties as rhodolite, but they do not fit the color description for this type of garnet.

THE CHEMISTRY OF GARNETS

A garnet can be composed of four or more chemical elements, represented by the formula $X_3Y_2Z_3O_{12}$, where X, Y, and Z each signifies one or more elements. X may include one or more of the elements calcium (Ca), manganese (Mn), magnesium (Mg), or iron (Fe); Y may be aluminum (Al), iron, titanium (Ti), vanadium (V), and/or chromium (Cr); and Z may be silicon (Si), iron, titanium, and/or aluminum. Those types of garnets that contain only the minimum four elements (i.e., one element for each of X, Y, and Z, plus oxygen) are referred to as "end members."

Theoretically, then, there is a possible total of 60 end members, involving the above-mentioned elements, for the garnet group. Some of these, however, may not exist for chemical or geologic reasons that we will not go into here. Others are so rare as to be insignificant to the gemologist. In this study, nine are examined, of which only five are abundant among gem garnets (table 1). Individual garnets are composed of two or more of these end members; stones that consist of one end member only are exceedingly rare in nature, although occasional specimens do exist in which a single end member is responsible for more than 95% of the composition.

There are two essential reasons for using the concept of end members to discuss the composition of individual garnets. First, it provides a practical procedure for correlating the relationships between physical properties and chemical composition. Second, it enables us to relate results obtained in this study with similar chemical analyses that have been published previously. Our

calculation of end members is based on the method formulated by Rickwood (1968), but we have changed the sequence of calculation slightly to better account for the nature of gem garnets, in particular by using as much of the Ti and the Fe^{3+} as possible. The macroanalytical techniques used for most of the analyses in Rickwood's article, principally wet chemical analysis, together with the fact that the non-gem garnets generally employed in prior studies were usually more included than the gem-quality garnets used here, required allowance for the presence of rutile, magnetite, and ilmenite as impurities. Such inclusions did not need to be considered in the chemical analysis of the gem-quality, relatively inclusion-free garnets used here, especially insofar as microprobe analysis permits selection of a microscopic inclusion-free area for testing (Dunn, 1977). In addition, we have calculated uvarovite before knorringite, in accordance with more recent findings by Sobolev et al. (1973) with regard to the existence of a pyrope-uvarovite series. In some of the calculations, Si, Al, and Fe^{2+} are present in excess of the amounts needed to satisfy the garnet formula. If there is any significance to the presence of these residuals beyond that of simple analytical error, it would not be surprising, since the geological environment and the processes involved in the formation of garnets suggest that these would be the most likely impurities present. Our scheme is further supported by the high percentage of cations accounted for by end members in the 96 stones studied: always over 97% and usually over 99% (see figure 2).

TABLE 1. Garnet end members.

Chemical formula	Name	Reference
$Ca_3Ti_2Fe_3^{3+}O_{12}$	Schorlomite	Ito and Frondel, 1967
$Ca_3Fe_2^{3+}Si_3O_{12}$	Andradite	Deer et al., 1962
$Mn_3V_2Si_3O_{12}$	(Yamatoite) ^a	Fleischer, 1965
$Ca_3Cr_2Si_3O_{12}$	Uvarovite	Deer et al., 1962
$Mg_3Cr_2Si_3O_{12}$	Knorringite	Nixon and Hornung, 1968
$Mg_3Al_2Si_3O_{12}$	Pyrope	Deer et al., 1962
$Mn_3Al_2Si_3O_{12}$	Spessartine	Deer et al., 1962
$Ca_3Al_2Si_3O_{12}$	Grossular	Deer et al., 1962
$Fe_3^{3+}Al_2Si_3O_{12}$	Almandine	Deer et al., 1962

^aThe vanadium analog of spessartine.

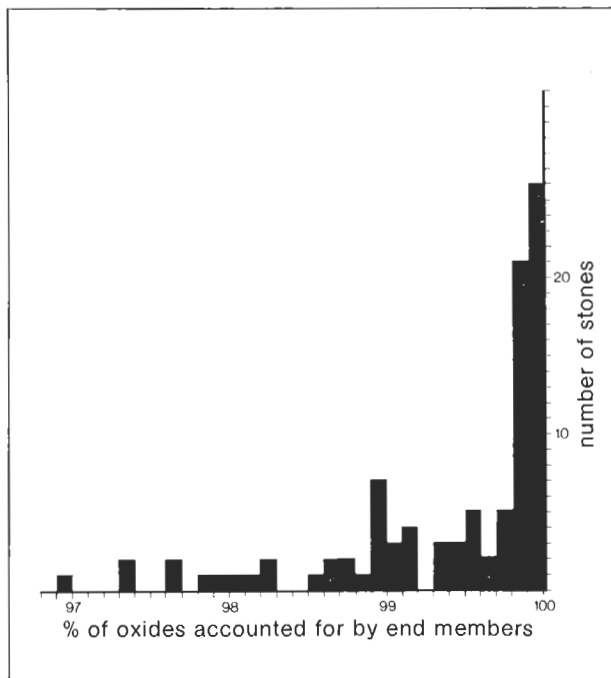


Figure 2. Histogram illustrating the percentages of oxides in the 96 garnets that are accounted for by nine end members.

It is important to remember that the garnet end member is merely a convenient theoretical concept for discussing the chemical make-up of this gem group. Garnets, even as end members, do not consist of discrete molecular units; the atoms of a garnet are combined in a continuous, three-dimensional framework (figure 3).

End members, then, were calculated for this study in the sequence shown in table 1, beginning with schorlomite. The calculation required two basic steps. Because the microprobe cannot determine to what oxidation state or states an element belongs, and because certain elements can occur in more than one oxidation state in garnet, one must first calculate the distribution of Al to the Y and Z sites, Fe to the X, Y, and Z sites, and Ti to the Y and Z sites according to the requirements of garnet stoichiometry. Any Al, Ti, and Fe allotted to the Z site are added to SiO_2 and treated as such in the absence of evidence to support preference for them by any particular end members. From the resulting oxide proportions, end members are then derived on the basis of stoichiometry. Inasmuch as Rickwood has discussed this procedure in depth, we need not go into it any further.

