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# A PROPOSED NEW CLASSIFICATION FOR GEM-QUALITY GARNETS

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By Carol M. Stockton and D. Vincent Manson

*Existing methods of classifying garnets have proved to be inadequate to deal with some new types of garnets discovered recently. A new classification system based on the chemical analysis of more than 500 gem garnets is proposed for use in gemology. Chemical, optical, and physical data for a representative collection of 202 transparent gem-quality stones are summarized. Eight garnet species are defined—grossular, andradite, pyrope, pyrope-almandine, almandine, almandine-spessartine, spessartine, and pyrope-spessartine—and methods of identification are described. Properties that can be determined with standard gem-testing equipment (specifically, refractive index, color, and absorption spectrum) can be used to identify a garnet as one of the eight species and, where appropriate, more precisely as one of several varieties that are also defined.*

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## ABOUT THE AUTHORS

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Over the past two decades, the discovery of new types of garnets in East Africa has led to a realization that garnet classification systems based on the early work of gemologists such as B. W. Anderson are no longer entirely satisfactory. This article proposes a new system of classification, derived from chemical data on a large collection of transparent gem-quality garnets, that requires only determination of refractive index, color, and spectral features to classify a given garnet. Thus, the jeweler-gemologist familiar with standard gem-testing techniques can readily and correctly characterize virtually any garnet he or she may encounter, and place it within one of eight rigorously defined gem species: grossular, andradite, pyrope, pyrope-almandine, almandine, almandine-spessartine, spessartine, and pyrope-spessartine. Several varietal categories (e.g., tsavorite, chrome pyrope, rhodolite, and malaia\*) are also defined.

In 1959, B. W. Anderson stated that "since chemical analysis is seldom possible in dealing with gem material, one has to rely on colour, absorption bands, and inclusions in addition to the density and refractive index in an attempt to place the garnet in its correct category." For all practical purposes gemologically, this is still the case. It was also known that the complexities of garnet chemistry made characterization difficult, such that "it cannot be said with certainty, therefore, that a red garnet having a refractive index of 1.771 and a density of 3.911 will consist exactly of 30 per cent almandine [sic] and 70 per cent pyrope [sic], since the presence of a small percentage of andradite will shift the proportions in favour of almandine, and the presence of grossular would produce a lowering

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\*Malaia has previously been spelled "malaya" in the gemological literature; the spelling used here is not only less confusing, but is also that used in East Africa, whence the word originated (C. Curtis, pers. comm., 1985).

effect on the values of the physical data" (Webster, 1983, p. 170).

Although chemical analysis is still not a practical routine test for the gemologist, it is an important tool in many related disciplines. Accurate, rapid, nondestructive chemical analysis became available to researchers in mineralogy in the 1960s with the commercial development of the electron microprobe (invented in 1949). However, the chemical work done by mineralogists (e.g., Reid et al., 1969) rarely includes information on color, clarity, or spectra that would make the data of real use to gemologists. On the other hand, gemology rarely ventured into new analytical areas during the 1960s and 1970s.

As a result, until recently the classification of garnets used by gemologists failed to benefit from these technological advances. The third edition of Webster's *Gems* (1975) describes six major types of garnets: andradite, grossular, spessartine, pyrope, almandine, and the pyrope-almandine intermediate series. The first three are considered discrete types with limited chemical variability (in spite of a brief introductory mention of a continuous series between almandine and spessartine). The series from pyrope to almandine, however, is divided arbitrarily into three parts based on refractive index and specific gravity according to a system devised by Anderson in 1947. The characteristic spectra for garnets, too, come from work done by Anderson 30 years ago (1953–1956).

Toward the end of the 1960s and through the 1970s, however, East Africa revealed a wealth of garnets, among which were some new types (most notably tsavorite and malaia; see Bridges, 1974, and Jobbins et al., 1978) that did not fit any existing definitions. Rhodolite, the characterization of which had already been in question, was also found in Africa and thus the debates on its terminology escalated (see, e.g., Martin, 1970, and Campbell, 1972). Some of the newer material has also presented problems in terminology (e.g., Curtis, 1980; Schmetzer and Bank, 1981; Gübelin and Weibel, 1975). It became evident that a thorough examination of gem-quality garnets—including chemical analysis as well as standard gemological tests—was needed to correctly identify the new material and provide a more definite and rigorous characterization of the established types.

This article reports the conclusions reached in a study that correlates the chemical compositions of an extensive collection of transparent, gem-

quality garnets with their optical and physical properties as acquired through routine gem-testing techniques. Many of our findings were published previously as groups of data were completed (Manson and Stockton, 1981, 1982, and 1984; Stockton, 1982; Stockton and Manson, 1982 and 1983). These papers have covered the five major garnet end members—pyrope, almandine, spessartine, grossular, and andradite—as well as garnets of intermediate composition (see figure 1). These data are assembled here into a unified system of description, classification, and nomenclature for garnets that is oriented toward the needs and practical methods of gemology (see table 1) and resolves many of the questions that have arisen with the newer types of garnets discovered.

## THE GARNET GROUP

Gem garnets belong to a complex group of minerals that share the general chemical-structural formula  $X_3Y_2Z_3O_{12}$ , where X is an ion (generally  $Ca^{2+}$ ,  $Mn^{2+}$ ,  $Fe^{2+}$ , or  $Mg^{2+}$ ) bonded to eight oxygen atoms in a dodecahedral formation, Y ( $Al^{3+}$ ,  $Fe^{3+}$ ,  $V^{3+}$ ,  $Cr^{3+}$ , or  $Ti^{3+}$ ) is bonded to six oxygen atoms in octahedral coordination, and Z ( $Si^{4+}$  or  $Ti^{4+}$ ) is bonded to four oxygen atoms in a tetrahedral coordination (figure 2). When each site is occupied by only one type of ion, the result is identified as an end member of the garnet mineral group. For example,  $Ca_3Al_2Si_3O_{12}$ , pure *grossular*, is such an end member. Five end members can be used to describe virtually all gem garnets: *pyrope* ( $Mg_3Al_2Si_3O_{12}$ ), *almandine* ( $Fe_3Al_2Si_3O_{12}$ ), *spessartine* ( $Mn_3Al_2Si_3O_{12}$ ), *andradite* ( $Ca_3Fe_2Si_3O_{12}$ ); and *grossular*. The complexity of garnets arises from the fact that these various chemical constituents can be present in virtually any proportions in the composition of a single stone. In addition,  $Cr^{3+}$ ,  $V^{3+}$ , and  $Ti^{3+/4+}$  are important chemical constituents of gem garnets and all have had corresponding end members described. However, they occur only as minor or trace elements in gem-quality garnets, and will thus be discussed here as "impurity" ions or oxides rather than as end-member components.