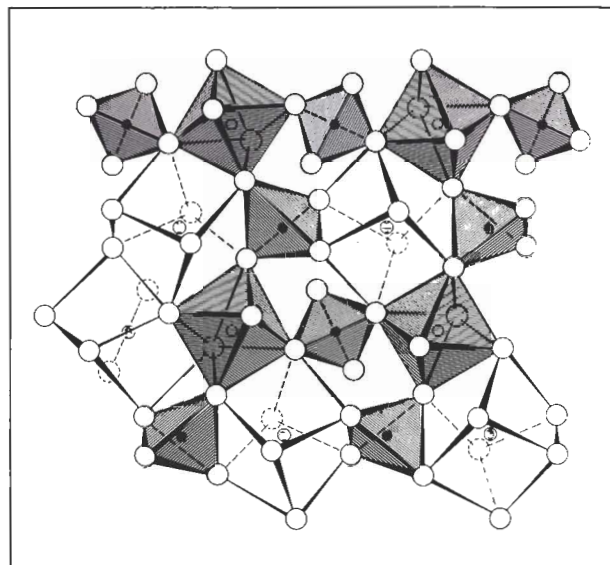


Figure 3. A portion of the garnet crystal structure. The large open circles represent oxygens, the smaller ones the Y cations, the solid circles the Z cations, and the hatched ones the X cations. (From Novak and Gibbs, 1971).

DATA COLLECTION

We selected specimen stones for the study on the basis of color, the most obvious criterion and, consciously or unconsciously, the test undoubtedly used most by gemologists in identifying variety. Thus, all the stones in the study are predominantly red to violet, but they vary widely in brightness and saturation of color.

The data collected for each stone are of three types: physical and optical (specific gravity and refractive index), spectral (11 absorption bands and two color coordinates), and chemical (nine end members), totalling 24 variables for 96 garnets.

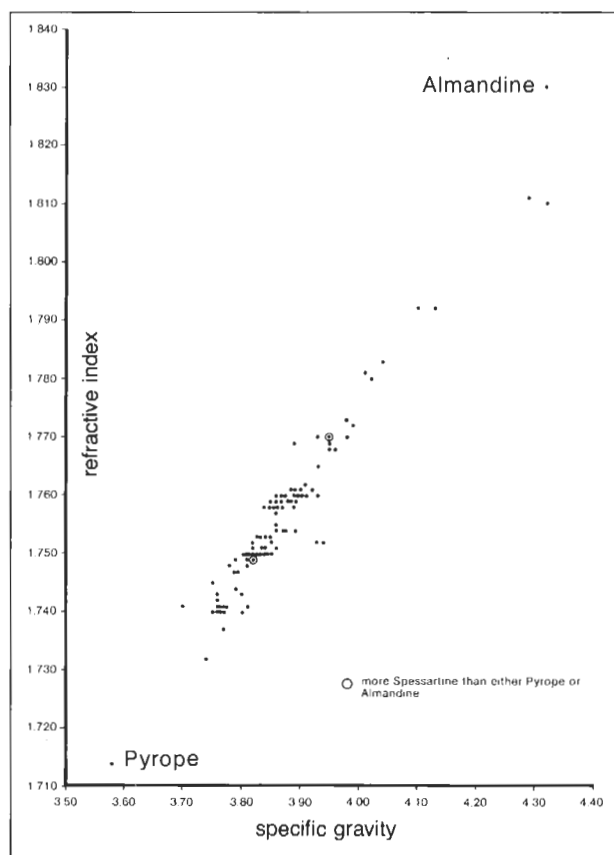
The instruments used in data collection included a GEM Duplex II refractometer and, for stones with refractive indices over 1.790, a prototype Duplex II with cubic zirconia hemisphere (Hurlbut, 1981). Specific gravities were obtained by means of the hydrostatic method with a self-taring balance. Spectra were obtained by two methods: (1) visually using a hand spectroscope, and (2) by the use of an automatic recording spectrophotometer (Hofer and Manson, 1981), which graphically displays the spectra and stores them on a magnetic disc. Color measurement was obtained using a GEM ColorMaster, and the readings were then converted to CIE (Commission Internationale de l'Eclairage) coordinates via a

computer program developed by one of the authors. Garnet compositions were determined on the MAC microprobe at the California Institute of Technology using the Ultimate correction program (Chodos et al., 1973). In addition, unit-cell measurements were obtained for selected specimens by the powder diffraction method with a Philips Debye-Scherrer camera.

DISCUSSION OF DATA

Physical and Optical Data. A plot of the refractive indices versus the specific gravities for these 96 stones (figure 4) shows a more or less continuous linear relationship extending from the coordinates for the end member pyrope to those for the end member almandine. Departures from this line are probably due to the effects of end member components other than pyrope and almandine in the individual garnet specimens, as well as to a certain amount of measurement error.

Figure 4. Refractive index plotted against specific gravity for the 96 garnets studied. Points for the ideal end members pyrope and almandine are also shown.



Unit-cell measurements were determined for about half the garnets in the study. A brief examination of their relationships with the other properties we measured revealed more complex interrelationships than we felt could be dealt with in this article alone, and so they will be discussed separately in a later article that will also include similar data for other types of garnets.

Spectral Data. The spectra obtained with the recording spectrophotometer showed 11 consistent bands (figure 5), which we refer to as A through I, I_1 , and I_2 (centered approximately at wavelengths of 4270, 4380, 4610, 4730, 5035, 5230, 5710, 6090, 6920 and, within the last broad band, 6750 and 6870 Å). We devised a simplified approach to expressing the relative strengths of these bands in which we rated each band according to the spectrophotometer graphs on a scale of zero (not visible) to five (very strong). There appears to be a relationship between the darkness of a stone and the number of bands visible, as might be expected based on the ability to transmit light: the darker the stone, the fewer bands visible, especially in the shorter wavelengths. With few exceptions, bands E through I were always visible

Figure 5. Representative spectral curves showing the absorption bands as observed in the 96 garnets with the spectrophotometer. Approximate wavelength equivalents are: A = 4270, B = 4380, C = 4610, D = 4730, E = 5035, F = 5230, G = 5710, H = 6090, I = 6920 and, within the last broad band, I_1 = 6750 and I_2 = 6870 Å.

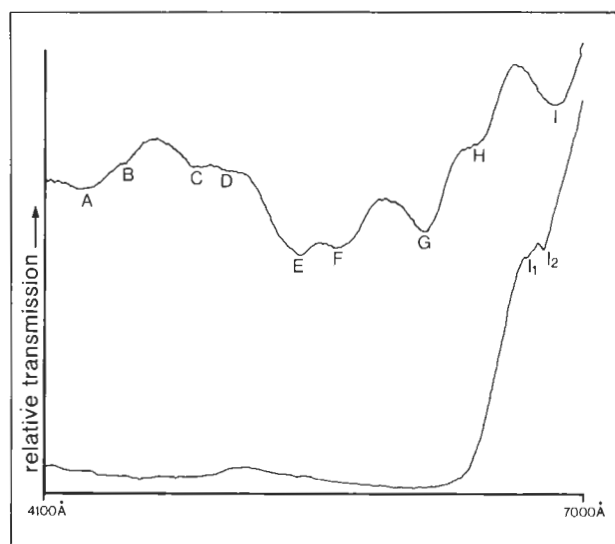
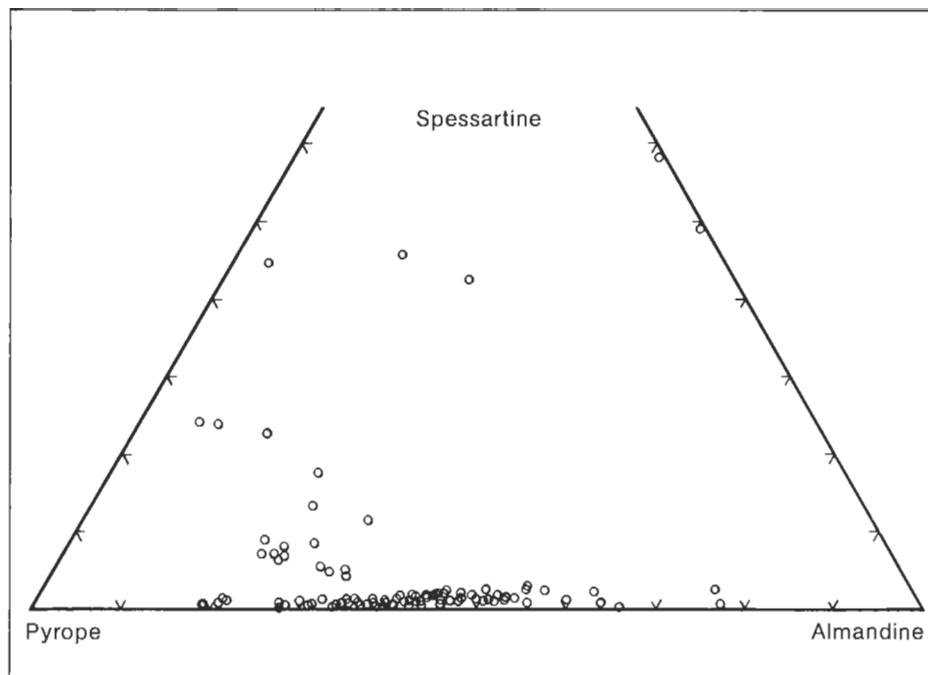


Figure 6. Points for the 96 garnets plotted on the pyrope versus almandine versus spessartine ternary diagram.



with the spectrophotometer; bands E through G could always be seen with the hand spectroscope as well. Bands B and D always appeared to be very weak, even with the more sensitive spectrophotometer. The former never appeared in the hand spectroscope, and the latter was seen only rarely, even though the spectrophotometer indicated that one or both bands were present.

A distinctly different curve was visible with both the spectrophotometer and the spectroscope for four very dark red stones. All four clearly showed the I_1 and I_2 bands, in three cases to the exclusion of all other absorption bands while the fourth did exhibit a very faint E band.

Chemical Composition. The interrelationships among end members can be portrayed, three end members at a time, by means of ternary diagrams. (An explanation of ternary diagrams is provided in the Appendix.) We plotted diagrams for various combinations of the five major end members and selected two that best exhibited the general patterns that appeared (the first illustrated in figures 6 and 7, the second in figure 8). The first ternary involves pyrope, almandine, and spessartine, as these three end members together comprise the largest portion of the composition of most of the garnets in the study. The second ternary was selected from a number of other diagrams illustrating various combinations of end members because it showed the most distinctive pattern. The end

members included are pyrope (on an average, the single most abundant end member), spessartine, and the sum of grossular and andradite.

Figure 6 (pyrope, almandine, and spessartine) displays a distinct trend among those garnets that contain 34% to 72% * pyrope, 28% to 66% almandine, and 0% to 4% spessartine. The trend illustrates a tendency for spessartine to increase slightly as the amount of almandine increases, probably because Mn easily substitutes for Fe^{2+} due to their similarity in atomic size and structure. It is this group that contains the greatest number of garnets in the study. Two garnets, both containing approximately 78% almandine and 22% pyrope, also may belong to this group, but they are notably higher in almandine content than the main group. Also in line with the principal trend are four garnets that are considerably higher in pyrope (around 80%) but that, in terms of oxide percentages, exhibit 1.7% to 2.0% Cr_2O_3 which translates to about 6.0% uvarovite. These are the same garnets previously noted as showing only the I_1 and I_2 absorption bands; this apparently reflects the large quantities of chromium they contain, since these stones are also the only

*These values as well as the other percentages in this paragraph refer to the amounts recalculated for plotting of the end members on the ternary diagram in figure 6.