Ambiguity in the use of terms such as *grossular* can result in confusion when discussing garnets. Often these terms are used both to refer to the above-mentioned theoretical pure end members and to denote actual garnets that are only more-or-less close in composition to the pure end member. To avoid such confusion in this presen-

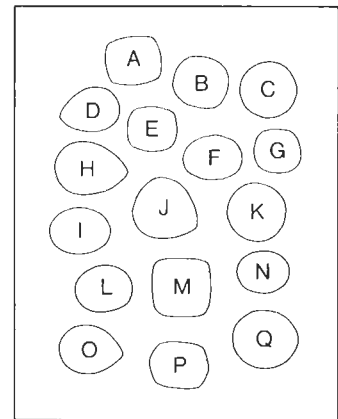
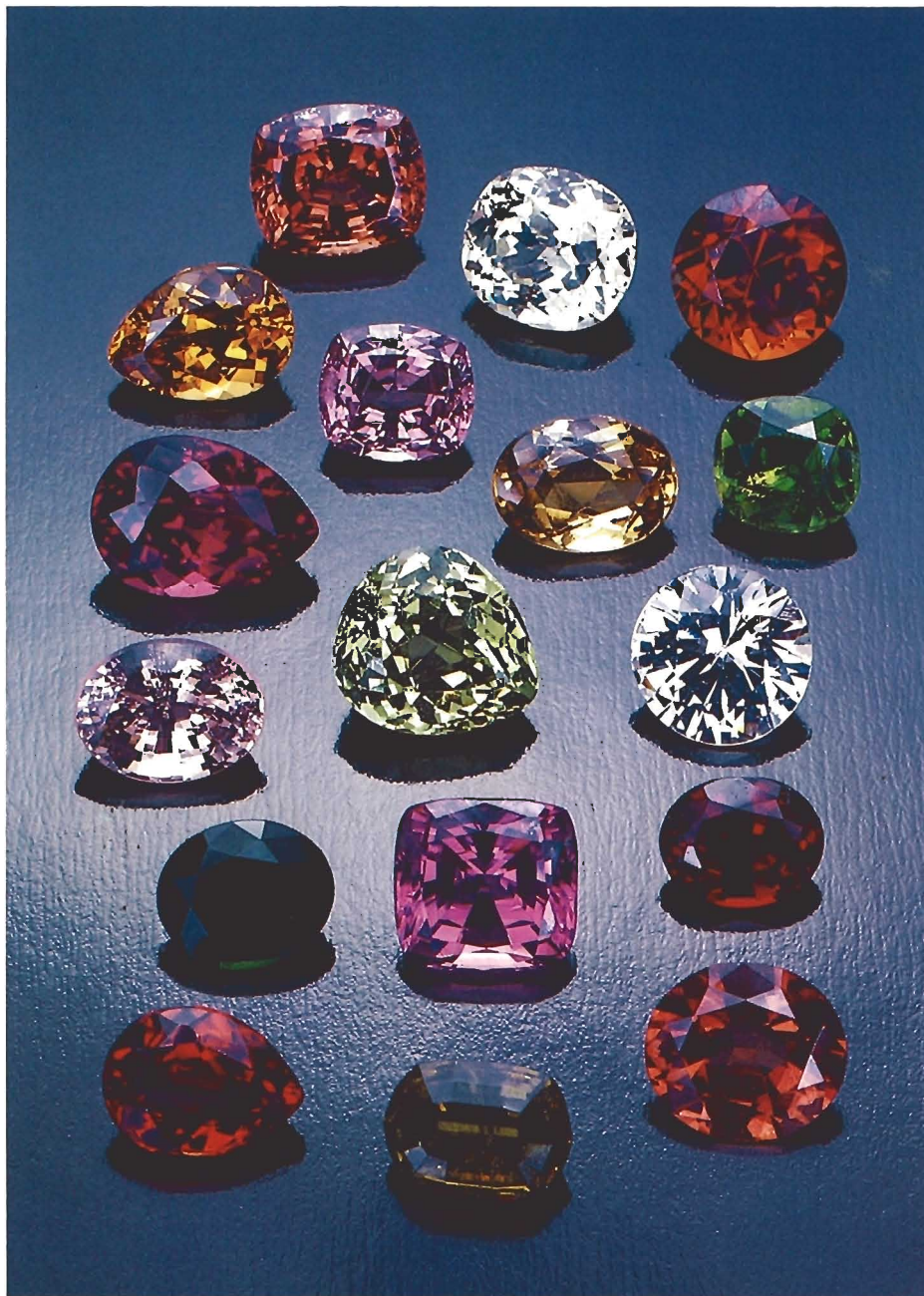


Figure 1. A selection of gem garnets from the study collection that shows the broad range of colors and chemical compositions encountered. These stones have been classified (in the system proposed in this article) as: A—malaya, B—grossular, C—pyrope-spessartine, D—hessonite, E—rhodolite, F—grossular, G—demantoid, H—color-change pyrope-spessartine, I—pyrope, J—tsavorite, K—grossular, L—tsavorite, M—rhodolite, N—chrome pyrope, O—spessartine, P—demantoid, and Q—spessartine (GIA catalogue numbers 234, 1/47, 8960, 7201, 5818, 5873, 1/167, 665, 1/132, 7202, 1/36A, 13319C, 1/84, 13113, 13047, 13234, and 5814, ranging in weight from 1.08 to 2.91 ct). Photo© Tino Hammid.

tation, all references to the theoretical end members will be italicized, as above.

#### DATA COLLECTION

More than 500 gem-quality garnets were examined and chemically analyzed over the past five years. From this group, we selected 202 stones that represent the full range of colors, physical properties, and chemical compositions that have been observed. For each of these 202 stones, we collected data on chemistry, color, visible-range absorption spectrum, refractive index, and specific gravity.

Chemical compositions were determined at least three times for each stone with a MAC automated electron microprobe, and then averaged and converted to end-member components. Color descriptions were obtained with a GEM ColorMaster and converted mathematically to CIE x, y, and z (or tone) coordinates. Absorption spectra were resolved with a Pye-Unicam 8800 dual-beam spectrophotometer as well as with a Beck hand spectroscope. Refractive indices were determined with a GEM Duplex II refractometer or prototype Duplex II with cubic zirconia hemicylinder for stones

**TABLE 1.** The proposed new system of garnet classification with key characteristics for identification.

Species	R.I. ranges	Hues	Spectral absorption features
Grossular	1.730– 1.760	Green through reddish orange, and colorless	None except with highly saturated orange to reddish orange stones (see variety hessonite), which show bands at 407 and/or 430 nm (see right).
Andradite	1.880– 1.895	Very slightly yellowish green through orangy yellow	None except with very slightly yellowish green to yellow-green andradites (see variety demantoid), which usually show a cutoff to about 440–445 nm and may also show additional bands as at right.
Pyrope	1.714–<1.742	Purplish red through reddish orange, and colorless	None when colorless; others with weak bands as for almandine and/or spessartine, or with a cutoff to about 440–445 nm and a broad 564 nm band that may be accompanied by additional bands (see variety chrome pyrope).
Pyrope-almandine	1.742–<1.785	Reddish orange through red-purple	Bands at 504, 520, and 573 nm, but may also show weak bands at 423, 460, 610, and/or 680–690 nm (see right).
Almandine	1.785– 1.830	Orangy red through purplish red	Bands at 504, 520, and 573 nm, as illustrated, but may also show weak bands at 423, 460, 610, and/or 680–690 nm.
Almandine-spessartine	1.810– 1.820	Reddish orange through orange-red	Cutoff to about 435 nm, and bands at 460, 480, 504, 520, and 573 nm, with more or less merging of the last four. In extremely dark stones, all the absorption regions will broaden further.
Spessartine	1.780–<1.810	Yellowish orange through reddish orange	Bands at about 410, 421, 430, 460, 480, and 520 nm, but the first three may merge to form a cutoff to about 435 nm. Weak bands at 504 and/or 573 nm may also be present.
Pyrope-spessartine	1.742–<1.780	Greenish yellow through purple	Bands at 410 and 430 nm, and usually at 421 nm, that occasionally merge to form a 435 nm cutoff. Also show some combination of bands at 460, 480, 504, 520, and 573 nm (see varieties malaia and color-change pyrope-spessartine). Examples are shown at right.

with indices over 1.800. Specific gravities were measured hydrostatically. Details of the microprobe operating conditions, correction program, and end-member conversion, as well as spectrophotometer parameters and actual data, are available on request from the authors.

#### CHEMISTRY

Although garnets theoretically may occur in any

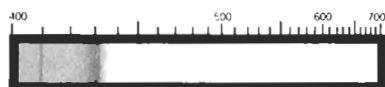
mixture of the end members *pyrope*, *almandine*, *spessartine*, *grossular*, and *andradite*, the observations of this and other studies of gem garnets have enabled us to distinguish eight categories of garnets based on chemical composition: (1) grossular, (2) andradite, (3) spessartine, (4) almandine-spessartine, (5) almandine, (6) pyrope-almandine, (7) pyrope, and (8) pyrope-spessartine.

Grossular garnets that were examined for this



(hand spectroscope)

Varieties



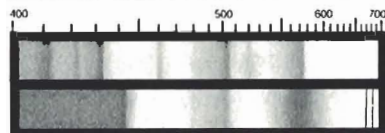
*Tsavorite*: a green to very slightly yellowish green variety of grossular. Shows no absorption spectrum visible with a hand spectroscope.

*Hessonite*: a yellow-orange to reddish orange variety of grossular. Shows no spectrum in lighter tones, but highly saturated stones have bands at 407 and/or 430 nm that are visible with a hand spectroscope (see left).

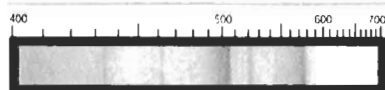


*Demantoid*: a very slightly yellowish green to yellow-green variety of andradite. Always shows a cutoff to about 440–445 nm, but may also show a pair of bands at 618 and 634 nm. Very intensely colored stones also show a pair of thin bands at 685 and 690 nm, as at left, and/or a broad absorption region centered around 600 nm.

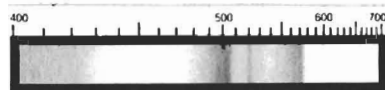
*Topazolite*: a yellow to orangy yellow variety of andradite. Shows no absorption features visible with a hand spectroscope.



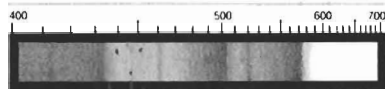
*Chrome pyrope*: an orange-red variety of pyrope that shows a 440–445 nm cutoff, a broad band at about 564 nm, and usually also a pair of thin bands at 670 and 684 nm (see left). May also show a weak band at about 504 nm.



*Rhodolite*: a very slightly purplish red to red-purple variety of pyrope-almandine. Spectral features are the same as for other pyrope-almandines (see left).



*Malaia*: a yellowish orange to red-orange variety of pyrope-spessartine. Always shows bands at 410, 421, and 430 nm that occasionally merge to form a cutoff at about 435 nm. Also shows some combination of bands at 460, 480, 504, 520, and 573 nm. See examples 1 and 2 at left.



*Color-change pyrope-spessartine*: this is a variety of pyrope-spessartine that exhibits a distinct change in the appearance of its body color between incandescent and fluorescent (or daylight) illumination. Hues that have been observed under fluorescent light range from greenish yellow through purple. All stones show bands at 410, 421, and 430 nm that may be merged to form a cutoff at about 435 nm, as well as some combination of bands at 460, 480, 504, 520, and 573 nm. In stones with a strong change of color, the 573 nm band is notably broadened and strengthened. See last three examples at left.

study all consist of more than 75.0 wt.% grossular, with up to 19.0 wt.% andradite. As much as 0.23 wt.%  $\text{Cr}_2\text{O}_3$ , 2.44 wt.%  $\text{V}_2\text{O}_3$ , and 0.52 wt.%  $\text{Ti}_2\text{O}_3$  were also measured in grossulars. *Pyrope*, *almandine*, and *spessartine* taken together never exceed 4.50 wt.% in gem grossulars.

All of the andradites studied consist of more than 95 wt.% *andradite*. Because their composition is so distinct, little needs to be said about their

chemistry. Although gem-quality andradites exhibit minimal chemical variability, this variability is significant with respect to different colors observed. Minor or trace levels of chromium and titanium are the most important additional elements [ $\text{Cr}_2\text{O}_3 \leq 0.20$  wt.% and  $\text{Ti}_2\text{O}_3 \leq 0.10$  wt.%].