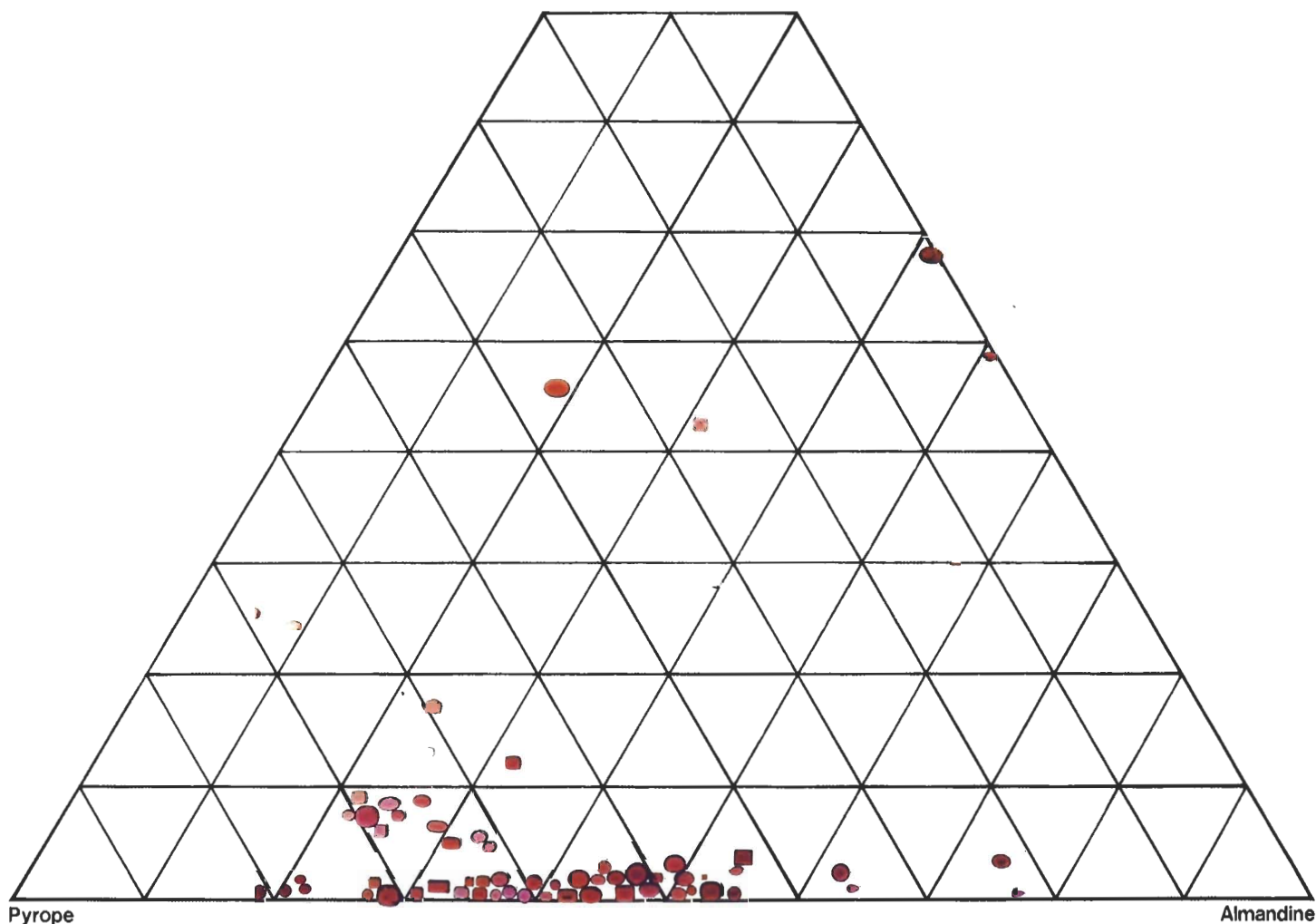


Figure 7. Pyrope versus almandine versus spessartine ternary diagram with garnets placed on their respective coordinates. It is obvious that color is not a function of chemistry with regard to these three end members.

garnets in the study that contain more than 1.0% of this oxide.

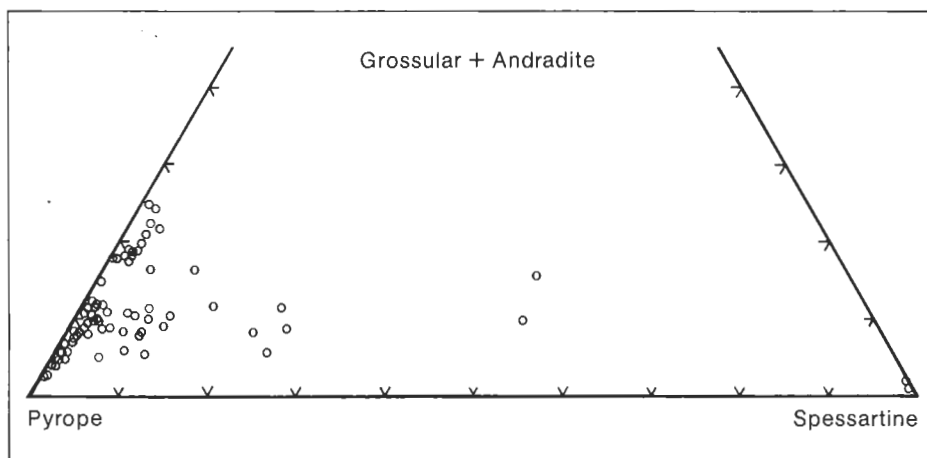
Another group of 11 garnets may be distinguished by the greater amounts of spessartine present, from 4% to 10%. Two other stones continue this trend toward even higher spessartine content. They are composed of (respectively): pyrope, 62% and 55.5%; almandine, 25% and 32%; and spessartine, 13% and 12.5%. In addition, seven garnets that each contain more than 17% spessartine do not belong to any group identifiable in this study. However, the colors of these stones and, in most cases, their readily observable physical and optical properties might otherwise place them among the group of gemstones traditionally recognized by gemologists as the pyrope-almandine garnets. Figure 7 displays 63 of the 96

stones in the study, a representative sample of the colors of these garnets, placed table down on the pyrope-almandine-spessartine ternary in their respective positions and photographed to illustrate the distribution of color. This dramatically shows the apparently random variation in hue associated with these major chemical components of the red-to-violet garnets.

The most obvious feature of the second ternary (figure 8: pyrope, spessartine, and grossular + andradite) is that the stones that fall along the line between pyrope and grossular + andradite clearly fall into two groups: (1) 2% to 12% ** gros-

**Values expressed in this paragraph refer to amounts recalculated for plotting in figure 8.

Figure 8. The 96 garnets plotted on the pyrope versus spessartine versus grossular + andradite ternary diagram.