The remaining garnets are composed of highly variable proportions of *pyrope* (0–83.0 wt.%),

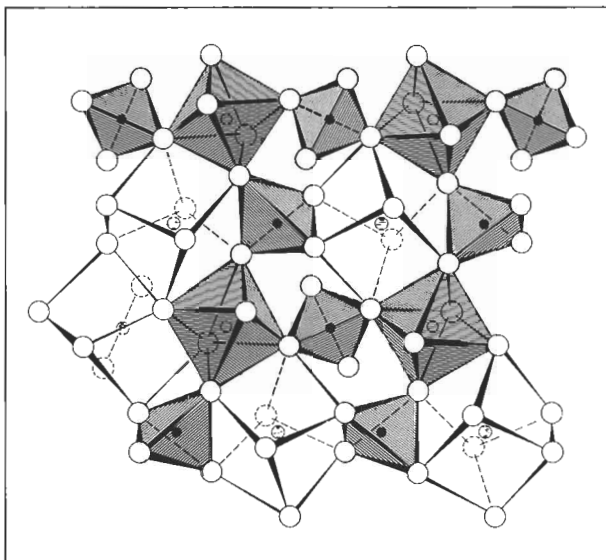


Figure 2. Schematic diagram of a portion of the garnet crystal structure. Hatched circles represent X cations, small open circles denote Y cations, black circles the Z cations, and large open circles the oxygen atoms bonded to the various cations (adopted from Novak and Gibbs, 1971).

*almandine* (2.0–78.0 wt.%), *spessartine* (0.2–94.0 wt.%), and *grossular* (0–24.0 wt.%). None contains more than 4.0 wt.% *andradite*. Figure 3 illustrates the relationship among these garnets with respect to their three major constituents. Heavily "populated" areas are mixtures of *pyrope* and *almandine*, *pyrope* and *spessartine*, and *almandine* and *spessartine*. Examples that approach pure *spessartine* exist, but neither *pyropes* nor *almandines* of such high purity have been encountered in gem-quality stones. There is discontinuity between the series *almandine-spessartine* and those of *pyrope-almandine* and *pyrope-spessartine*. The possibility exists, however, that the latter two may represent one continuous series; there are high *pyrope* stones that include substantial and roughly equal amounts of *almandine* and *spessartine*. On the other hand, there is no apparent reason why gem-quality garnets should not occur that fill any of these gaps. Discovery of new provenances for garnets might easily provide such stones; the *pyrope-spessartine* series, for example, was unknown prior to the discovery of such garnets in East Africa about 20 years ago. Thus, classification of stones in this chemical array seems likely to involve arbitrary decisions, at least insofar as chemical distinction is involved.

## COLOR

Natural gem garnets occur in a wide variety of hues, from green through yellow and red to purple (figure 4). Some of these colors are characteristic of certain types of garnets. For example, intense greens are found only among *grossulars* and *andradites*. Generally, any green garnet will belong to one of these two species, although the study collection contains a single color-change *pyrope-spessartine* (GIA 96A) that is greenish yellow in fluorescent light or daylight—close enough to green to suggest that sweeping generalities about green garnets must be avoided. Colorless and yellow garnets have as yet been confined to the *grossular* category. Yellowish orange to reddish orange (including brown) garnets may be *grossulars*, *spessartines*, or any of various mixtures of *almandine*, *spessartine*, and/or *pyrope*. Red to purplish red garnets belong to mixtures of *pyrope* and *almandine*. Red-purple garnets may be *almandines*, *pyrope-almandines*, or color-change *pyrope-spessartines*. The few purple stones encountered have all proved to be color-change *pyrope-spessartines*.

## ABSORPTION SPECTRA

There is considerable disagreement in the interpretation of many of the spectral absorption bands that may be observed in the visible-light range for garnets (see, for example, Manning, 1967 and 1972; Slack and Chrenko, 1971; Moore and White, 1972; Frentrup and Langer, 1981). Empirically, however, correlations can be made between certain absorption features and the chemical constituents typically associated with various colors. While these relationships should not necessarily be interpreted as cause and effect, they nonetheless fulfill our present needs for the identification and classification of gem garnets. Characteristic absorption spectra for the various types of gem garnets are illustrated in table 1 and discussed below.

**Grossular.** With the exception of some intense orange to reddish orange stones, *grossulars* do not exhibit any features visible with a hand spectroscope. For the exceptions, an absorption band can be resolved at about 430 nm. It is accompanied by a very thin band at 407 nm that can sometimes also be seen with a hand spectroscope. Less intensely colored orange and yellow *grossulars* exhibit increasing absorption toward the blue end of the spectrum, but no distinct bands. Greenish yellow

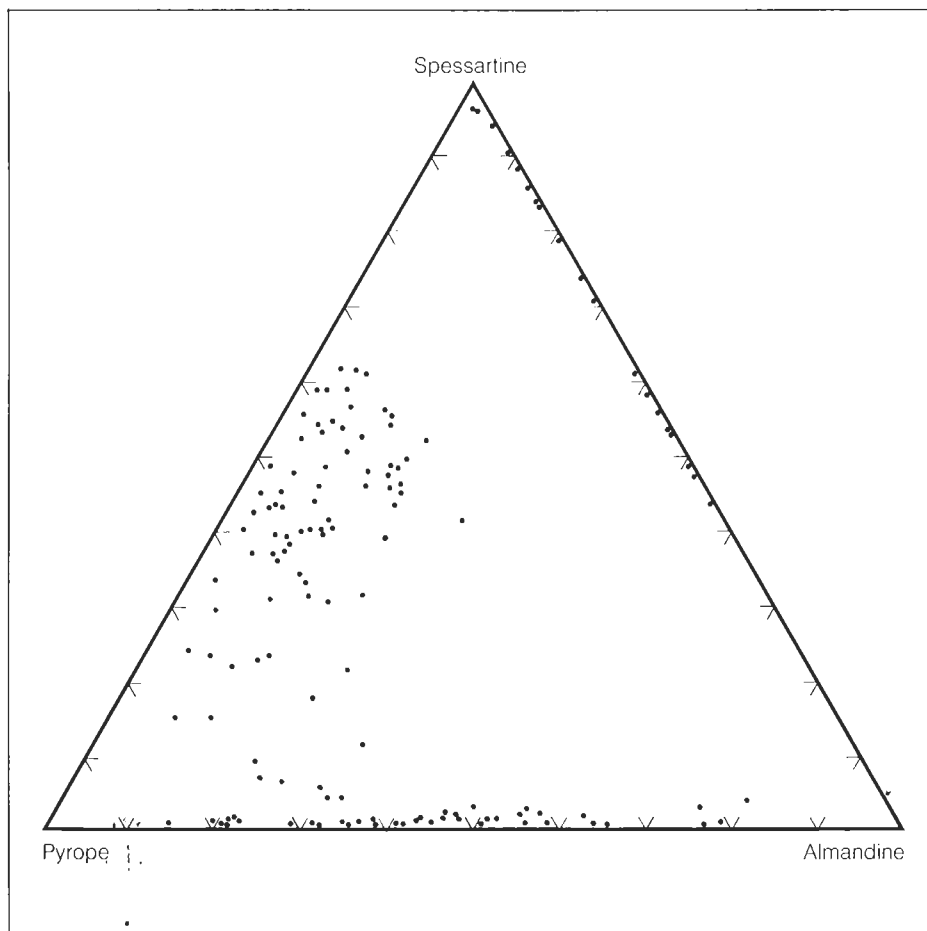
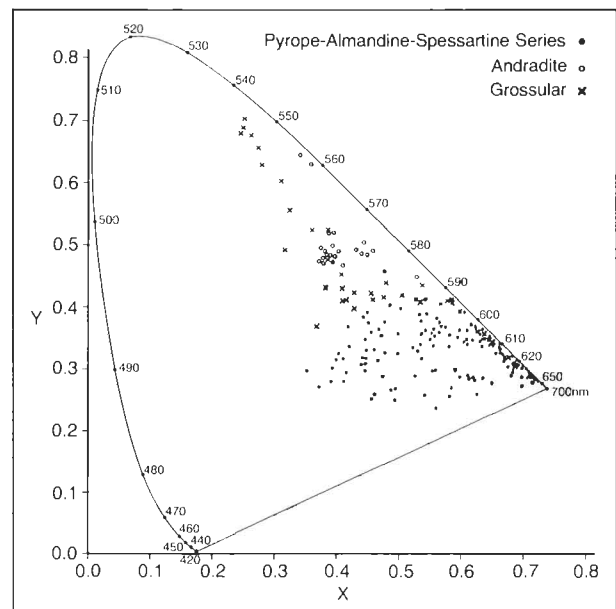


Figure 3. Compositional ternary diagram for garnets in the study collection that are composed primarily of pyrope, almandine, and/or spessartine (i.e., less than 25 wt.% grossular).

low to green grossulars have two broad regions of absorption centered around 425 and 600 nm that are too attenuated to be visible with a hand spectroscope.

**Andradite.** Very slightly yellowish green to yellow-green andradites invariably exhibit complete absorption to about 440–445 nm that is due to a very strong band centered at about 434 nm. Less yellowish and more intense green stones may also show a pair of bands at approximately 618 and 634 nm. Occasionally, with very intense green demantoids, a pair of thin bands is also visible at about 685 and 690 nm. In addition, all green andradites have a broad absorption region centered at about 600 nm that can be resolved with the spectrophotometer but not usually with a hand spectroscope. The single orangy yellow andradite examined showed no features with a hand spectroscope, but displayed bands at about 438 and 600 nm on the spectrophotometer. The 600 nm band was considerably weaker than its counterpart in the green stones.

Figure 4. CIE chromaticity diagram (tone level 5) with coordinate points plotted for the 202 garnets in the study collection. The range of hues extends from green to purple.



**Pyrope.** Pure *pyrope*, not found in nature, is colorless and has no absorption features in the visible wavelengths. (Colorless pyrope that exceeds 97% of that end member has recently been found, but not in gem sizes; Chopin, 1984.) However, gem-quality garnets high in *pyrope* vary considerably in color and spectral features. Some exhibit features common to almandine, spessartine, or both. More common are the intense, dark red pyropes with strong, broad bands centered at about 410 and 564 nm; the 410 nm band appears as a cutoff to about 440–450 nm when observed with a hand spectroscope. Some of these stones also reveal a pair of narrow bands at about 670 and 684 nm.

**Pyrope-Almandine.** Pyrope-almandine garnets display spectra consistent with that described below for almandines.

**Almandine.** High-*almandine* garnets exhibit strong bands at 504, 520, and 573 nm, as well as weaker bands (not usually visible with a hand spectroscope) at 420, 460, 610, and 680–690 nm.

**Almandine-Spessartine.** Stones of mixed *almandine* and *spessartine* content exhibit spectra with strong features contributed by both end members: a 435 nm cutoff, with a usually distinct band at 460 nm, and bands at 480, 504, 520, and 573 nm that generally merge into a single broad region of absorption.

**Spessartine.** Garnets with a high *spessartine* content exhibit a spectrum that, at the least, contains bands at 407, 411, 421, 430, 460, 480, and 520 nm. The first four bands, however, are very strong and overlap in such a way that they appear in the hand spectroscope as either two broad bands at about 410 and 430 nm (a weak 421 nm is also sometimes visible) or as a cutoff to about 435 nm. Bands at about 504 and 573 nm are at times present, but they are invariably weaker than the others and apparently relate to the amount of *almandine* in a given stone.

**Pyrope-Spessartine.** Garnets composed primarily of *pyrope* and *spessartine* invariably have strong bands in the blue, as in spessartines, and usually bands at 504, 520, and/or 573 nm. However, these bands vary considerably in relative strength, and 460 and/or 480 nm bands may also be present in some specimens.

The pyrope-spessartines also include the color-change garnets, which have a 435 nm cutoff due to a strong set of overlapping 407, 411, 421, and 430 nm bands, and in most cases a broad band centered at approximately 573 nm. Bands at about 460, 480, 504, and 520 nm may also be visible with a hand spectroscope in some specimens. In lighter-colored specimens, individual bands may be resolved in the blue. Occasionally, the 573 nm band is too weak to be resolved, in which case only 407–411, 421, and 430 nm bands, as well as very weak 460 and 480 nm bands, are visible.

#### PHYSICAL DATA

A graphic distribution of refractive-index and specific-gravity data for the 202 garnets studied (figure 5) reveals three relatively distinct groups. Andradites have a considerably higher refractive-index range ( $\geq 1.880$ ) than any other type of garnet ( $\leq 1.816$ ). The specific-gravity range for grossulars is lower than that of any other garnet examined: Gem grossular has not yet been observed to exceed 3.66, while the lowest value for any specimen that might be visually mistaken for grossular is 3.75 (pyropes, however, have been observed to have densities as low as 3.67). The remaining coordinates form more or less of a continuum between 1.731–1.816 and 3.75–4.29. There is so much overlap in specific-gravity ranges for the various types of garnets (again, see figure 5) that the usefulness of this property is questionable. Moreover, the difficulty of accurately measuring density as well as the considerable variability introduced by the presence of inclusions suggests that this is not a reliable characteristic for the identification and classification of gems. The graph also shows that there are minor discontinuities in the distribution of the observed refractive indices, but all of these gaps, with the probable exception of that separating andradite, are small enough that they could disappear with additional data.