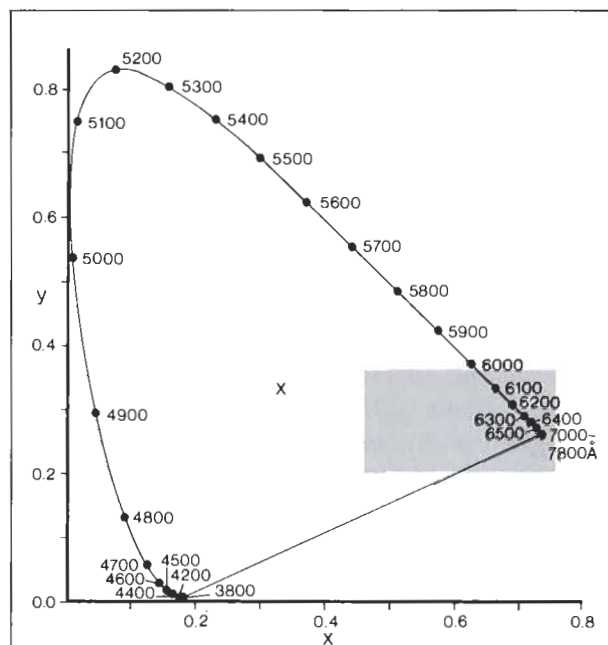
sular + andradite, and 86% to 98% pyrope; and (2) 17% to 25% grossular + andradite, and 74% to 82% pyrope. Stones in both groups have roughly less than 4% spessartine. One stone that has 15% grossular + andradite lies between the two groups and suggests that the gap may simply be due to sampling bias. On this diagram, the higher-spessartine-content stones appear to have about 4.5% to 25% spessartine. Two of these contain more than 15% grossular + andradite, as in the second group mentioned above, while the rest have less than 12% grossular + andradite, as in the first group above. However, there are not enough stones in this region to draw any conclusions about the significance of such a split among the higher-spessartine-content stones. There are two stones with a still higher spessartine content of about 49.5% and 51% and with, respectively, 35% and 39.5% pyrope and 15.5% and 9.5% grossular + andradite. The two stones containing no pyrope appear here as containing 98% and 99% spessartine since almandine has been excluded.

Color. The color of each garnet in the study was described in terms of GEM ColorMaster notations that were then converted to the CIE system of color measurement, so called after the Commission Internationale de l'Eclairage, an international committee devoted to the study of the behavior of light and color. CIE is supported by many organizations and is the most widely recognized authority in the field, attempting to consolidate the immense quantity of research done in the area of light and color into standardized and internationally acceptable systems of description.

While the CIE system is described fully elsewhere (Wright, 1969), as well as with particular reference to gemology and the GEM ColorMaster

(Manson, in preparation), a brief explanation of the chromaticity diagram integral to this system is warranted here. A set of coordinates was developed to express the relationship among all colors from the most saturated hues to white light (or neutral gray) on the basis of a "standard observer's" response to various color stimuli (the average of observations of a large number of people). The chromatic portions of these measurements were plotted on an x-y coordinate graph to produce the chromaticity diagram (figure 9), standardized in 1931. This diagram consists of a

Figure 9. The CIE chromaticity diagram, with points for white light (X) and selected wavelengths. The shaded area indicates the portion of the diagram reproduced in figure 10.



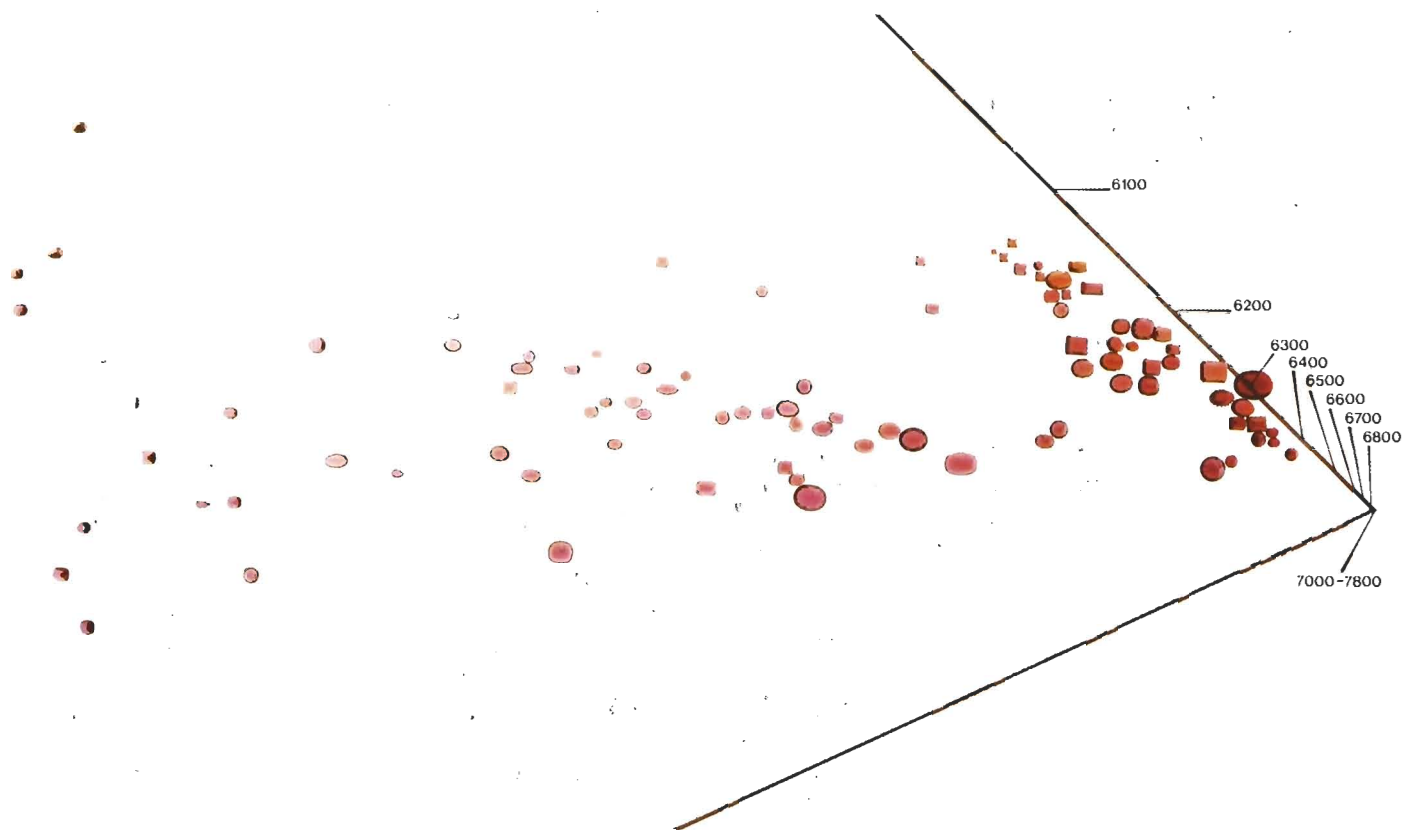


Figure 10. The red-to-violet region of the CIE chromaticity diagram with the 96 garnets positioned according to their x-y coordinates. Hues range from violet at the lower left, through red at the lower right, into orangish red at the upper right. Pale colors appear in the upper left, near the coordinates for white light.

skewed parabolic curve along which lie the saturated hues and in the approximate center of which is the location of the white light coordinates.