#### DISCUSSION

Classification of garnets has been impeded not only by the complex compositional variability of the material itself but also by a lack of well-defined and well-characterized terminology. Thus, debates on the use of varietal terms (e.g., Trumper, 1952; Anderson, 1959; Martin, 1970; Curtis, 1980; Schmetzer and Bank, 1981) suffer largely from a case of building castles on sand. Before defining specific gemological terminology, we need to ex-



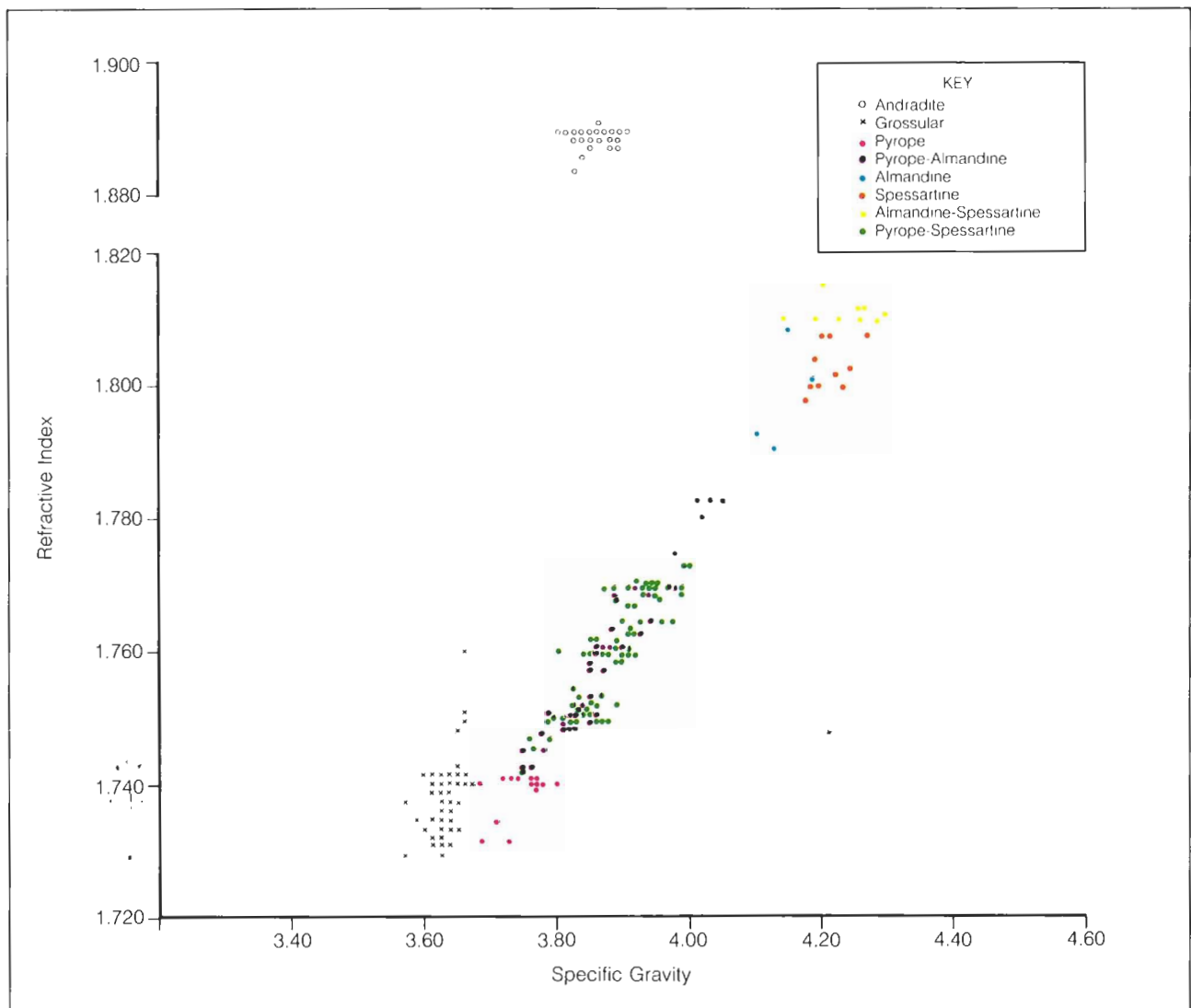


Figure 5. Refractive-index and specific-gravity coordinates plotted for the 202 gem garnets in the study collection. Apart from the separation of andradites, no obvious distinctions appear on the basis of either property individually or both properties together.

amine what is meant mineralogically by the terms *series*, *species*, and *variety*; determine whether these definitions can be practically applied to gemology; and, if they cannot, decide what modifications are needed to provide gemologists with a working system that can be used to classify mineral group gems such as garnets.

**Mineralogical Terminology.** According to the seventh edition of *Dana's System of Mineralogy* (Palache et al., 1944, Vol. 1, p. 3), a series consists of "minerals sharing a continuous variation in their properties with a change in composition." A mineral species has been defined as "a natural inorganic substance which is either definite in chemical composition and physical characters or varies

in these respects between definite natural limits" (Winchell, 1937, Pt. 1, p. 1); this is the fundamental unit for classification in mineralogy and, as such, has been well characterized. Varieties have been defined as subdivisions of species that "may have distinctive physical properties . . . or chemical composition" (Mason and Berry, 1968, p. 198). In the latter case, it has been proposed that an adjectival modifier that indicates the chemical variability be prefaced to the appropriate species name. Varieties distinguished by characteristic physical properties such as color may be affixed with a special name. This practice, however, has only recently been widely recognized by mineralogists, so the bulk of mineralogical classification does not reflect this nomenclature, nor do all min-

eralogists agree to its usage even now. In fact, the multitude of ways in which the variety concept has been applied is confusing, to say the least (see, for example, Hey, 1955, p. xiii).

The garnet group has been subdivided into "species" (almandine, grossular, etc.) that represent end members of chemically continuous series (Deer et al., 1963). However, the use of the species concept to subdivide the garnets contradicts the foregoing definition, since there is a lack of "definite natural limits." Varieties such as rhodolite and hessonite are occasionally included in mineralogical references but, aside from a brief mention of color and a vague identification of their species, they are not defined.

**Gemological Terminology.** While mineralogical classification is somewhat inconsistent, it is still the best precedent available to gemology. This inconsistency, however, allows a great deal of flexibility in gemological classification without extensively contradicting mineralogical precedents. Since the concept of species as defined by mineralogy (see above) is inadequate with respect to mineral groups such as garnets, we propose that, for gemological purposes, the *species* subdivision of a mineral group be defined as *a naturally occurring inorganic substance that has a definite crystal structure and a fixed (natural or arbitrary) range of chemical composition within the compositional limits of its mineral group*. A species will thus have characteristic ranges of properties, including ones that can be determined by gemological techniques. Similarly, we recommend that the gemological concept of *variety* be explicitly defined as *a subdivision of a species that may be differentiated either by distinctive physical characteristics such as color and phenomena or by consistent minor chemical disparity*.

## CONCLUSIONS

### Proposed Classification of Gem-Quality Garnets.

Table 1 outlines the proposed classification of gem garnets based on correlations among the data discussed in this article and organized according to the definitions of species and varieties discussed in the preceding section. Transparent gem garnets can be divided into eight species; a number of these are subdivided further into specific varieties. Most of the varietal terms recommended for use in gemology are based on color: tsavorite, hessonite, demantoid, topazolite, rhodolite, and malaia.

There are still many garnets that have not been given variety names, and these should be referred to only by terminology that incorporates the appropriate species name. This latter practice discourages the proliferation of special, frequently confusing, terms. Thus, while a purplish red pyrope-almandine is a rhodolite, a red stone of otherwise similar properties would be referred to only as pyrope-almandine. Chrome pyrope is a chemical variety based on the presence of appreciable amounts of  $\text{Cr}^{3+}$  that produce a characteristic color and spectrum. The varietal modifier *color-change* is recommended for pyrope-spessartines of any color that exhibit that phenomenon. (Change-of-color pyropes have also been found, in certain peridotite rocks and as inclusions in diamonds, but as yet no stones have been encountered that are large enough to be cut as gems. Should this occur, however, such stones would be called "color-change pyropes.")

Observed ranges of refractive indices were extended to cover the gaps between the observed data. For example, we encountered no specimens that have spessartine:pyrope ratios of more than 2:1 and less than 90:1. However, there is no reason to think that such stones could not occur and, given the correlation between refractive index and chemistry, we can extrapolate and predict the properties of garnets that we have not encountered yet but that we might expect to come across in the future. Thus, while we know of no spessartines with refractive indices below 1.798, or pyrope-spessartines with R.I.s above 1.773, we have drawn the boundary between these two types of garnet at 1.780.

The boundaries and property values expressed in this classification system are not necessarily consistent with interim groupings discussed in previous articles on this extended study of garnets, most especially with respect to the first in the series (Manson and Stockton, 1981). It was with this eventuality in mind that we reiterated in each of those papers that properties and terms discussed prior to this article were entirely provisional. Only comparison of all the data on a full range of gem garnets has enabled us to identify what appear to be useful and logical divisions.

We have avoided the issue of determining which suffixes, *-ine* or *-ite*, should be applied to species names in those cases where they have been disputed. Both forms are in common usage and both adequately communicate the intended idea,



Figure 6. These three garnets all look very similar to one another, but they differ considerably in their properties and chemical composition. Clockwise, from lower right, they are grossular (hessonite), spessartine, and pyrope-spessartine (malaia).

so we leave the choice to individual preference. It should also be pointed out that this proposed system of classification is designed specifically for use by gemologists and does not imply either acceptance by mineralogy or even the suggestion that it should be adopted by mineralogists, although it can be clearly and unambiguously understood by mineralogists.

**Determination of Garnet Species.** The identity of a given stone can be established by the combined use of color, refractive index, and spectral features, according to the values provided in table 1. While determination of only one or two properties is at times adequate to identify the species and/or variety of a given garnet, it is recommended that the practicing gemologist determine no less than all three properties (i.e., refractive index, color, and absorption spectrum) whenever possible before confirming the identity of a stone. Thus, given a stone of a particular color (its most easily observable property), once its refractive index is measured, its identity rests on the determination of its spectrum. For example, three stones of almost identical appearance (see figure 6) are submitted for identification. According to color, possible identities are grossular (hessonite), pyrope, pyrope-almandine, almandine, almandine-spessartine, spessartine, or pyrope-spessartine; only andradite is eliminated, as reddish orange and red-orange colors do not occur in that species. The stone at lower right in figure 6 has a refractive index of 1.758 and the spectrum shown in figure 7a; reference to table 1 will show that this stone must be grossular (variety hessonite). The stone at lower left has a refractive index of 1.795 and the spectrum in figure 7b; this stone must, therefore,

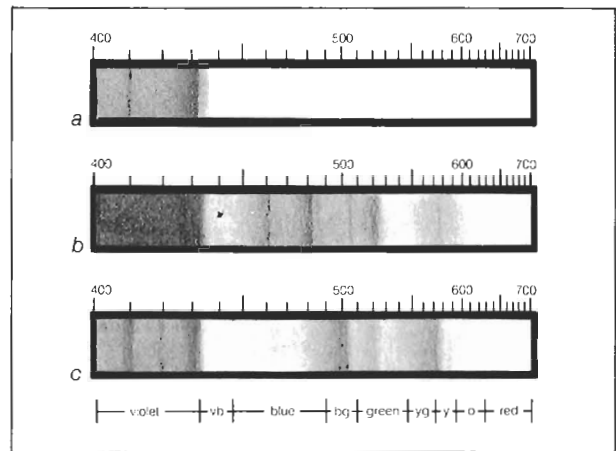


Figure 7. Absorption spectra of the three garnets in figure 6: (a) grossular (hessonite), (b) spessartine, and (c) pyrope-spessartine (malaia). In conjunction with refractive indices, these spectra will distinguish the three similarly colored garnets from one another.

be a spessartine. The third stone in figure 6 (top center) has a refractive index of 1.765 and spectral features as shown in figure 7c; the properties as summarized in table 1 indicate that this garnet must belong to the species pyrope-spessartine (variety malaia).

Separations of garnet species are straightforward in most cases, but there are borderline cases that may present difficulties, especially among the garnets that are mixtures of *pyrope*, *almandine*, and/or *spessartine*. Figure 8 will help illustrate how decisions can be made, along with the following list of paired species and their key distinguishing features:

- Pyrope can be distinguished from any other garnet except grossular on the basis of its low refractive index ( $<1.742$ ).
- Pyrope vs. grossular can be determined by spectrum or, if colorless, by refractive index (colorless grossular will be  $\geq 1.730$ , while colorless pyrope will be  $<1.730$ ).
- Pyrope-spessartine vs. pyrope-almandine can be distinguished by spectrum (the latter has no 410 and 430 nm bands) and frequently by color (pyrope-spessartine occurs in oranges not encountered in pyrope-almandines). Moreover, color change occurs only in the pyrope-spessartines.
- Pyrope-spessartine vs. almandine can be determined by R.I. ( $<1.780$  and  $\geq 1.785$ , respectively) as well as by spectrum (lack of 410 and 430 nm bands in the latter).
- Pyrope-spessartine can be distinguished by refractive index from both spessartine and almandine-spessartine, since the latter two exceed the top R.I. value of  $<1.780$  for pyrope-spessartine.
- Pyrope-almandine vs. almandine can be determined by R.I. ( $<1.785$  and  $\geq 1.785$ , respectively).
- Pyrope-almandine vs. spessartine can be distinguished by spectrum (no 410 and 430 lines in the former), usually by color, and by R.I., except for a narrow range of overlap between 1.780 and 1.785.
- Pyrope-almandine vs. almandine-spessartine can be distinguished by R.I. ( $<1.785$  and  $\geq 1.810$ , or over the limits of a standard gem refractometer) and by spectrum (the former has no 410 and 430 nm lines).
- Almandine can be separated from spessartine by spectrum (no 410 and 430 nm bands in the former) and by color (the former are predominantly red, the latter predominantly orange).
- Almandine vs. almandine-spessartine can be determined by spectrum (the former has no 410 and 430 nm lines) and if a C.Z. refractometer and high-R.I. liquid are available, by refractive index as well.
- Spessartine vs. almandine-spessartine can be distinguished by spectrum (weak but distinct bands at 480, 504, 520, and/or 573 nm in the former, as compared to a broad region of ab-

sorption between 470 and 580 nm in the latter; both have strong absorption in the blue) in conjunction with color (more orange in spessartines, and more red in almandine-spessartines).