Thus, any hue and saturation can be represented by a set of x-y coordinates and plotted as a point along or within the chromaticity curve—going from violet and blue at the extreme lower left, through green at the top of the curve, to red at the extreme lower right. In the region defined by the straight line that connects the two ends of the curve lie the nonspectral hues, from violet through purple to red. Spectrophotometric measurements have enabled us to correlate the coordinates of the saturated hues with their respective dominant wavelengths, as shown in the diagram in figure 9. Along any radial line drawn between white light and a saturated hue lie colors of increasing saturation as one approaches the curve, but that are of the same hue and dominant wavelength. For example, on such a line between white light and the coordinate point for red at 7000 Å,

the color near white light would be pale pink, increasing to deep red as the line approached the chromaticity curve, but any point along the line would have the dominant wavelength 7000 Å.

Color notations for the garnet specimens were obtained with a GEM ColorMaster and were then converted mathematically to x and y CIE coordinates. The color notations used represent averages of readings obtained on the ColorMaster by three trained observers. The ColorMaster proved to be extremely useful as a simple and efficient means of obtaining measurements that could be converted to CIE coordinates, of which there is only one set for any given color. Once converted, the CIE coordinates were plotted on a chromaticity diagram (figure 10), as well as employed in the factor analysis described later in this article.

DISCUSSION OF ERROR

While we feel confident that the results obtained in this study are significant, we must also point out that no scientific research is without uncer-

tainties. Sources of error do exist in the operation, function, and mathematics of microprobe analysis; in the possible chemical inhomogeneity of some of the stones tested; in the coating and mounting of gem specimens for chemical analysis; and in simple human error in measuring the physical and optical properties. However, we feel that the error factors in this study are minor and do not significantly affect our conclusions.

As a measure of the error associated with the microprobe, we examined the extent to which sample compositions expressed by microprobe chemical analyses deviate from the actual composition of a given stone. This variability is caused by slight irregularities in operating conditions such as the preparation of the specimen, the position of the specimen relative to the electron beam, electronic fluctuations in the microprobe, mathematical and statistical error in the interpretation of microprobe data, and the like. A sample of the McGetchin standard garnet (McGetchin, 1968) at the California Institute of Technology was analyzed at intervals over the same span of time that the 96 garnet specimen analyses were performed for this study, and 27 control analyses with total weight percentages between 99% and 101% were obtained. To provide an idea of the amount of error that could exist in our microprobe analyses, we compared the various results for the control garnet, which produced the averages and standard deviations from the original weight percentages shown in table 2.

Deviation from the average varies from case to case depending on the amount of any given oxide present in a specimen; the greater the amount of an oxide present, the smaller the relative variability due to the greater sensitivity of

the microprobe as the amount of any element present increases.

STATISTICAL ANALYSIS

The final analytical method used was a mathematical procedure known as factor analysis (explained in Manson, 1967). This is a sophisticated method of data reduction designed to look simultaneously at the interrelationships among large numbers of variables measured on many samples. The nature of physical space limits us graphically to three or, by means of models, four dimensions in dealing with variables. Factor analysis, especially with the aid of a computer, enables us to handle as many dimensions at once as we wish, in this case 24. However, routinely describing any given garnet by 24 properties would be entirely too cumbersome and might involve some variables that were completely or partly redundant. For example, if refractive index and specific gravity were so perfectly correlated that knowing one would allow you to exactly predict the other, then there would be no need to obtain both of these properties in testing for the identity of a stone. Essentially, the factor analysis checks for such correlations, though the relationships are usually more subtle than in the above example.

This procedure provides us with a set of new variables, or "factors," that are composites of the relevant original data variables. The factor analysis tells us how much of the variability among the specimens can be accounted for by each factor and rates the factors accordingly. Thus, the first five factors might account for 85% of this variability, the first eight for 90%, the first 10 for 92%, and so on. It is up to the investigator at this point to decide what amount of variability adequately describes the situation at hand, extract the minimum number of factors that provide this optimum amount of information about the samples, and then interpret the factors in terms of the original variables.

In this case, the factor analysis provided us with seven factors, as described below, which account for more than 90% of the overall variability in the garnets examined. The original 24 variables are represented by, or "load" onto, the factors as shown in table 3, in which the factors are arranged from the most variability accounted for (factor 1) to the least (factor 7). The factor analysis also describes the percentage of variability in each stone as accounted for by each individual factor.

TABLE 2. Measurement of error.

Oxide	Average weight %	Range	Standard deviation
SiO ₂	41.93	40.73-42.80	0.54
TiO ₂	0.16	0.10- 0.20	0.03
Al ₂ O ₃	22.41	21.67-22.92	0.34
V ₂ O ₃	0.03	0- 0.09	0.03
Cr ₂ O ₃	1.37	1.28- 1.45	0.04
MgO	20.00	19.49-20.39	0.26
CaO	4.58	4.42- 4.77	0.18
MnO	0.37	0.27- 0.44	0.05
FeO	9.18	8.56-10.23	0.32

Factors 1 and 2 generally describe the collection of 97 garnets as a whole, that is, by the end members pyrope and almandine and, to a lesser extent, by andradite and grossular. Factor 3 accounts for stones that are high in uvarovite content. The fourth factor represents garnets that contain yamatoite, which correlates positively with pyrope and negatively with almandine. (It must be noted, however, that the quantities of yamatoite on which this correlation is based are very small, less than 0.85%.) Similarly, schorlomite forms the basis for factor 5, correlating with grossular. Factor 6 represents spessartine, which correlates negatively with andradite and pyrope; the negative correlation with pyrope was already evident in the trend seen in figure 6. The final factor correlates knorringite positively with andradite and negatively with grossular, but again it

must be kept in mind that the knorringite only occurs in small quantities.