The most difficult separations that have been encountered are those close to the border between spessartine and almandine-spessartine (see figure 8), where identification depends on subtle differences in color and spectra, and at the boundary between pyrope-spessartine and pyrope-almandine, where the decision depends on the visibility of the 410 and 430 nm bands. Under no circumstances, however, should we have to classify a garnet simply as "garnet;" the very worst one can do is decide that a stone is near the boundary between two species, although such cases should be rare.

Figure 8 displays a large unlabeled trapezoidal area in its center, bounded by pyrope-spessartine, spessartine, almandine-spessartine, and almandine. No gem garnets have yet been reported to have chemical compositions that would place them in this region. Should such garnets be encountered, however, it is most likely that they would represent an expanded range for the almandine-spessartines.

In the past, specific gravity has been used in conjunction with refractive index to classify garnets. Although we generally discourage the use of this property in gemology, it nonetheless can provide some useful indications. Grossulars have so far been observed to have densities below those of any other species of gem garnet, although by only an extremely small margin. Almandines, spessartines, and almandine-spessartines in the study collection invariably had specific gravities above the range observed for pyropes, pyrope-almandines, and pyrope-spessartines. Once again, however, the potential for overlap of these ranges is great. In the event that a refractive index cannot be determined for a sample of questionable identity, the determination of specific gravity may assist the identification by making use of figure 5, but it should be used with caution.

The system of classification for gem garnets that has resulted from this study is totally consistent with chemical variability within the garnet group. Application of the system, however, depends entirely on the use of practical gemological techniques: color, refractive index, and absorption spectrum as determined with a hand spectroscope.



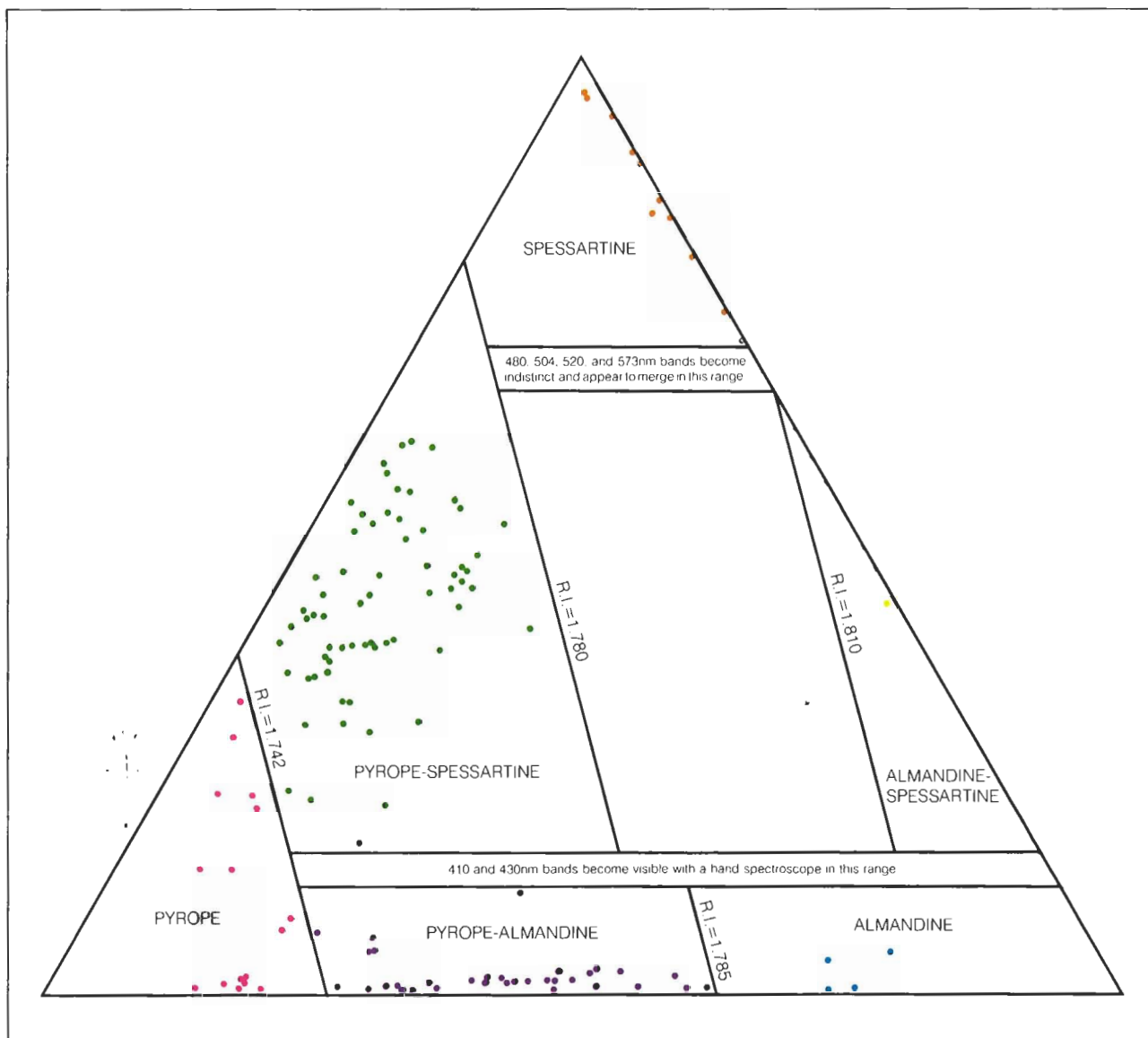


Figure 8. Ternary diagram with data points based on molecular percentages for the garnets of mixed pyrope, almandine and/or spessartine composition in the study collection. (Figure 3 is based on weight percentages, and so has a slightly different appearance with respect to the location of data points.) Superimposed are important refractive index and spectral boundaries that can be used to distinguish among the six proposed garnet species labeled, as discussed in the text. The locations of these boundaries were determined by correlations with the chemical compositions determined in this study.

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