Table 3 also illustrates how the physical, optical, and spectral properties relate to the various end members. However, caution must be used in interpreting these relationships, since differing scales of measurement that were used have varying effects on the mathematics of factor analysis. Generally, the patterns that emerged from this statistical analysis confirm the ideas we had formed along the course of the project, but subtle interrelationships also appeared that might prove more important as further detailed investigation is conducted in the future.

Because of the strong relationship indicated by the factor analysis between refractive index, specific gravity, and the pyrope and almandine constituents of the red-to-violet garnets, we reexamined the graph of refractive index versus specific gravity (figure 4) and at the same time distinguished between high pyrope content, high almandine content, and approximately equal content of pyrope and almandine for each stone in the study (figure 11). It can be seen that, for the most part, a refractive index of less than 1.752 in conjunction with a specific gravity of less than 3.86 represents garnets that contain more pyrope than almandine. A refractive index of more than 1.779 with a specific gravity over 4.00 indicates garnets that have more almandine than pyrope. Approximately equal portions of pyrope and almandine (1.5:1 to 1:1.5) yield a range of refractive index over 1.751 and up to 1.774, with a range of specific gravity of more than 3.81 and up to 3.99. There is a continuation from the range of the high pyrope properties to that of properties for the stones having approximately a 1:1 ratio of pyrope to almandine; in fact, a small area of overlap can be seen in figure 11. Other exceptions to the ranges described with respect to composition are also visible in figure 11. Three high-pyrope stones lie well within the range for those stones usually having a 1:1 ratio of pyrope to almandine, and another stone with a 1:1 ratio lies within the range for high-pyrope garnets. Two of these stones contain more spessartine than either pyrope or almandine, which might explain this anomaly, but the other two garnets are definitely members of the pyrope-almandine series that contain more pyrope than almandine. Thus far we have been unable to determine what causes their properties to be so high.

TABLE 3. Factor loadings.

Variables	Factors						
	1	2	3	4	5	6	7
<i>End Member</i>							
Almandine	+++			--			
Pyrope	+++	+	+	++	+	--	
Spessartine						+++	
Grossular	++	-			++	+	--
Andradite	++	-		+	-	--	++
Schorlomite					+++		
Uvarovite			+++				
Knorringite							+++
Yamatoite				+++			
<i>Physical Properties</i>							
R.I.	+++						
S.G.	++			---			-
Color	+++						
<i>Spectral Bands</i>							
A		+++					
B	-	+++		--	++		
C		+++				+	
D		+++				--	-
E	+	+++		++	-		
F	+	+++		++	-		
G	++	++		++	-		
H	++	+++			--		
I	+++	+			--		
I ₁			+++				
I ₂			+++				
+++ strong positive correlation ++ moderate positive correlation + weak positive correlation --- strong negative correlation -- moderate negative correlation - weak negative correlation							

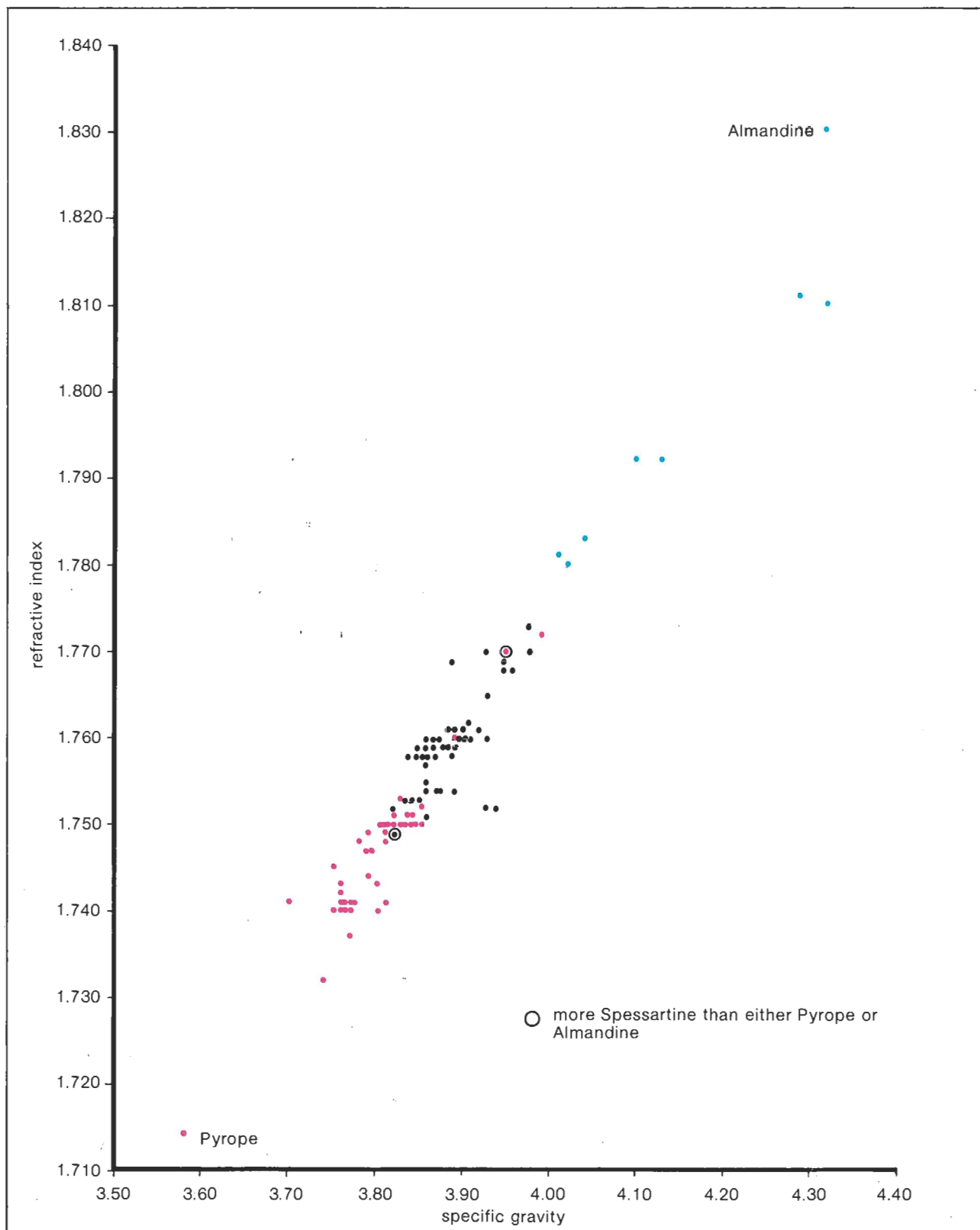


Figure 11. The graph of refractive index versus specific gravity, color coded to indicate the ratio of pyrope to almandine for each of the 96 garnets. Red indicates a pyrope:almandine ratio of greater than 1.5:1, black indicates an approximately 1:1 ratio (1.5:1 to 1:1.5), and blue denotes a ratio of less than 1:1.5.

CONCLUSIONS

In practical terms, the gemologist is essentially limited to the use of three tests in the identification of garnets: refractive index, specific gravity, and absorption spectrum. For the red-to-violet garnets, this study shows that these three determinations do provide certain indications of the composition of the stones studied. In one case, that of chrome pyrope, we can use the spectroscopic to observe absorption bands that are characteristic of the high Cr_2O_3 content of these garnets. In addition, refractive index and specific gravity together give us a reasonably reliable indication of the ratio of pyrope to almandine for any specific stone. Anomalies between the two properties may indicate the presence of significant amounts of end members other than pyrope and almandine, especially spessartine. More often, though, stones that contain large amounts of other end members have a relationship between refractive index and specific gravity that still falls within the trend shown by the pyrope-almandine series, as one can see in figure 11. Generally, however, we can define ranges of refractive index and specific gravity that, taken together, indicate whether pyrope or almandine predominates in any given specimen.

To avoid proliferation of names, and for convenience, we support using the name of the end member that predominates. In the less rigorous application of these terms, we can label stones in the red-to-violet color range as being *pyrope* if the refractive index and specific gravity indicate that there is more pyrope than almandine present (R.I. below 1.752 and S.G. less than 3.86), or as *almandine* if these properties indicate that this end member predominates (R.I. above 1.799 and S.G. more than 4.00). In the case of red-to-violet stones having approximately a 1:1 ratio of these two end members (R.I. between 1.751 and 1.774 and S.G. between 3.81 and 3.99), we recommend that the term *pyrope-almandine* be applied. Rhodolite, according to the original definition of the variety, falls within the region to which we would also apply the term *pyrope*.

The spectral data support the existence of a general absorption spectrum associated with garnets in this color range, but there is no clear association between a particular spectrum and any individual end member, including almandine. With the exception of the chrome bands I_1 and I_2 , the variations that can be observed are of ques-

tionable usefulness within this color range. Some bands appear to be affected by various end members, as indicated by the factor analysis (see table 3), but combinations of such end members may cancel out or enhance these effects in such a way as to conceal any correlations. In addition, the general absorption of light associated with stones of deeper color masks many of the bands in the shorter wavelengths.

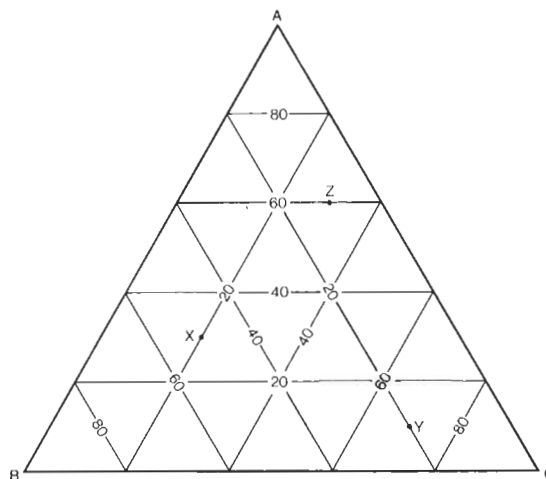
The relationship between color and bulk chemistry for the garnets in this color range seems to be, as can be seen from figure 7, entirely random. This is not surprising, as garnet has long been recognized as allochromatic. The presence of trace elements or ions not readily measurable by the microprobe is undoubtedly responsible for some or all of these variations in color. The quantities in which these trace elements are present, however, apparently are not sufficient to affect refractive index or specific gravity (both of which reflect bulk chemical composition). Thus, the common gemological tendency to associate color with a particular type of garnet such as pyrope or almandine is likely to be misleading if one is interested in an indication of chemical composition within the red-to-violet color range of garnets. Because of the importance of color in the appreciation of gem garnets and based on the results of this study, however, the color criterion must be an important consideration in any gemological classification of garnets. The precise role of color in the classification of all gem garnets, as well as the roles of the other properties examined in this study, must remain unresolved until we have completed the examination of garnets in the other ranges of color and chemical composition.

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The data gathered on the 96 garnets used for this article will be published at a later date, upon the completion of the entire GIA garnet project. Until that time, the authors will provide these data on specific request.

APPENDIX: TERNARY DIAGRAMS

The graphic illustration of the relationship between three components is complicated by the difficulty of visualizing three dimensions on paper (which is two-dimensional). A ternary diagram achieves this illustration by the use of an equilateral triangle scaled from 0% to 100% in each of its three directions (see diagram at right). Each point of the triangle represents 100% of its respective component (e.g., A, B, or C in this diagram), while the side opposite represents 0% of that component (e.g., the line between points B and C represents 0% of A). In order for a specimen to be represented as a single point on this diagram, $A + B + C$ must total 100%. If a specimen is made up 80% of components A, B, and C, and 20% of other components, but one only wishes to examine the relationships between A, B, and C, this can be done by recalculating A, B, and C to add up to 100%. For example, sample X contains 24% A, 40% B, and 16% C. Dividing A, B, and C each by their total (80%) and multiplying by 100% yields recalculated amounts for A, B, and C equalling, respectively, 30%, 50%, and 20%, which now total 100% and can be plotted on a ternary diagram. So, to locate the point for X, read the percentage scale for each component in the appropriate direction (bottom to top for A,



upper right side to lower left corner for B, and upper left side to lower right corner for C). Likewise, the percentages of components represented by points Y and Z can also be read: Y consists of 10% A, 20% B, and 70% C; while Z has 60% A, 10% B, and 30% C.

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